COMPARISON OF FEA SIMULATIONS AND EXPERIMENTAL RESULTS FOR AS-BUILT ADDITIVELY MANUFACTURED DOGBONE SPECIMENS

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Overview

- Introduction
  - Motivation
  - Objective
  - Scope
- Literature Review
  - What others have done
  - Methods adopted
- Methodology
- Results
- Work remaining
- Conclusion
- Future Work

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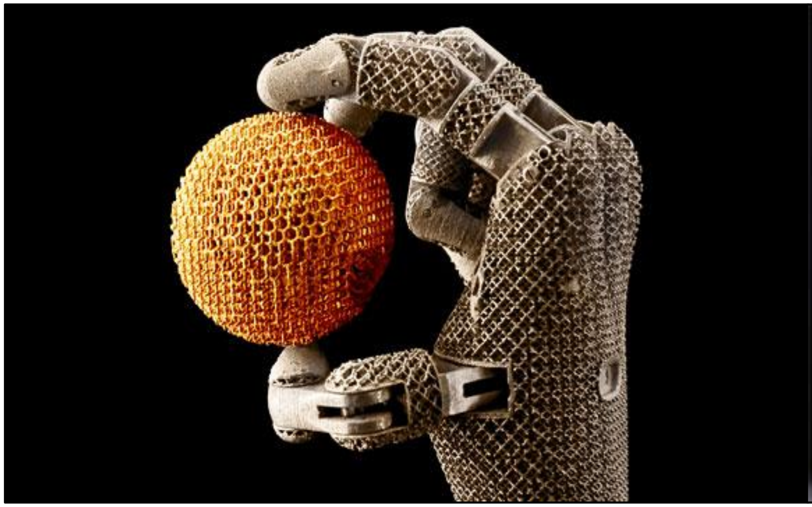
What is Additive Manufacturing (AM)?

- Additive manufacturing refers to the methods of building 3D objects in which material is **added**/deposited layer-by-layer.
- Represents additive processes like FDM, SLA, SLS etc.



Source: http://ie.sabanciuniv.edu/en/announcements-detail/62827

Source: https://www.pinterest.com/pin/469359592385258477/

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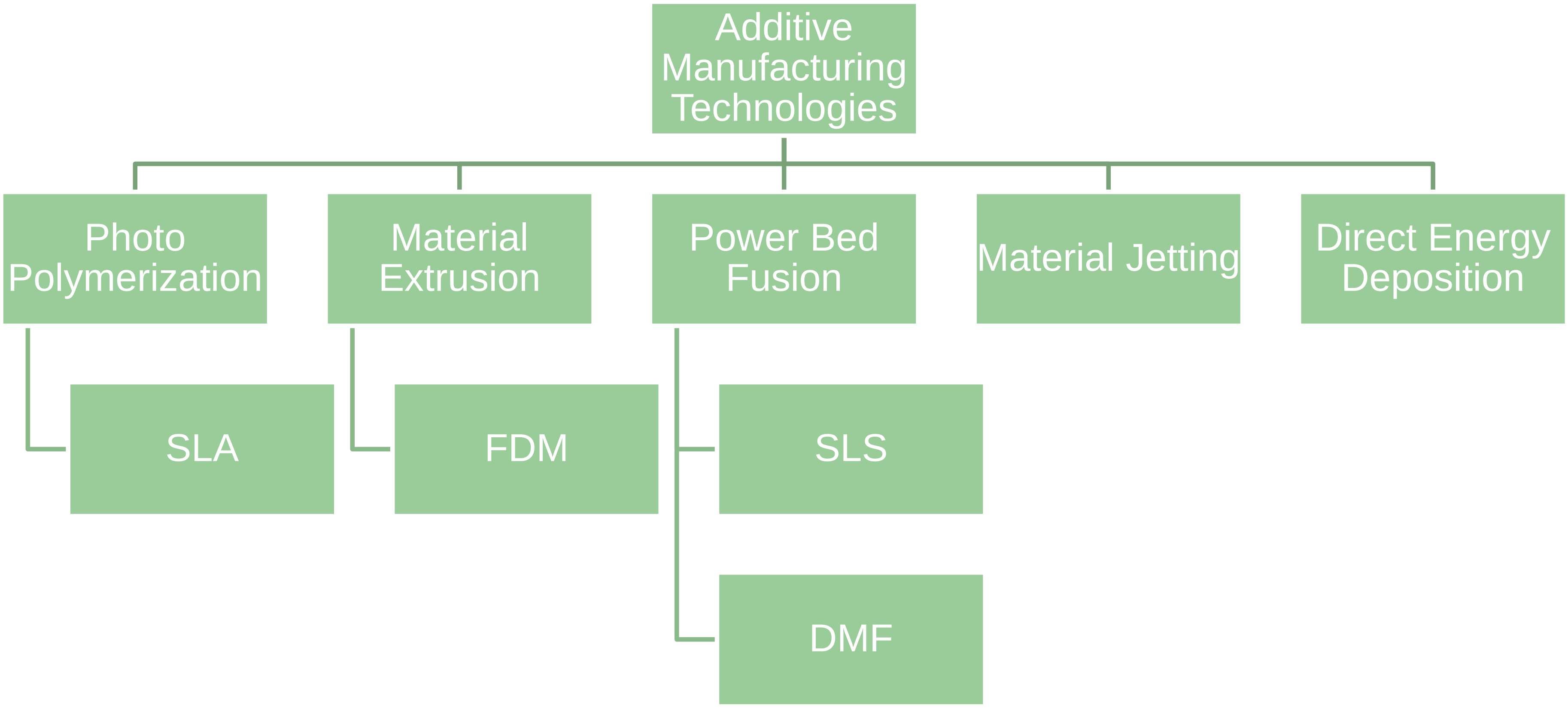
AM Technologies



Source: https://www.3dhubs.com/talk/thread/additive-manufacturing-infographic

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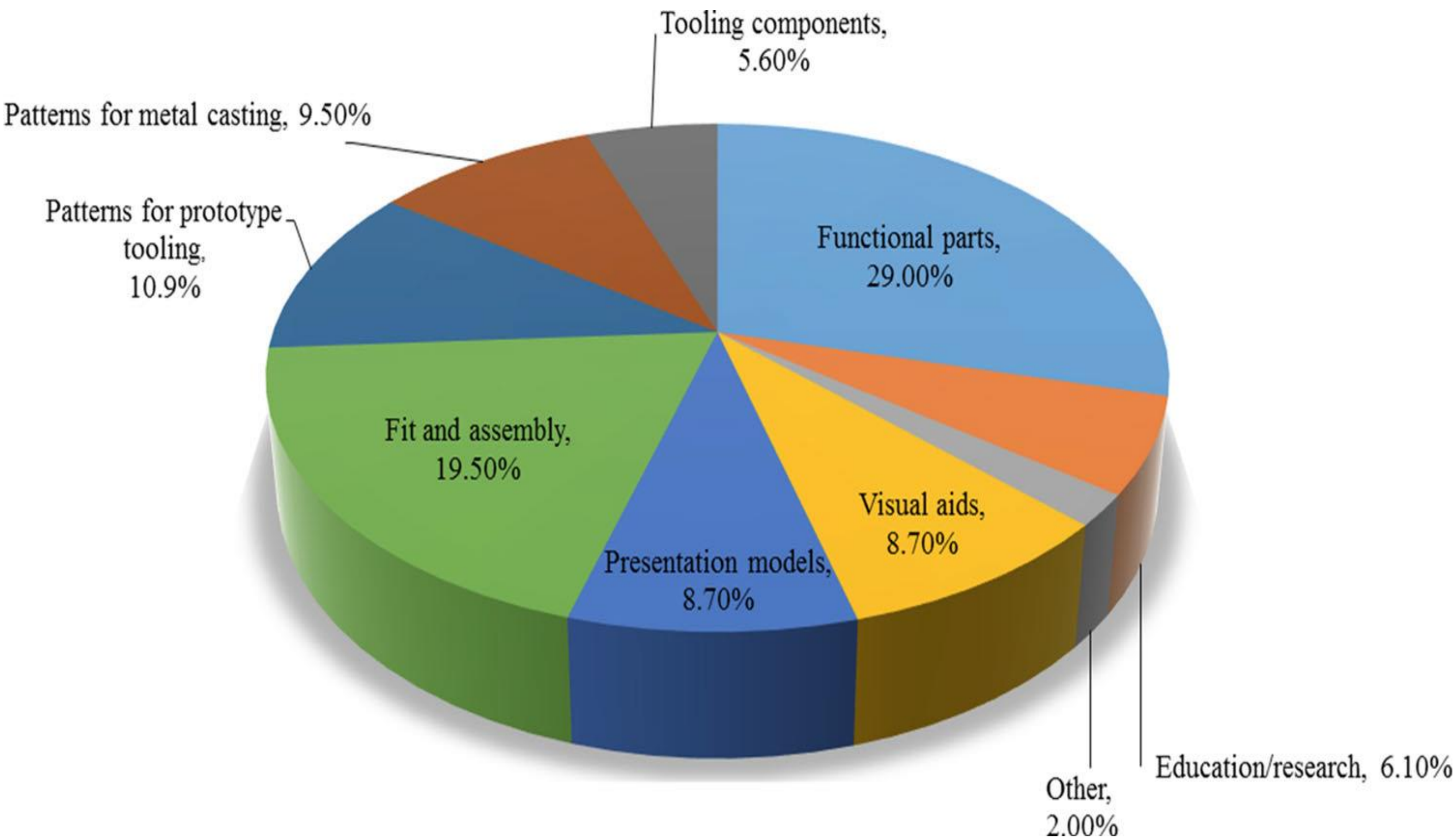
Applications



Source: [4] T. Wohlers, "U.S. Manufacturing Competitiveness Initiative Dialogue," presented at the Council on Competitiveness, Oak Ridge, TN, 18-Apr-2013.

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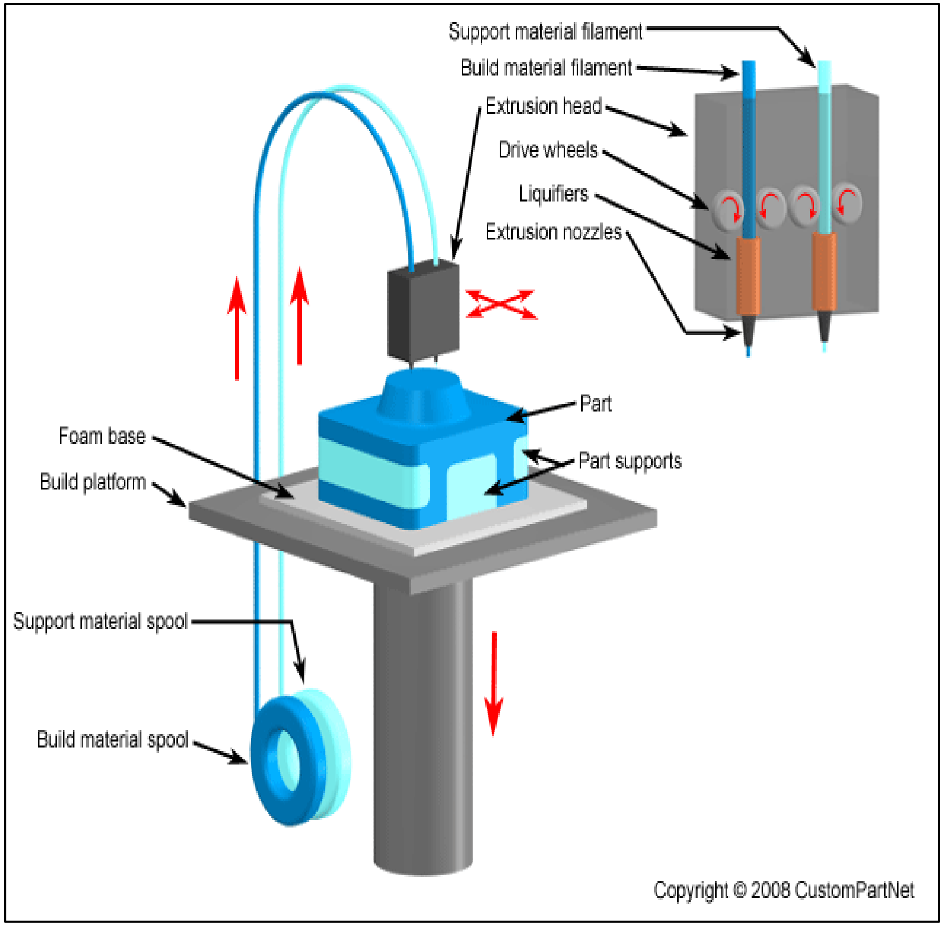
Fused Deposition Modeling (FDM)

- FDM is layered manufacturing technology that produces parts with complex geometries layer by layer by extruding and depositing material.
- Variety of polymers: ABS, PLA
- Applications: Tooling, Functional Prototypes, Low volume production parts etc.



Source: http://www.custompartnet.com/wu/fused-deposition-modeling

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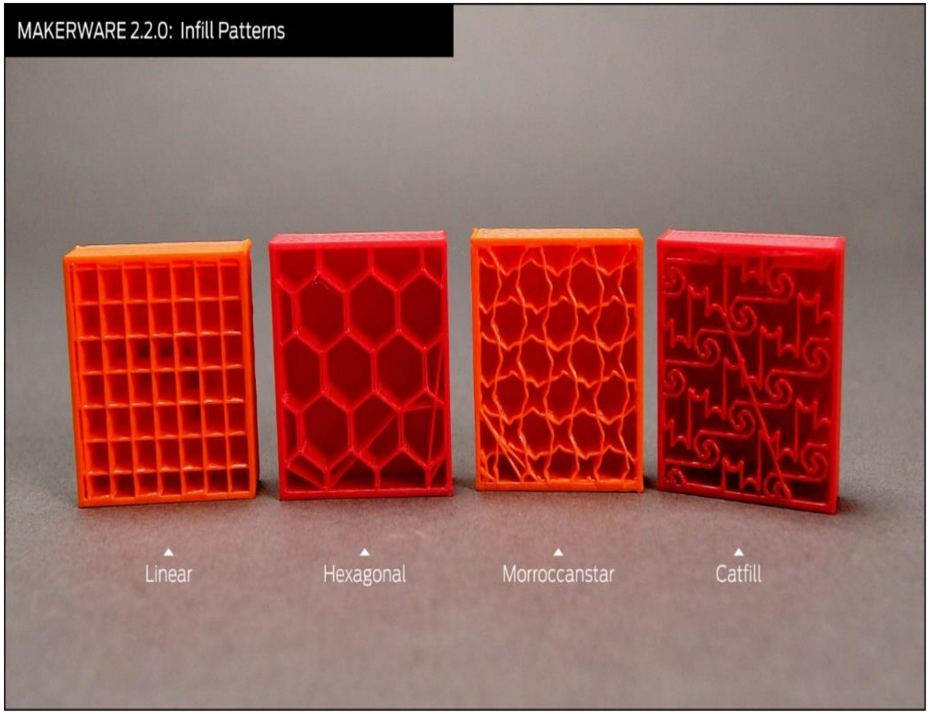
Infill pattern and Complex geometries



Source: https://engineerdog.com/2015/03/08/3d-printing-a-3d-honeycomb-infill-concept/

Source: http://www.makepartsfast.com/solid-concepts-expands-fdm-capacity/

Source: http://www.stratasys.com/materials/fdm/nylon

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General FDM/AM process

Pre-processing

- Create a 3D CAD model.
- Convert into STL file format
- Use a slicing software which slices the model into successive layers for the printer

Production

- The printer heats the filament to a semi-molten state and deposits the filament on the extrusion path.
- After a layer is completed, the build platform moves down and the subsequent layer is deposited on top of it.
- Since the material is extruded in a semi-molten state, the newly deposited material fuses with adjacent material.
- Supports are printed simultaneously in case of overhangs.

Post-processing

- Break away supports or use water in case of dissolvabl e support.
- Polish rough areas if any.

Advantages of FDM/AM technologies

- Build lightweight, durable parts.
- Ability to design complex parts including complicated, internal features.
- Absence of tooling, saves time and money included in tooling process.
- Ability to build durable and effective parts in low volume.
- Additive process reduces material waste.
- Ideal for concept modeling and prototyping.

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Disadvantages

- Manufactured part is not a perfect rendition of the 3D CAD model.
- Owing to the microstructure and imperfect bonding, material properties are not as expected.
- The properties depend greatly on the layer orientation (filament direction within layers).
- The part as a whole behaves as an anisotropic part, even though the material is isotropic

Motivation

- With increasing use of AM parts in functional applications, the need for simulating parts in loading conditions arises.
- With weight-savings from infill patterns and different layer orientations, analyses of these parts is important.
- Analyses like FEA in which the part is discretized into a continuum of finite elements which can be used.
- Due to the microstructure of FDM, FEA may not be able to effectively predict the behavior of FDM parts in their entirety.
- Comparing and validating the FEA results with experimental results will informs us about the prediction reliability of FEA models for AM parts.

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Objective

- To analyze as-built FDM parts by Finite Element Analysis, using isotropic and orthotropic properties.
- To validate FEA results with experimental results using FDM printed parts.

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Scope

- To develop as-built parts with different infill patterns.
- Print the parts and conduct tensile tests to obtain experimental results.
- To simulate the tensile tests and analyze these parts using bulk material properties.
- Analyses are also carried out using derived isotropic properties and orthotropic properties.
- ANSYS and Abaqus are used as FEA solvers.
- Parts are analyzed only in the elastic region.

Literature Review

- Review effect of process parameters to get effective or best possible print.
- Review parameters causing anisotropy.
- Review approaches used for analysis.
- Review research needed.

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Literature Review - Effect of process parameters

	Raster / Layer Orientation	Temperature	Filament Width	Air gap	Layer Thickness
Gajdos et al [9]		✓			
Sun et al [10]	✓	✓			
Bagsik *et al* [11], Es-Said *et al* [12], Zieman et al [13], Upadhyay et al [14]	✓				
Ahn et al [15]	✓	✓	✓	✓	
Wu et al [16], Syamsuzzaman et al [17]	✓				✓

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Analytical Approaches used for material model

Isotropic Model[18]

$$\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{zx}\end{bmatrix} = \begin{bmatrix}\frac{1}{E_I} & -\frac{\nu}{E_I} & -\frac{\nu}{E_I} & 0 & 0 & 0\\ -\frac{\nu}{E_I} & \frac{1}{E_I} & -\frac{\nu}{E_I} & 0 & 0 & 0\\ -\frac{\nu}{E_I} & -\frac{\nu}{E_I} & \frac{1}{E_I} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G_I} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G_I} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_I}\end{bmatrix} \begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{xy}\\ \tau_{yz}\\ \tau_{zx}\end{bmatrix}$$

Transversely Isotropic Model[19]

$$\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{zx}\end{bmatrix} = \begin{bmatrix}\frac{1}{E} & -\frac{\nu'}{E'} & -\frac{\nu}{E} & 0 & 0 & 0\\ -\frac{\nu'}{E'} & \frac{1}{E'} & -\frac{\nu'}{E'} & 0 & 0 & 0\\ -\frac{\nu}{E} & -\frac{\nu'}{E'} & \frac{1}{E'} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G'} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G'} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{2(1+\nu)}{E}\end{bmatrix} \begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{xy}\\ \tau_{yz}\\ \tau_{zx}\end{bmatrix}$$

	Material Models Used	Results
Zou et al [20]	Isotropic, Transversely Isotropic	2% difference between the 2 models. Recommends using anisotropic model.

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Analytical Approaches used for material model

Orthotropic Model[21]

$$\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \varepsilon_{yz}\\ \varepsilon_{zx}\\ \varepsilon_{xy}\end{bmatrix}=\begin{bmatrix}\frac{1}{E_x} & -\frac{v_{yx}}{E_y} & -\frac{v_{zx}}{E_z} & 0 & 0 & 0\\ -\frac{v_{xy}}{E_x} & \frac{1}{E_y} & -\frac{v_{zy}}{E_z} & 0 & 0 & 0\\ -\frac{v_{xz}}{E_x} & -\frac{v_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{2G_{yz}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{2G_{zx}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{xy}}\end{bmatrix}\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{zx}\\ \sigma_{xy}\end{bmatrix}$$

Classical Laminate Theory[22]

$$\begin{bmatrix}\frac{E_1}{1-v_{12}v_{21}} & \frac{v_{12}E_2}{1-v_{12}v_{21}} & 0\\ \frac{v_{21}E_1}{1-v_{12}v_{21}} & \frac{E_2}{1-v_{12}v_{21}} & 0\\ 0 & 0 & G_{12}\end{bmatrix}$$

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Analytical Approaches used for material model

	Material Model Used	Results
Casavola et al [23]	Classical Laminate Theory	Results are in accordance with experimental data for majority of the stress-strain curve; Results deviate at 2% strain.
Magalha˜es et al [24]	Classical Laminate Theory	Mechanical Behavior not predicted accurately using CLT; Suggest using a better analytical model.
Alaimo et al [25]	Classical Laminate Theory	Results obtained using CLT are consistent with the experimental data.

Simulation Approach

	Approach	Results	Work needed.
Hambali *et al* [26]	Orthotropic Material properties used.	Result in XY direction in accordance. Not all are results consistent.	Inconsistency
Martinez *et al* [27]	Uses a laminate model with orthotropic properties and compares with a solid model	Considerable differences in the results obtained from both the models.	Difference in results
Sayre [28]	Composite laminate model used in Abaqus, compared with isotropic model.	Composite model closer to experimental data.	Shell elements used in composite layup

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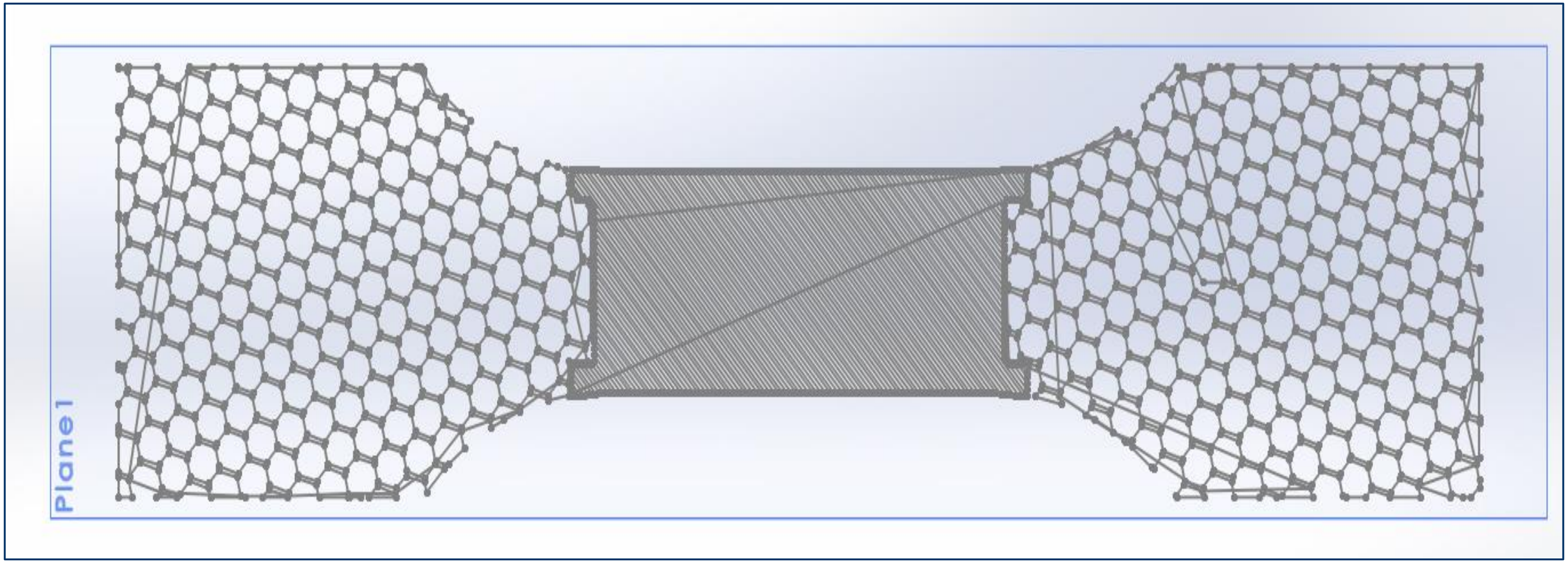
Methodology

- Design CAD geometries:
  - Accommodate infill patterns
  - Suitable for tensile testing
- Experimental work
  - Print parts on a FDM printer
  - Printed parts are tested on a tensile test bed.
  - Data is post-processed to obtain stress-strain curves and material properties
- FEA
  - Simulate tensile test using bulk material properties for the parts.
  - Simulate tensile test using derived isotropic properties.
  - Simulate tensile test using orthotropic properties.
- Compare and Discuss

Modeling – Initial Approach

- Trace gcode path in Solidworks to create geometry.
- Use ‘Sweep’ feature to model intra-layer fibers.
- Build model layer by layer to achieve high fidelity with actual part.



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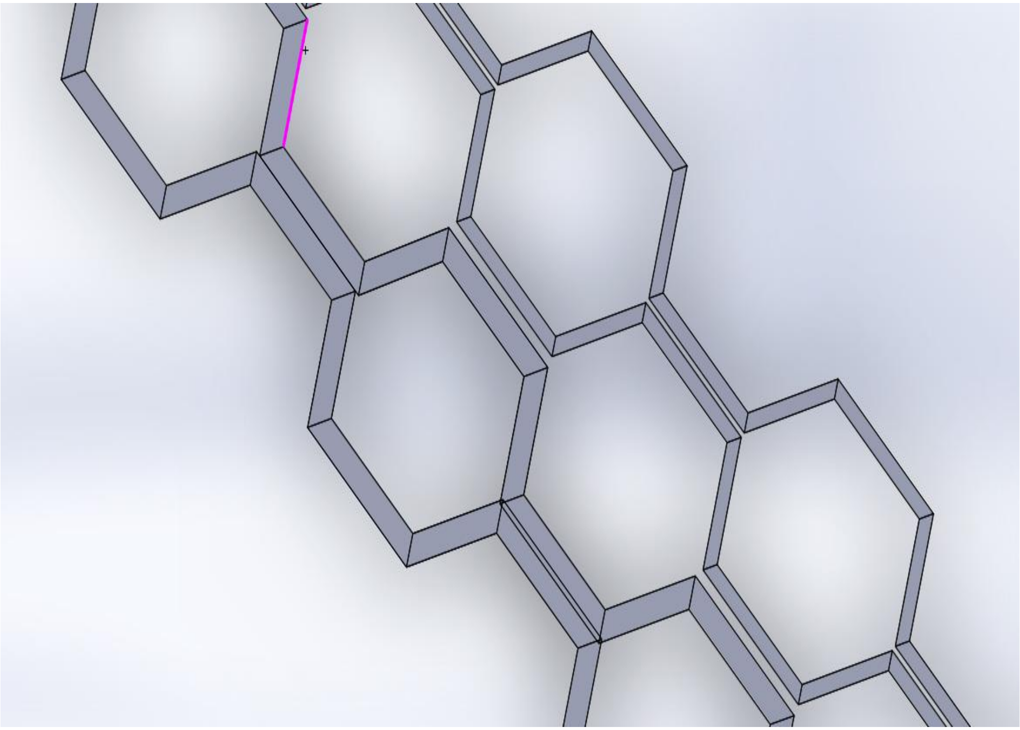
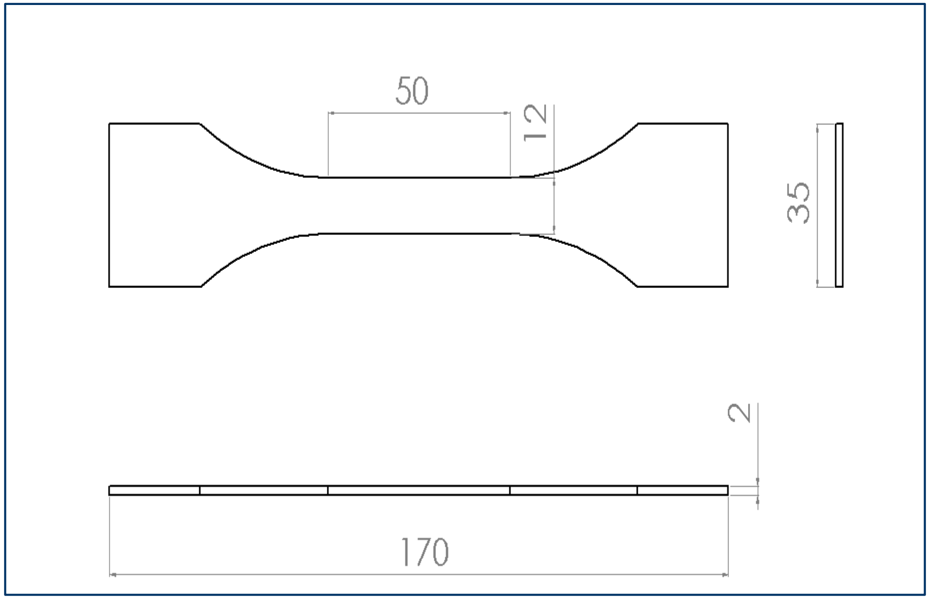
Modeling – Initial Approach

- Problems with intersecting surfaces (Adjacent and successive).
- Created a huge part file, which took hours to be saved.
- Meshing, if possible was computationally intensive (9 hours).



Geometry

- Since tensile tests are conducted: Dogbone geometry is used.
- Narrow gage section to ensure fracture
- Shoulders for gripping.
- Similar to ASTM standards.
- Used to obtain derived isotropic properties.



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Parts printed

- Hexagonal Infill
- Circular Infill – Straight
- Circular Infill – Packed
- Linear Infill – Straight
- Linear Infill – Cross-Hatch
- Hilbert Curve
- Infill-less
- Continuous Specimens – To derive material properties

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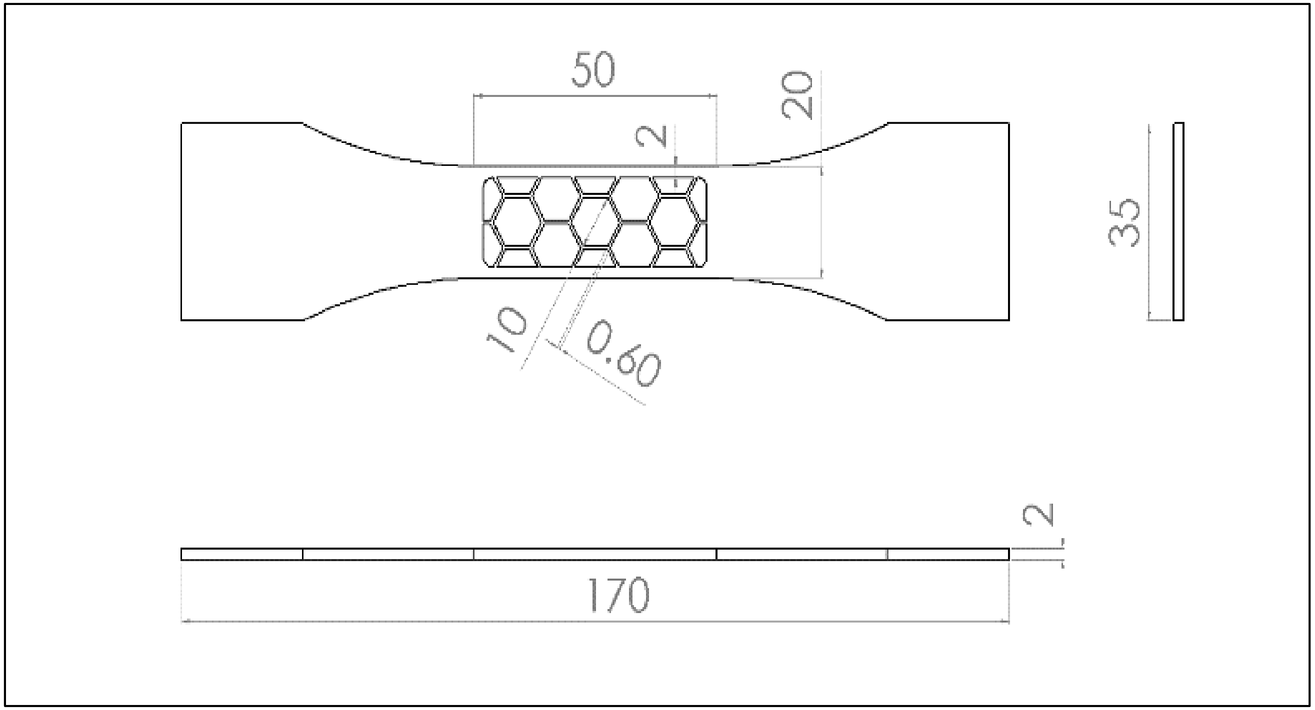
Printing Parameters

- Gage dimensions decided so as to accommodate the features of the infill pattern.
- Maximum dimensions decided based on the size of the printer bed and the tensile test bed.
- Printing parameters used so as to obtain best possible part quality within reasonable amount of time.
- Printer used: MakerBot Replicator 2X
- Slicers used: Slic3r, Simplify 3D.
- Extruder Temp: 230º C ; Bed Temp: 130º C

Hexagonal Infill

- Layer Height: 0.2 mm
- Filament width: 0.67 mm
- Infill density: 20 %



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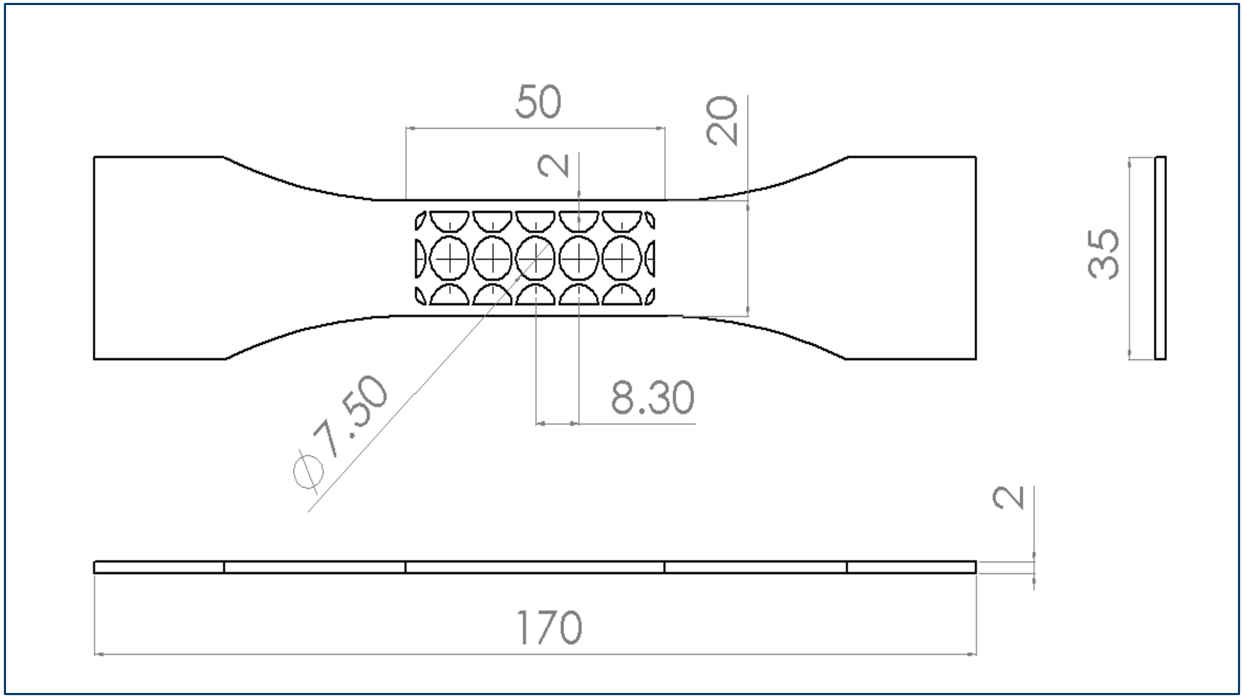
Circular Infill: Straight arrangement

- Layer Height: 0.4 mm
- Filament width: 0.42 mm
- Infill density: 30 %



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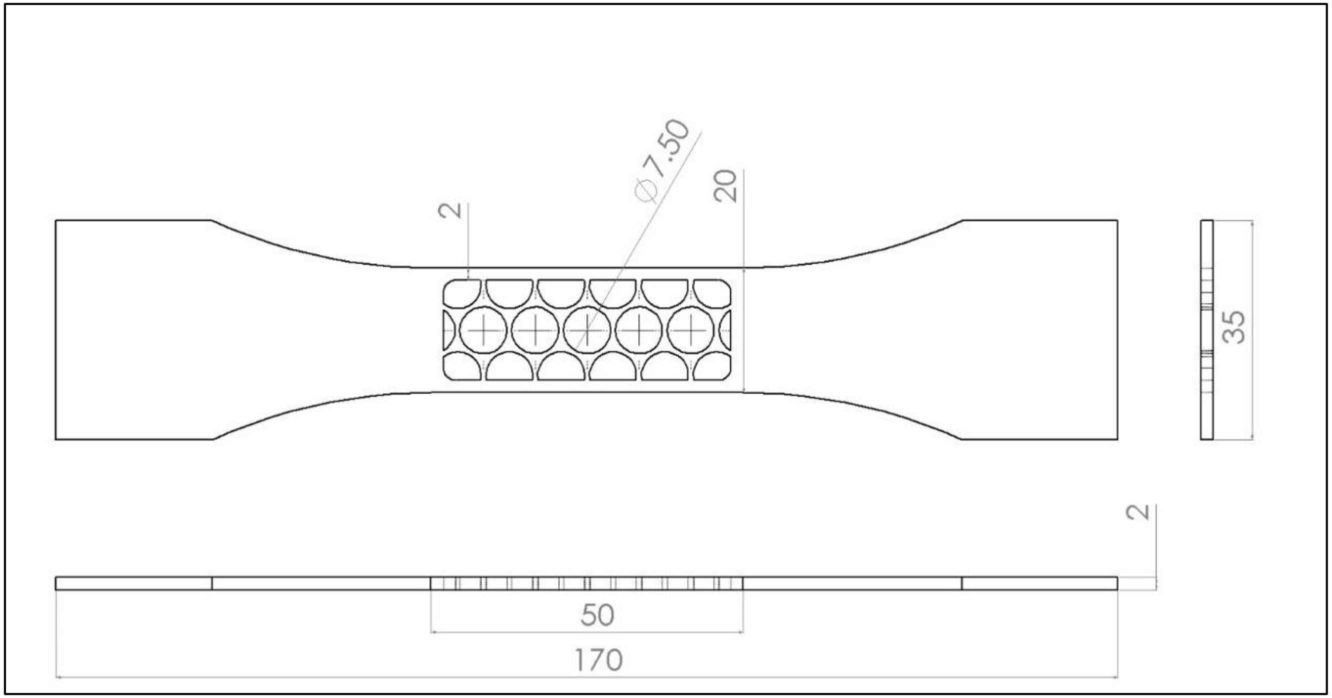
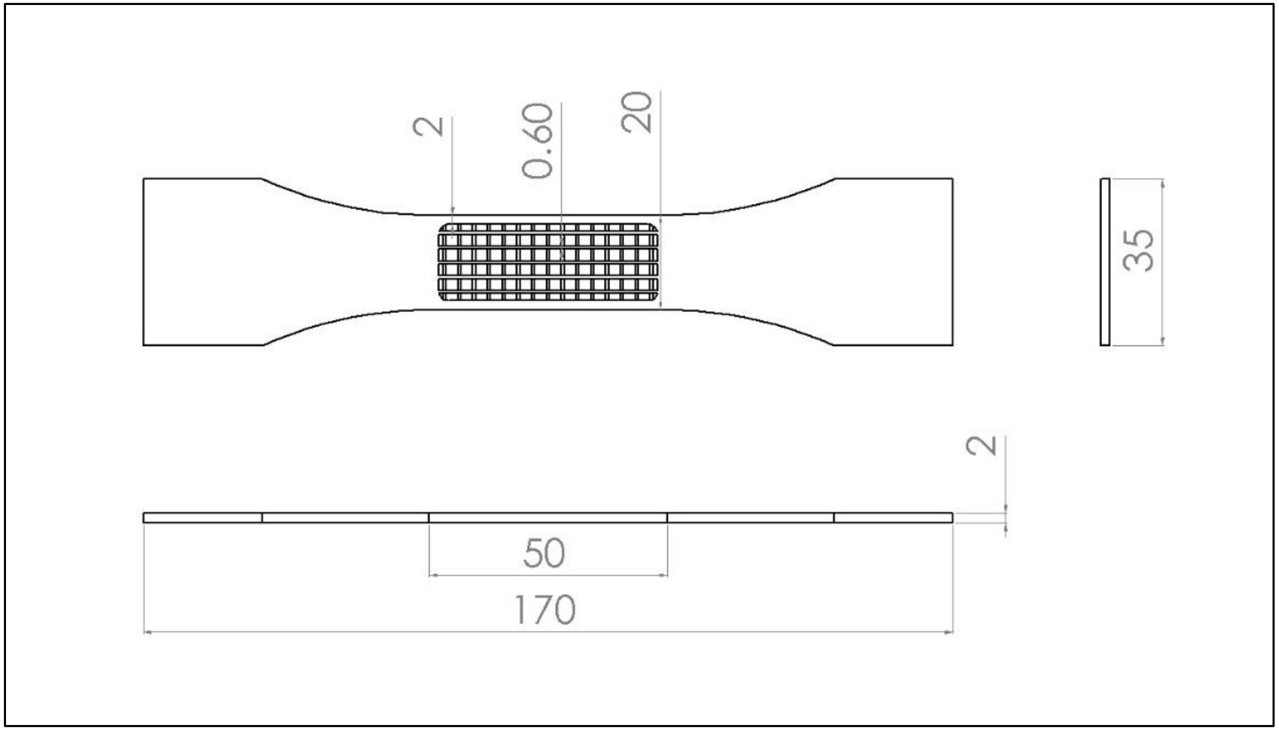
Circular Infill: Packed arrangement

- Layer Height: 0.4 mm
- Filament width: 0.42 mm
- Infill density: 30 %



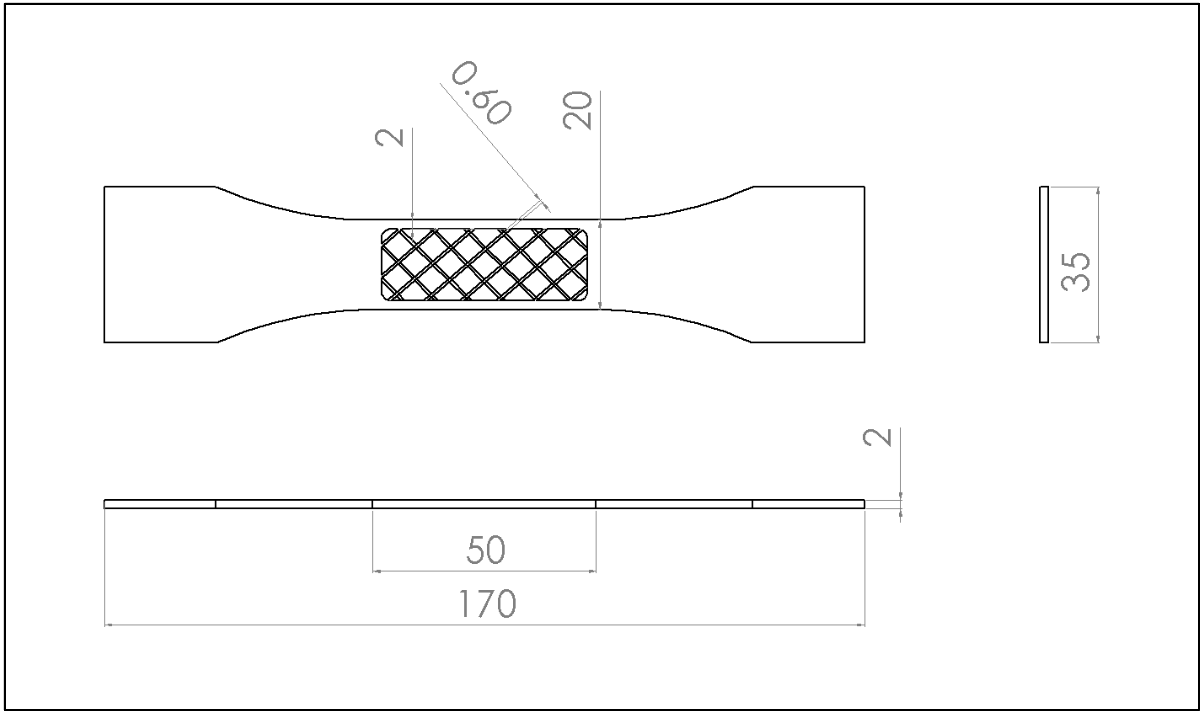
Linear Infill: Straight arrangement

- Layer Height: 0.2 mm
- Filament width: 0.67 mm
- Infill density: 40 %



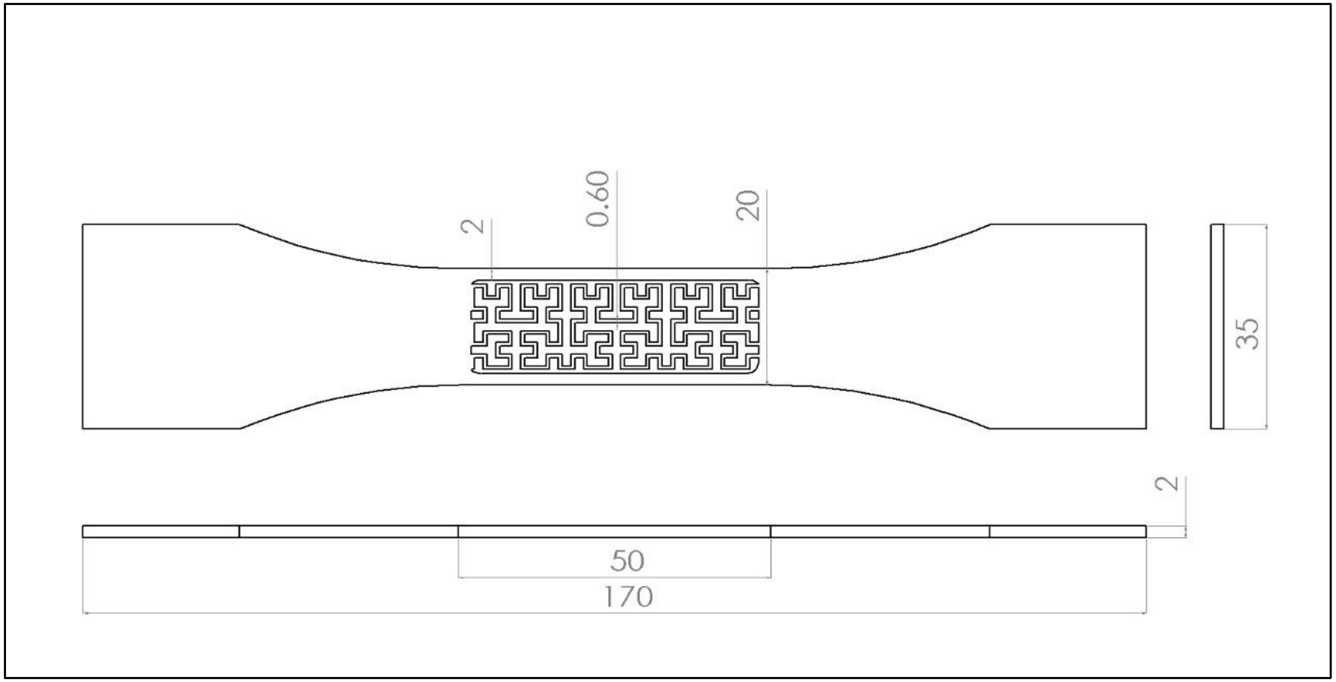
Linear Infill: CrossHatch arrangement

- Layer Height: 0.2 mm
- Filament width: 0.67 mm
- Infill density: 40 %



Hilbert Curve

- Layer Height: 0.2 mm
- Filament width: 0.67 mm
- Infill density: 30 %



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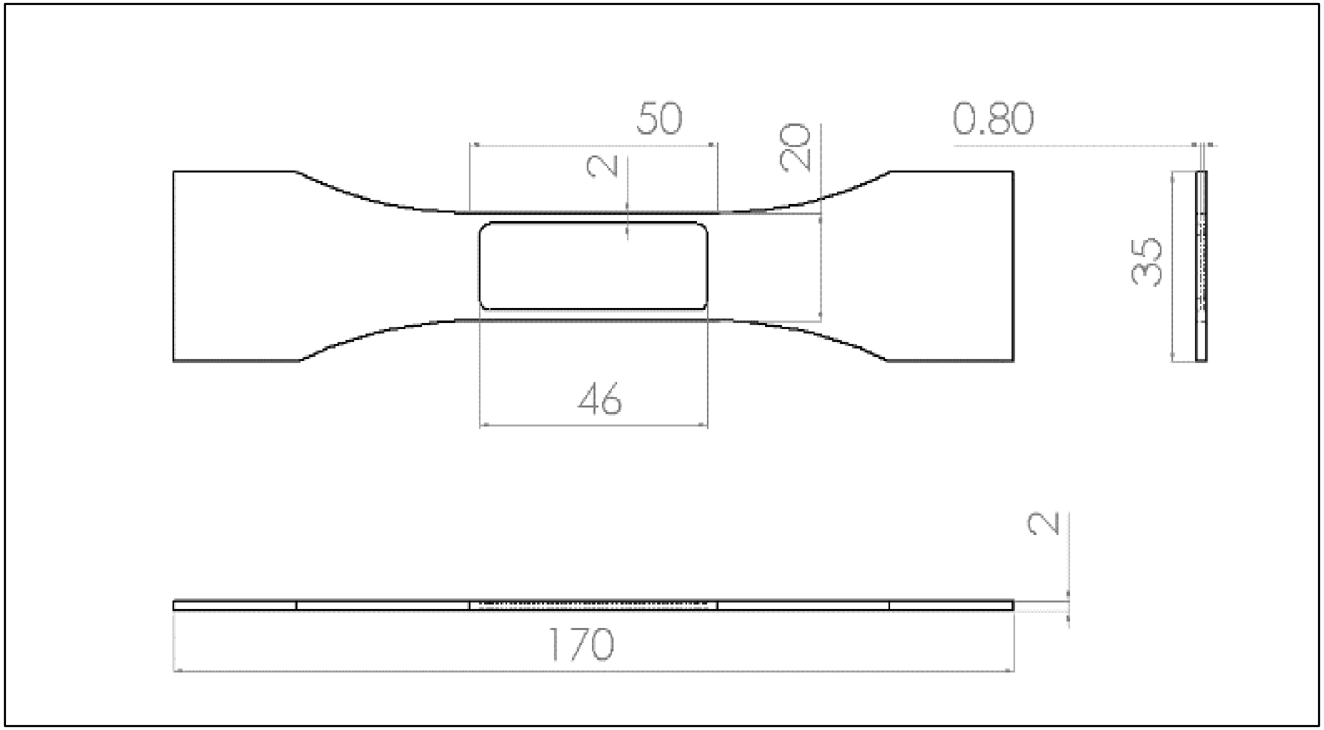
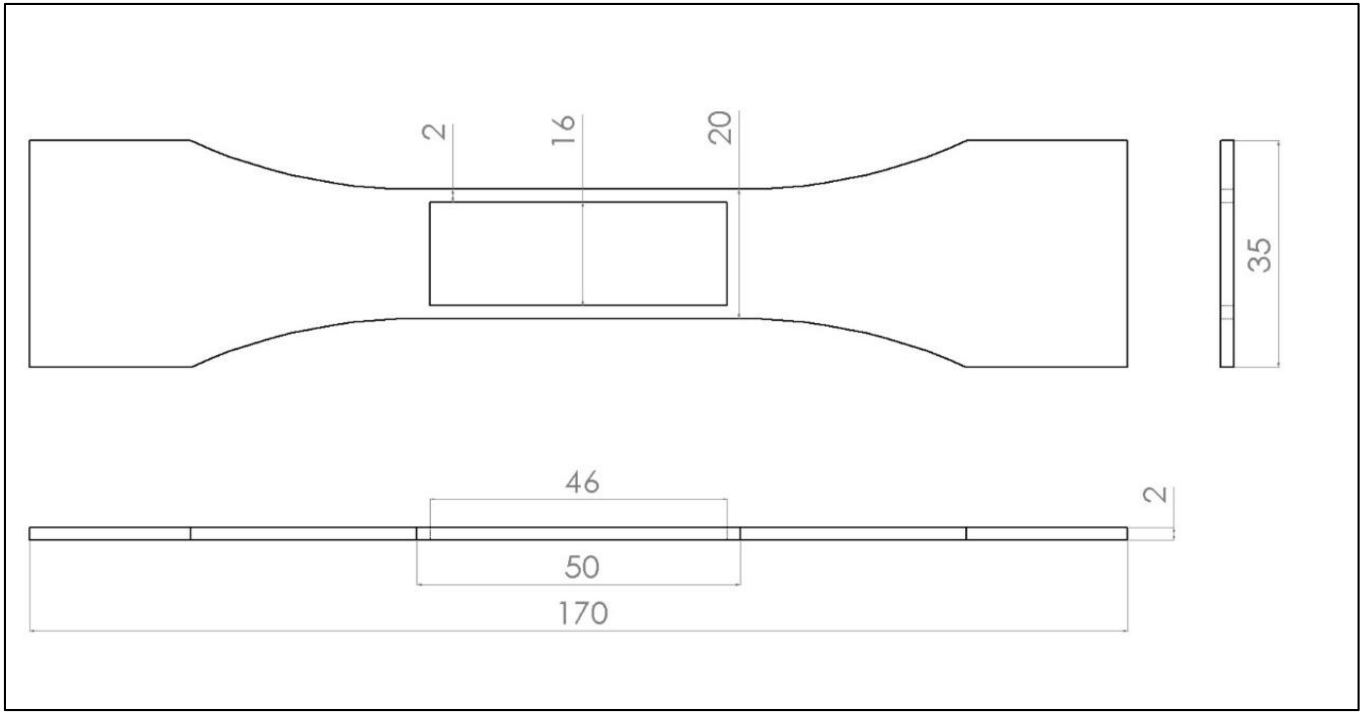
Continuous Pattern

- Layer Height: 0.4 mm
- Filament width: 0.42 mm
- Infill density: 100%



Infill-less Pattern

- Layer Height: 0.2 mm
- Filament width: 0.67 mm
- Infill density: 100 %



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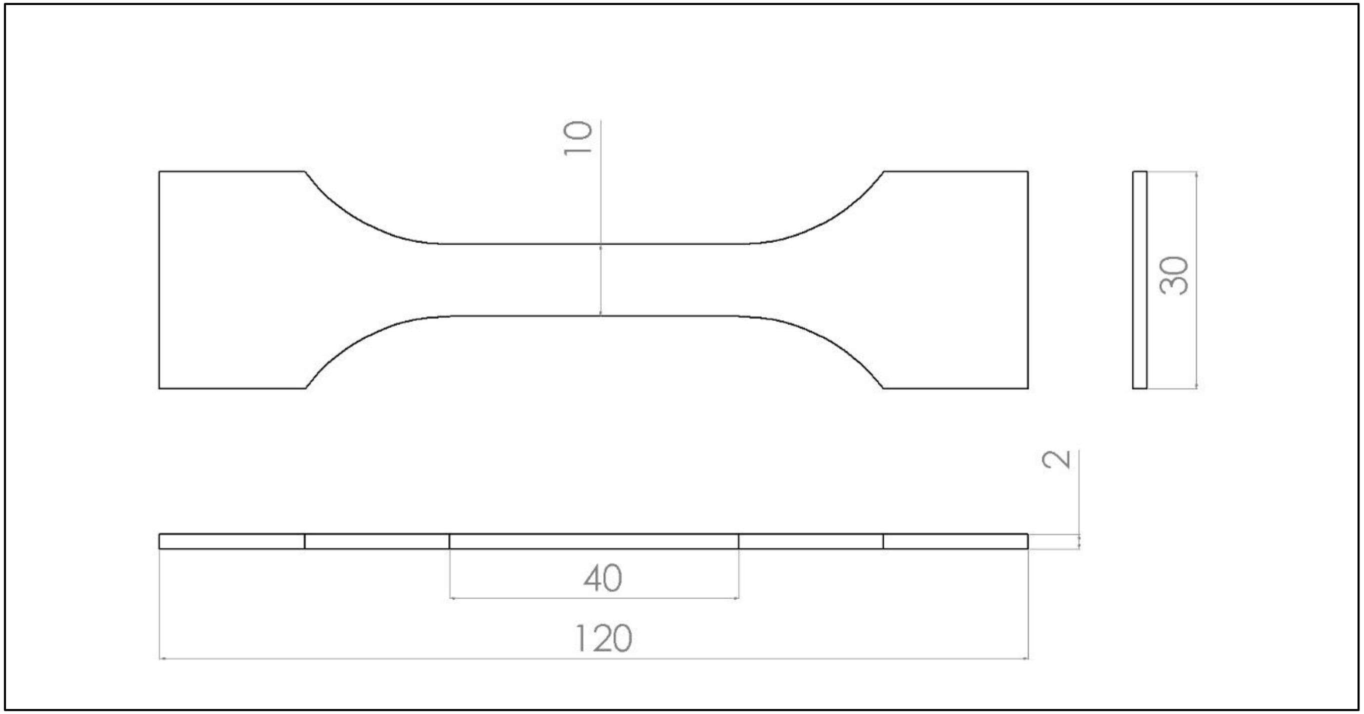
Dogbone for deriving Orthotropic Properties

- Layer Height: 0.2 mm
- Filament width: 0.67 mm
- Infill density: 100 %



Tensile Tests

- Psylotech - µTs 'Modular under Microscope Mechanical Test System'
- Displacement controlled tensile test was performed at a rate of 50 µ/s.
- Test is conducted till fracture occurs.
- Data points are recorded every 0.05 secs.
- Displacement and corresponding force required at every time step is obtained.
- A sample set 20 samples is used.
- Results are post-processed to obtain material properties.

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Finite Element Analysis

- Transient Analysis using ANSYS and Abaqus .
- One end of the shoulder is fixed.
- Displacement is applied on the other shoulder.
- Average displacement of a particular sample set is used.
- Mesh convergence is used to decide appropriate mesh size.
- Metrics for Comparison: Stress at 2% strain, Area of fracture, stress-strain curve.

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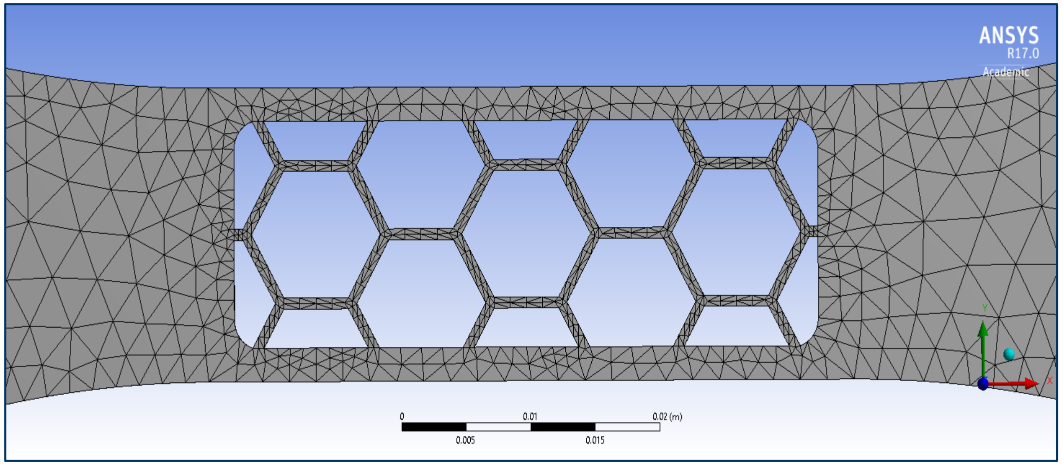
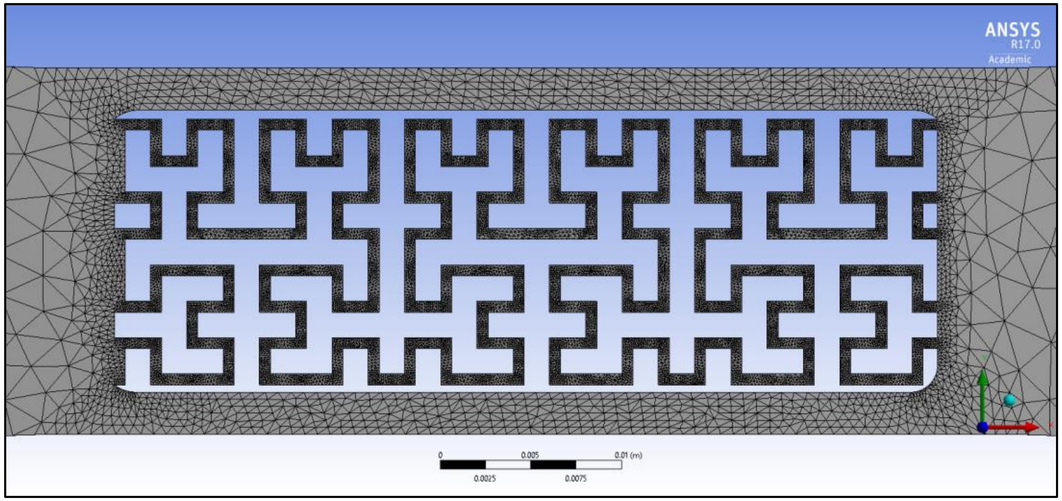
Meshed Part

Hexagonal Infill

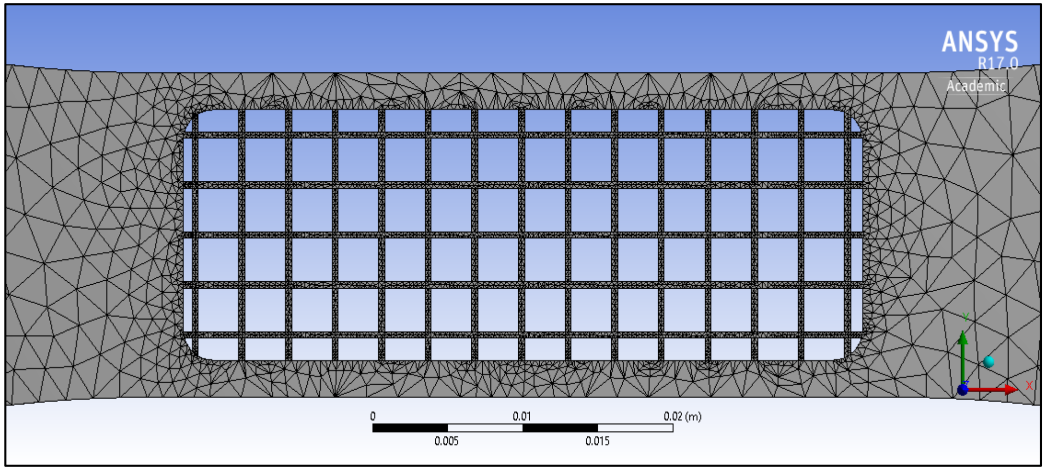


Hilbert Curve Infill

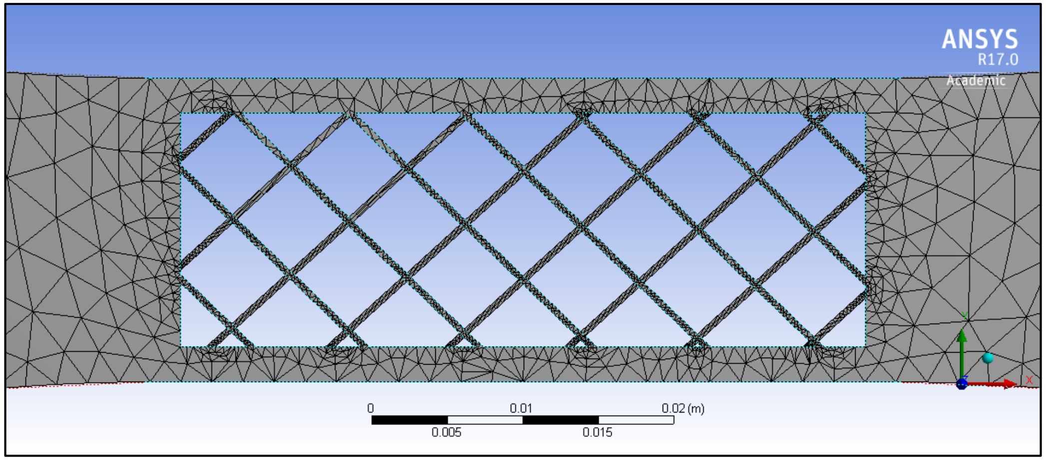


Meshed Part

Linear Straight Infill



Linear CrossHatch Infill



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Analysis using Bulk Material Properties

- Use material properties of the Bulk ABS material.
- Use Isotropic Material Model.
- Solve for Stress and Strain plots for given displacement.
- Compare with experimental Values

Material Property of ABS	Value
Young's Modulus	2 GPa
Poisson's Ratio	0.394
Density	1020 kg/m^3

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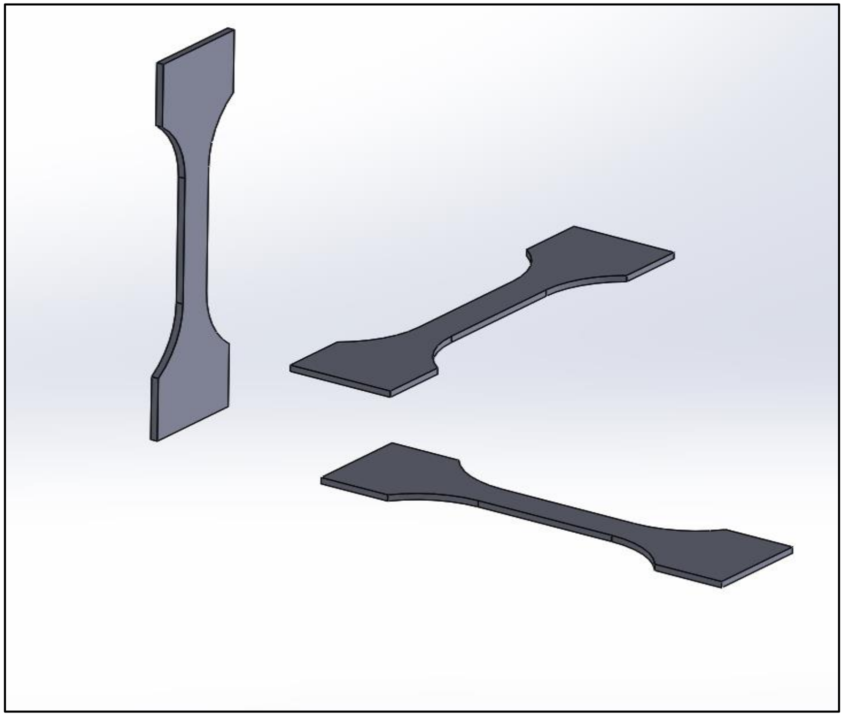
Analysis using Derived Material Properties

- Derive Material Properties by using a continuous model with the same printing parameters
- Use Isotropic Material Model with derived properties.
- Solve for Stress and Strain plots for given displacement and compare with experimental values.

Material Property of ABS	Value
Young's Modulus	1 GPa
Poisson's Ratio	0.394
Density	1020 kg/m^3

Analysis using Orthotropic Material Properties

- Derive Orthotropic Material Properties by using a continuous model built in three orientations: X, Y, Z.
- Use Orthotropic Material Model with derived properties.



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Orthotropic properties

Material Property of ABS	Value
Young's Modulus in X (E_x)	1.1 GPa
Young's Modulus in Y (E_y)	0.9 GPa
Young's Modulus in Z (E_z)	0.88 GPa
Poisson's Ratio ($v_{xy} = v_{xy} = v_{xy}$)	0.394
Shear Modulus (G_{xy})	0.39 GPa
Shear Modulus (G_{yz})	0.32 GPa
Shear Modulus (G_{xz})	0.31 GPa
Density	1020 kg/m^3

$$G_T = \frac{E_T}{2(1 + \nu_T)}$$

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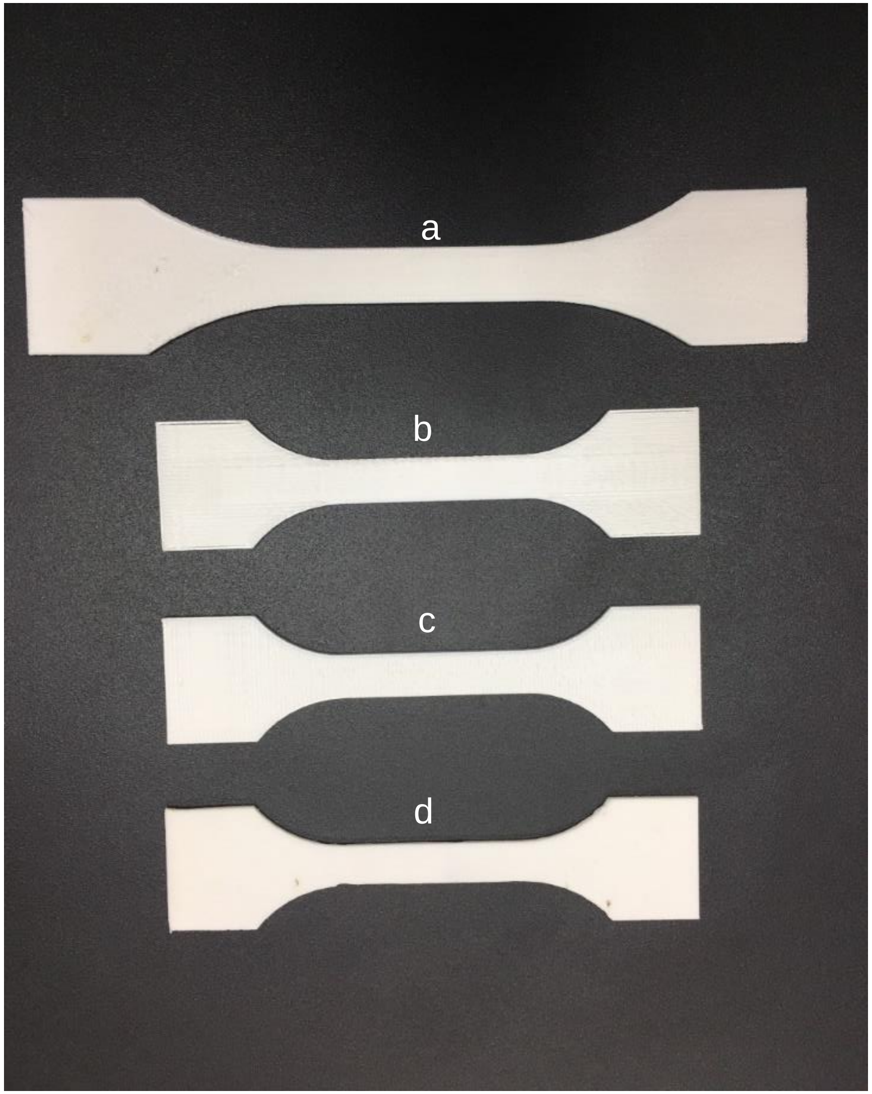
Composite Analysis using Abaqus.

- Apply Composite Layup to solid 3D model as FDM part is built in layers.
- Enables specification of fiber direction within each layer.
- Use CLT along with orthotropic properties to define model.

$$C = \begin{bmatrix} \frac{E_1}{1-\nu_{12}\nu_{21}} & \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} & \frac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix}$$

Printed parts

- Derived isotropic properties (a)
- Orthotropic properties in X (b)
- Orthotropic properties in Y (c)
- Orthotropic properties in Z (d)



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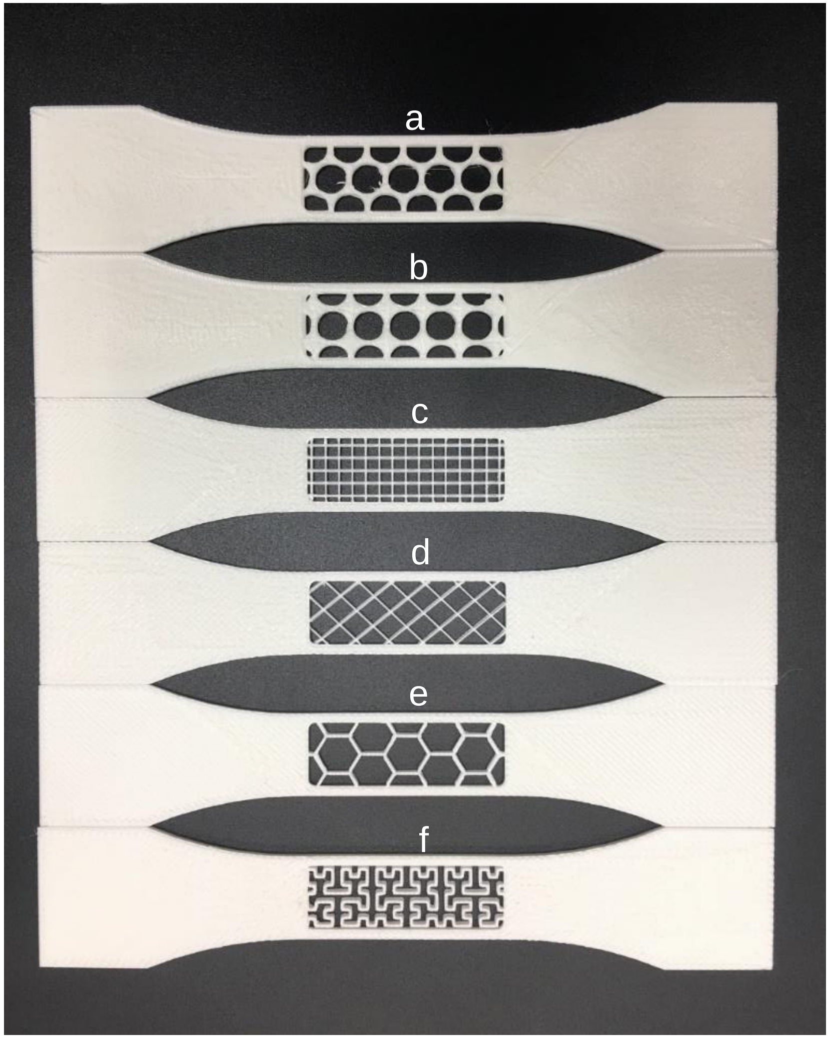
Printed parts

- Circular Packed (a)
- Circular Straight (b)
- Linear Straight (c)
- Linear Cross-Hatch (d)
- Hexagonal (e)
- Hilbert Curve (f)



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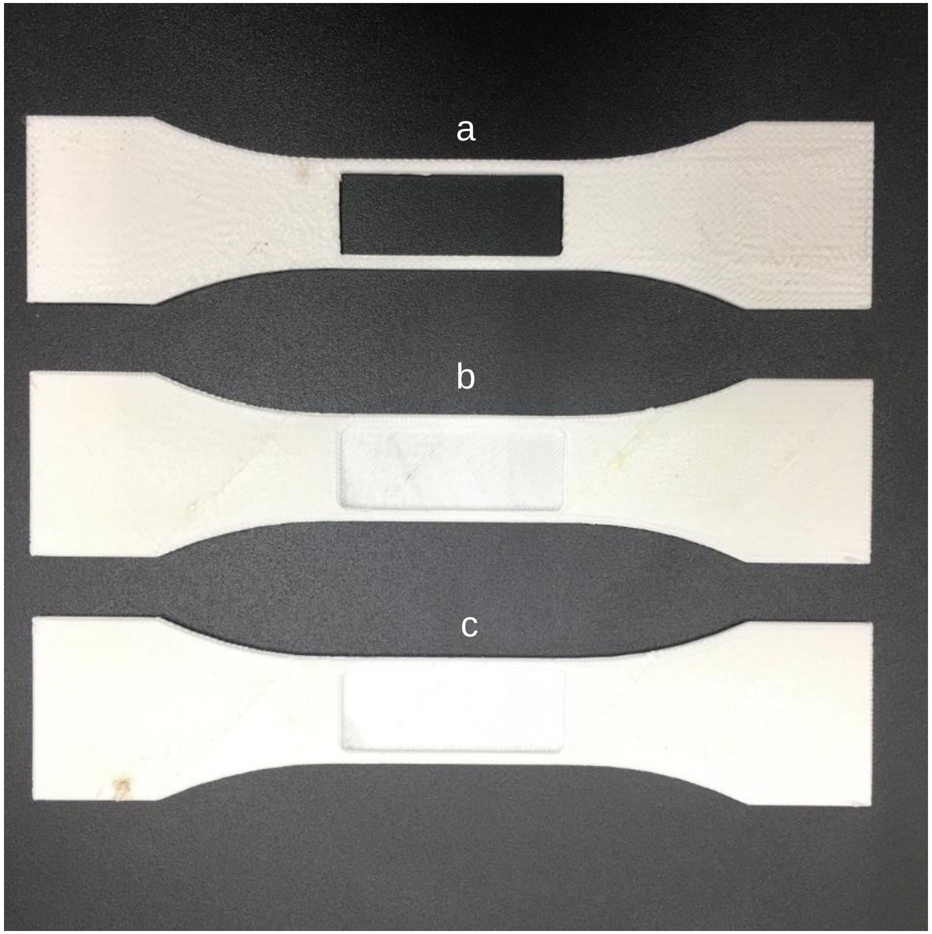
Printed parts

- Infill-less (a)
- Continuous specimens (b) (Hexagonal, Hilbert)
- Continuous specimens (c) (Circular-Packed, Straight Linear-Straight, CrossHatch)



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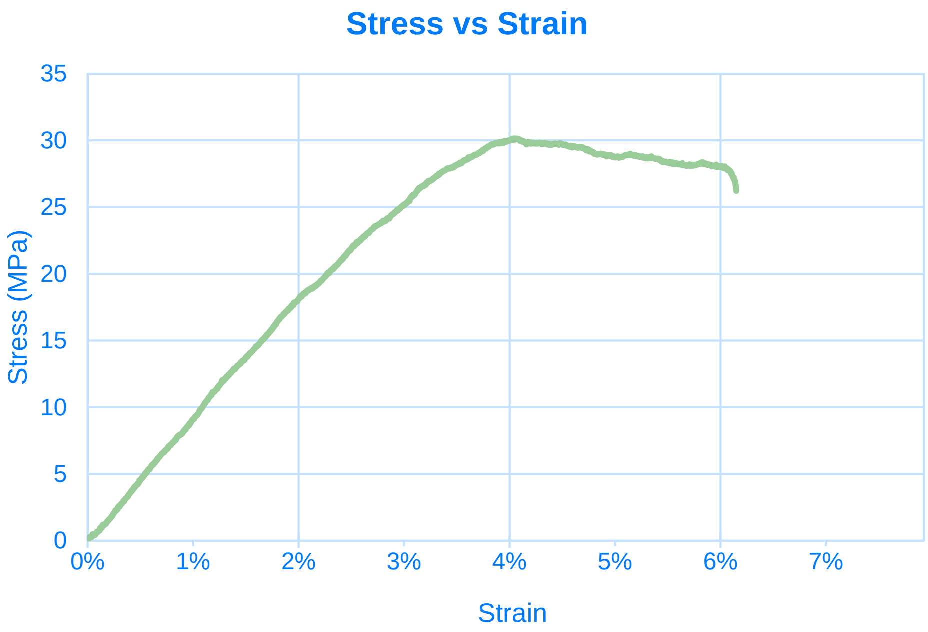
Tensile Test Results

Derived properties for isotropic model



Result	Value
Yield Stress	30 MPa
Yield Strain	0.039
Stress at 2% strain	18.5 MPa
Elastic Modulus	1 ± 0.1 GPa

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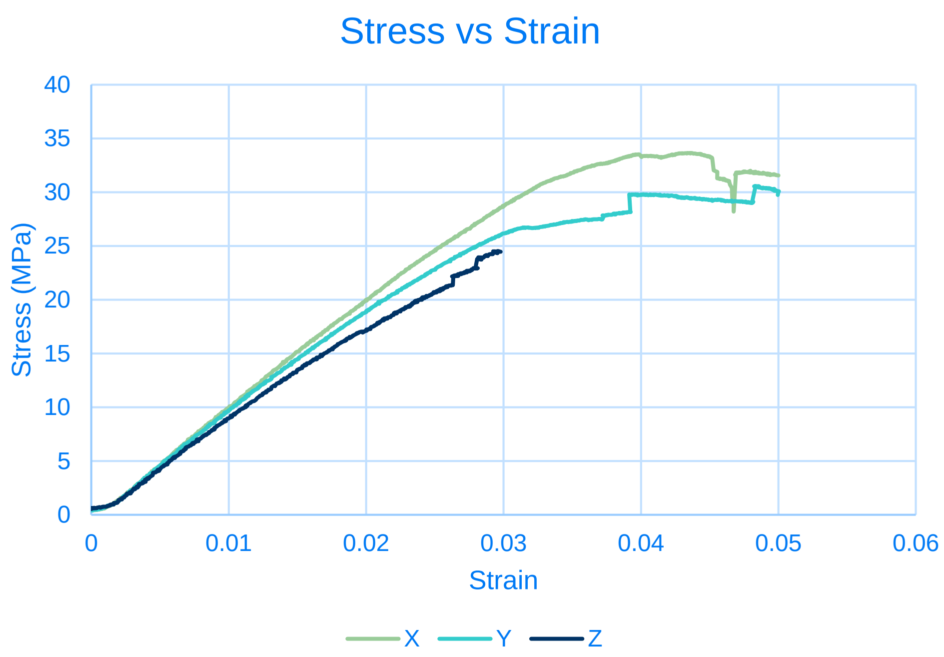
Tensile Test Results

Derived properties for orthotropic model



Material Property of ABS	Value
Young's Modulus in X (E_x)	1.1 GPa
Young's Modulus in Y (E_y)	0.9 GPa
Young's Modulus in Z (E_z)	0.88 GPa
Poisson's Ratio ($v_{xy} = v_{xy} = v_{xy}$)	0.394
Shear Modulus (G_{xy})	0.39 GPa
Shear Modulus (G_{yz})	0.32 GPa
Shear Modulus (G_{xz})	0.31 GPa
Density	1020 kg/m^3

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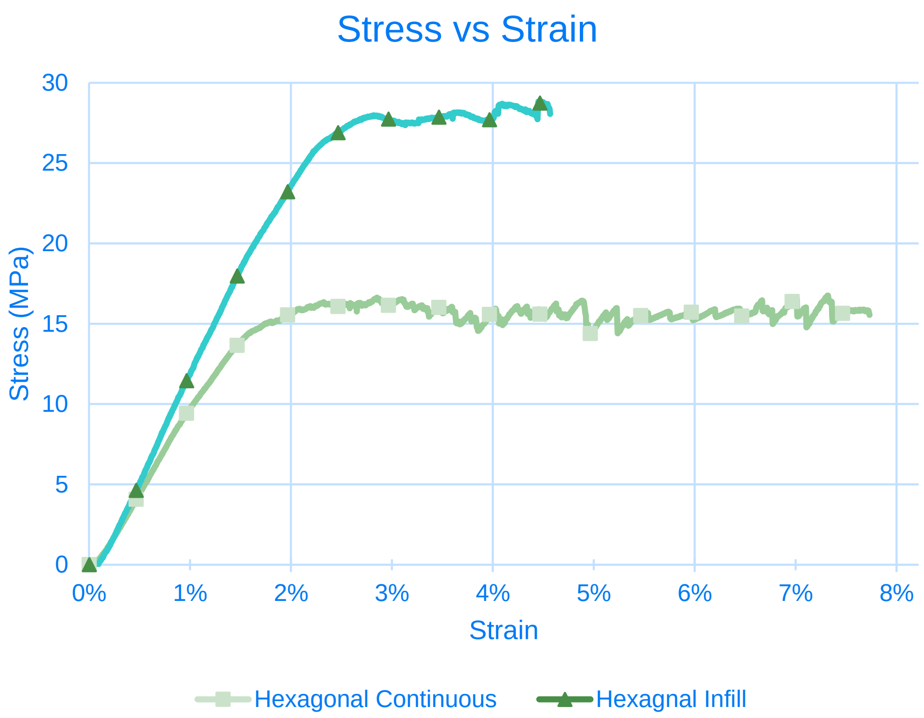
Tensile Test Results

Hexagonal Infill and Continuous



Infill

Result	Value
Yield Stress	27.9 Mpa
Yield Strain	0.028
Stress at 2% strain	24 MPa
Elastic Modulus	1.25 ± 0.2 GPa

Continuous

Result	Value
Yield Stress	16 MPa
Yield Strain	0.023
Stress at 2% strain	15.7 MPa
Elastic Modulus	1 ± 0.1 GPa

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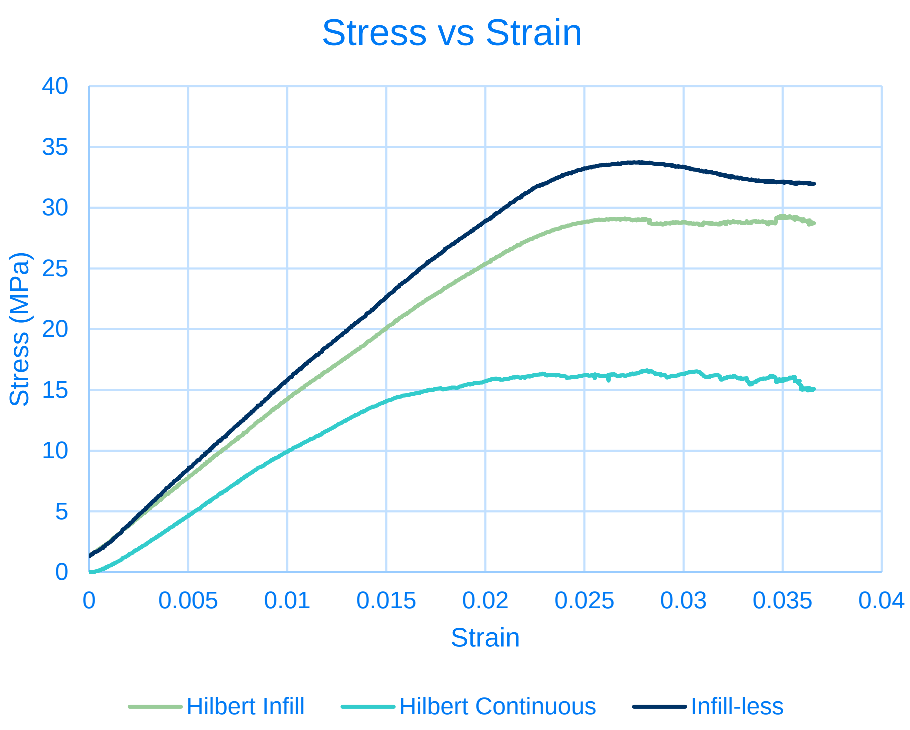
Tensile Test Results

Hilbert Curve Infill and Continuous & Infill-less



Infill

Result	Value
Yield Stress	29.1 Mpa
Yield Strain	0.025
Stress at 2% strain	25.4 Mpa
Elastic Modulus	1.3 ± 0.2 GPa

Infill-less

Result	Value
Yield Stress	32.9 MPa
Yield Strain	0.025
Stress at 2% strain	28.8 MPa
Elastic Modulus	1.5 ± 0.1 GPa

Continuous

Result	Value
Yield Stress	21.2 MPa
Yield Strain	0.023
Stress at 2% strain	18.9 Mpa
Elastic Modulus	0.9 ± 0.1 GPa

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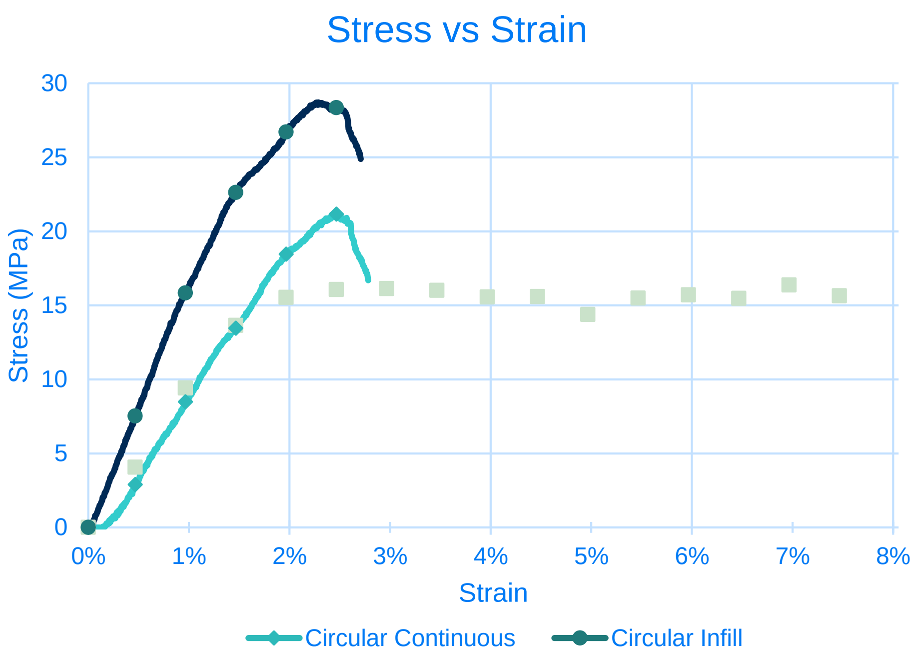
Tensile Test Results

Circular - Straight Infill & Continuous



Infill

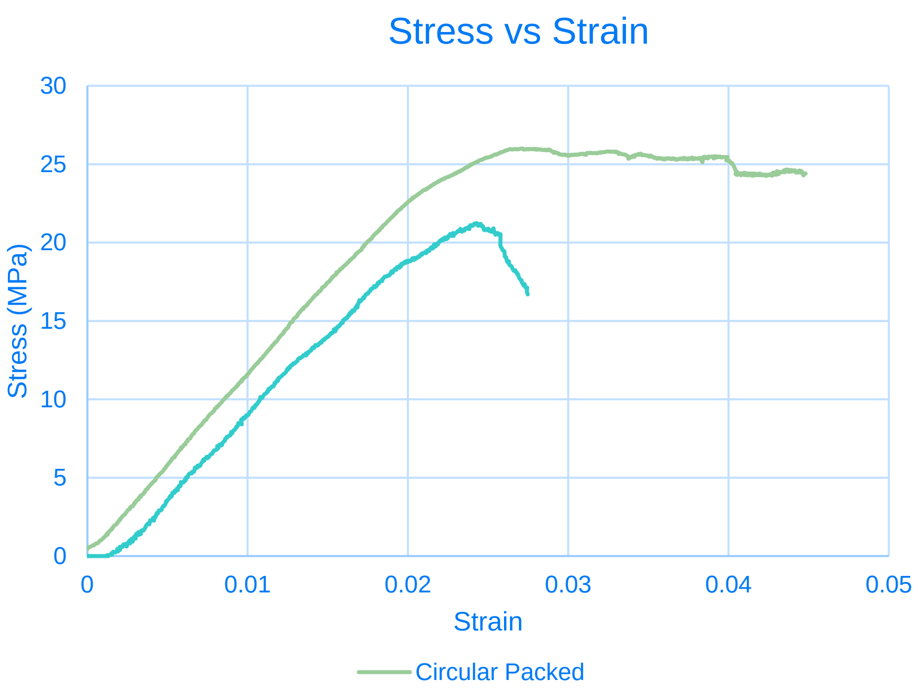
Result	Value
Yield Stress	28.6 MPa
Yield Strain	0.023
Stress at 2% strain	27.4 MPa
Elastic Modulus	1.6 ± 0.2 GPa

Continuous

Result	Value
Yield Stress	21.2 MPa
Yield Strain	0.024
Stress at 2% strain	18.9 MPa
Elastic Modulus	0.99 ± 0.1 GPa

Tensile Test Results

Circular - Packed Infill & Continuous



Infill

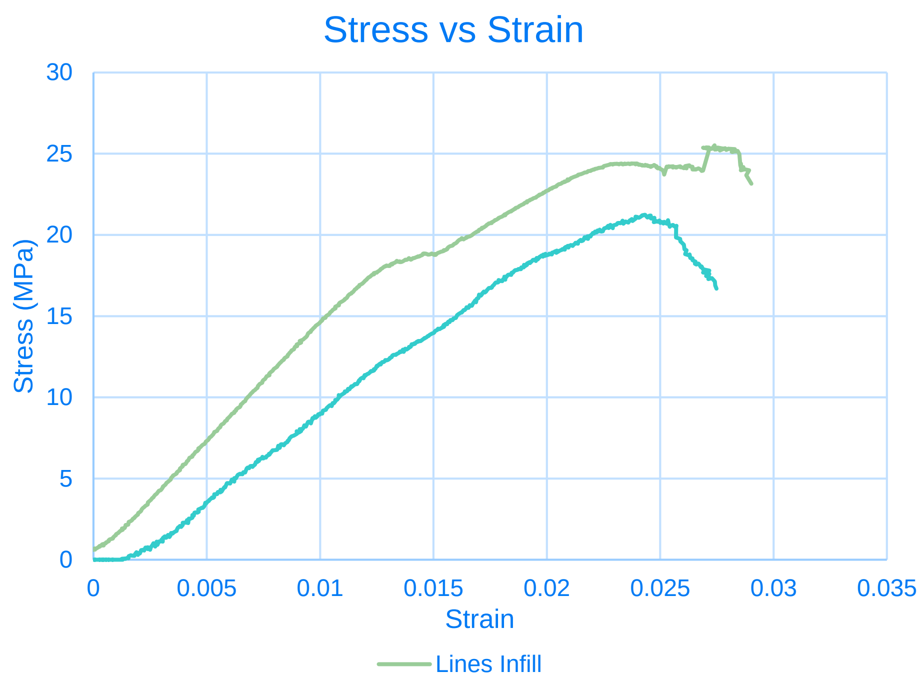
Result	Value
Yield Stress	26.5 Mpa
Yield Strain	0.026
Stress at 2% strain	22.5 MPa
Elastic Modulus	1.1 ± 0.1 GPa

Continuous

Result	Value
Yield Stress	21.2 MPa
Yield Strain	0.024
Stress at 2% strain	18.9 MPa
Elastic Modulus	0.99 ± 0.1 GPa

Tensile Test Results

Linear - Straight Infill & Continuous



Infill

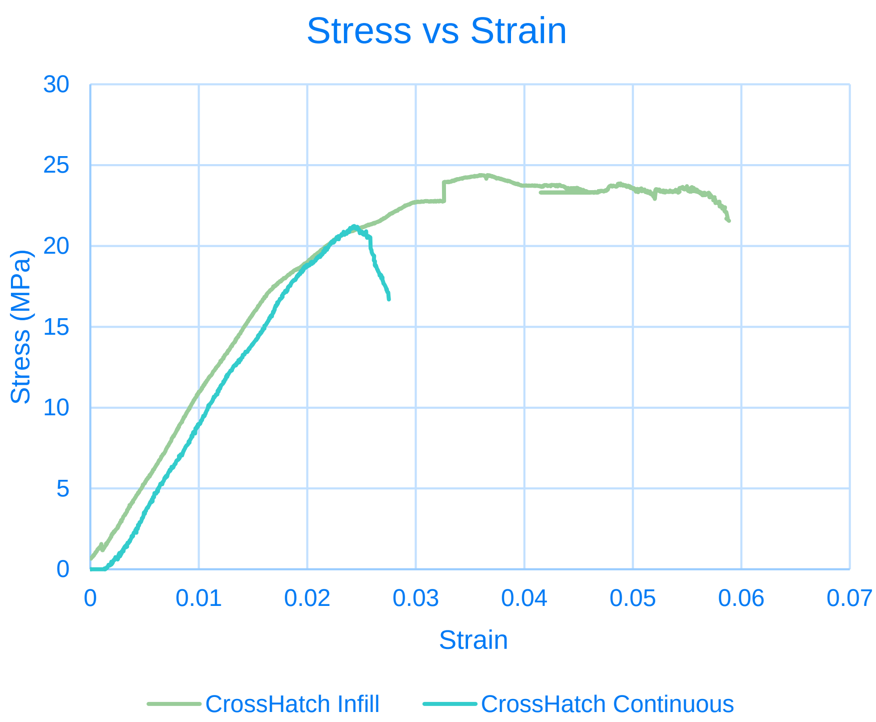
Result	Value
Yield Stress	24.6 Mpa
Yield Strain	0.023
Stress at 2% strain	22.7 MPa
Elastic Modulus	1.4 ± 0.2 GPa

Continuous

Result	Value
Yield Stress	21.2 MPa
Yield Strain	0.024
Stress at 2% strain	18.9 MPa
Elastic Modulus	0.99 ± 0.1 GPa

Tensile Test Results

Linear - CrossHatch Infill & Continuous



Infill

Result	Value
Yield Stress	22.8 Mpa
Yield Strain	0.03
Stress at 2% strain	18.9 MPa
Elastic Modulus	1 ± 0.1 GPa

Continuous

Result	Value
Yield Stress	21.2 MPa
Yield Strain	0.024
Stress at 2% strain	18.9 MPa
Elastic Modulus	0.99 ± 0.1 GPa

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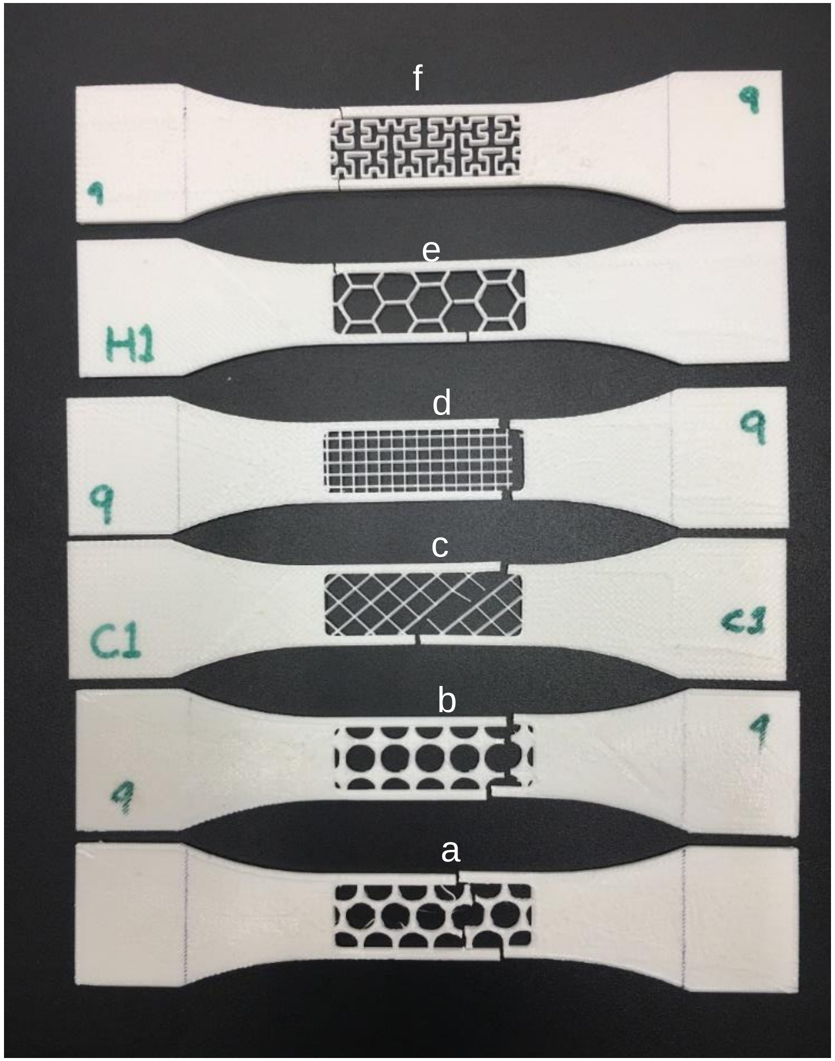
Fractured Specimens

- Circular Packed (a)
- Circular Straight (b)
- Linear Straight (d)
- Linear Cross-Hatch (c)
- Hexagonal (e)
- Hilbert Curve (f)



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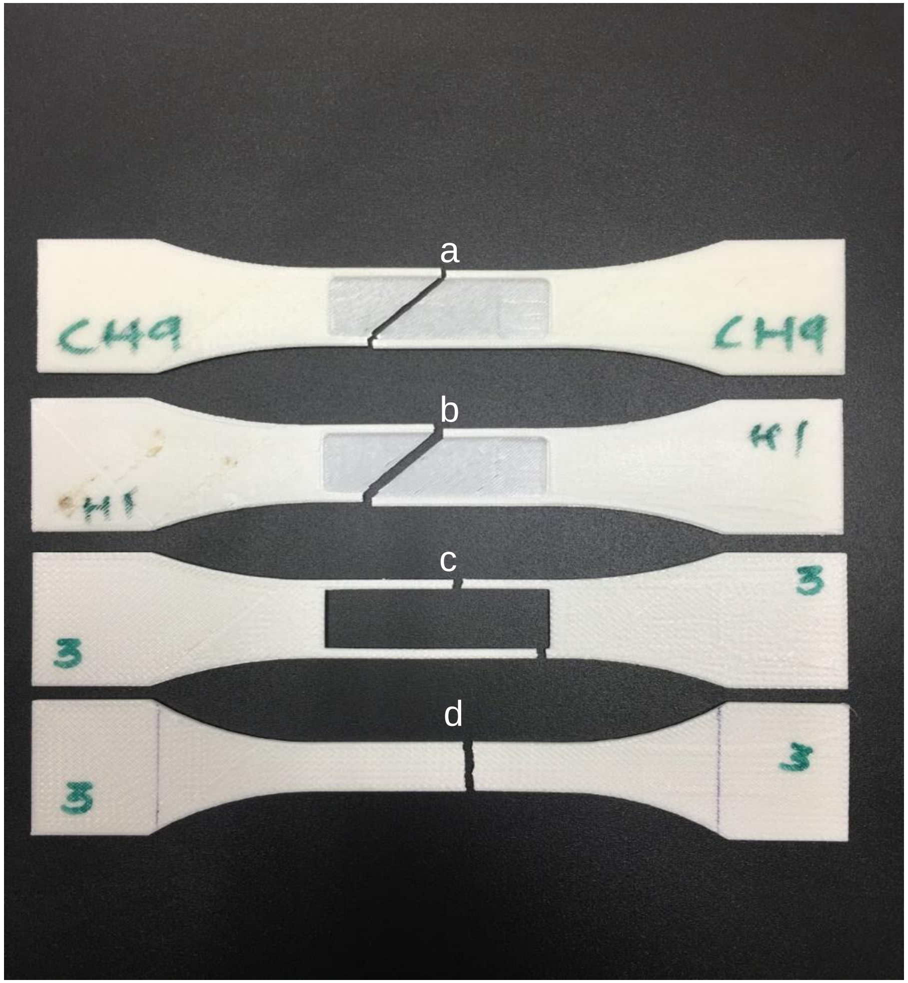
Fractured Specimens

- Continuous specimens (a)

  (Circular-Packed, Straight

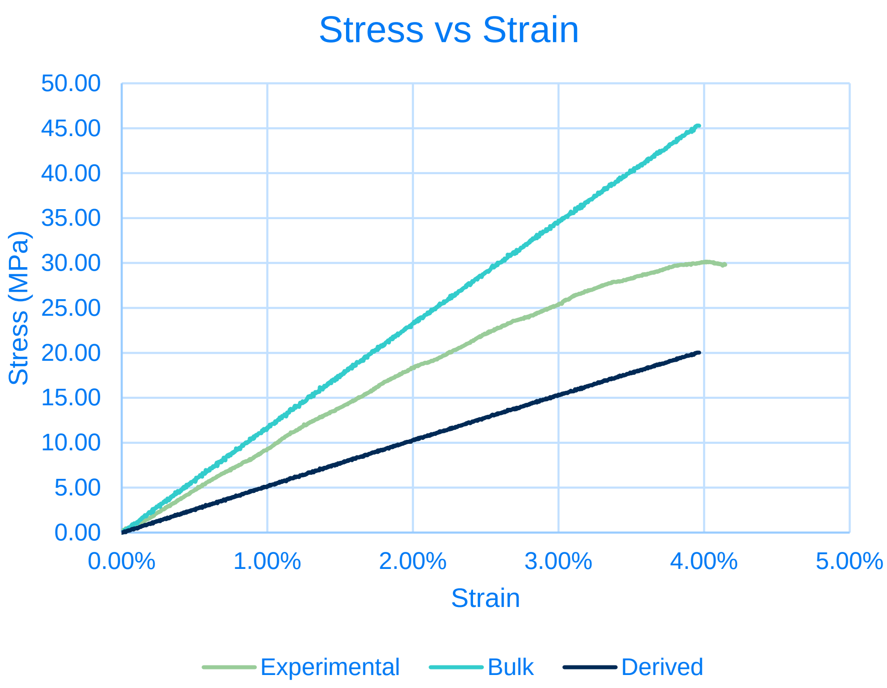
  Linear-Straight, CrossHatch)
- Continuous specimens (b)

  (Hexagonal, Hilbert)
- Infill-less (c)
- Completely Continuous (d)



FEA Results – Bulk and Derived Isotropic Model

Completely Continuous



	Error	
	Bulk Model	Derived Model
Stress at 2% strain	25%	45%
Stress at 1% strain	25%	40%

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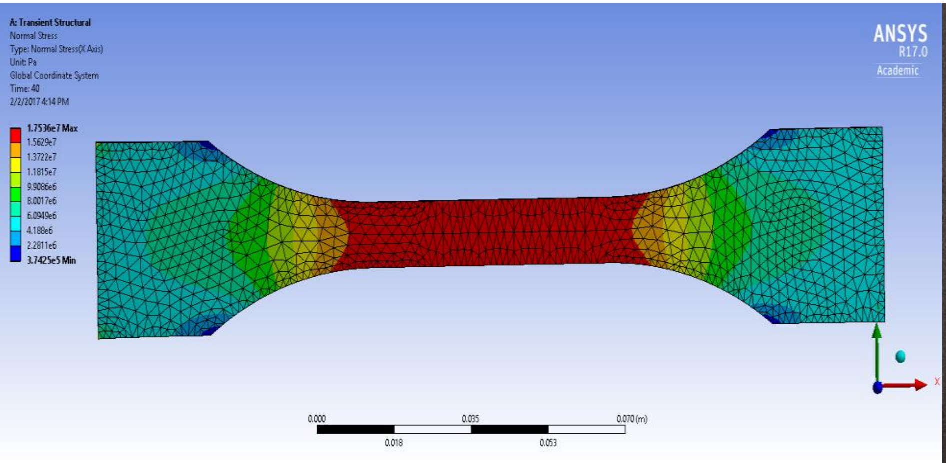
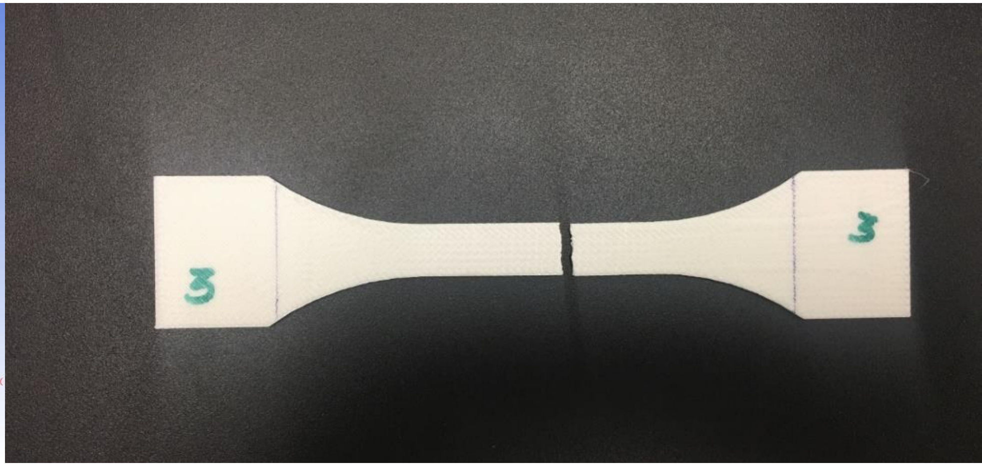
FEA Results – Bulk and Derived Isotropic Model

Completely Continuous





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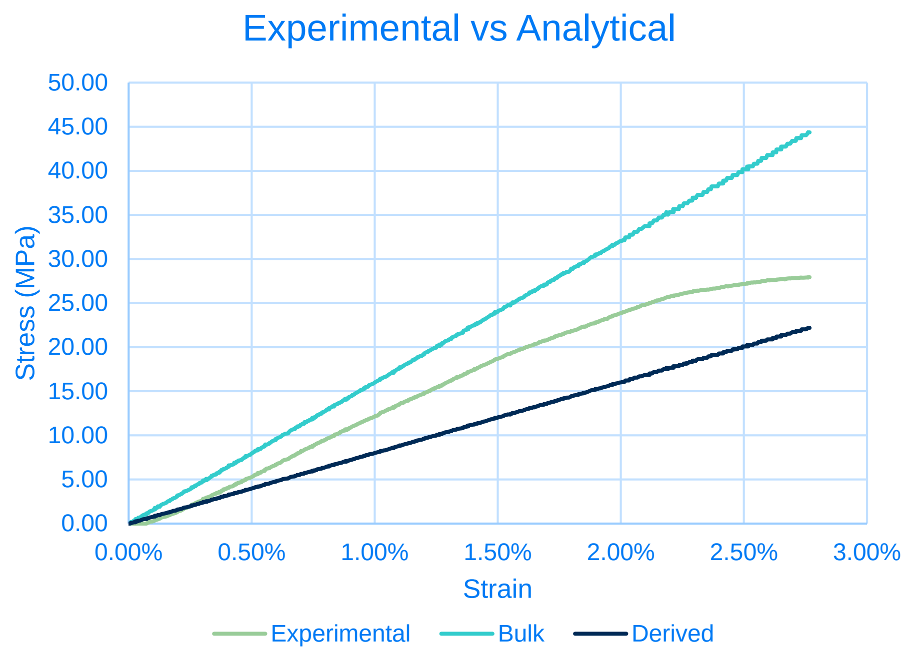
FEA Results – Bulk and Derived Isotropic Model

Hexagonal Infill



	Error	
	Bulk Model	Derived Model
Stress at 2% strain	33%	33%
Stress at 1% strain	30%	33%

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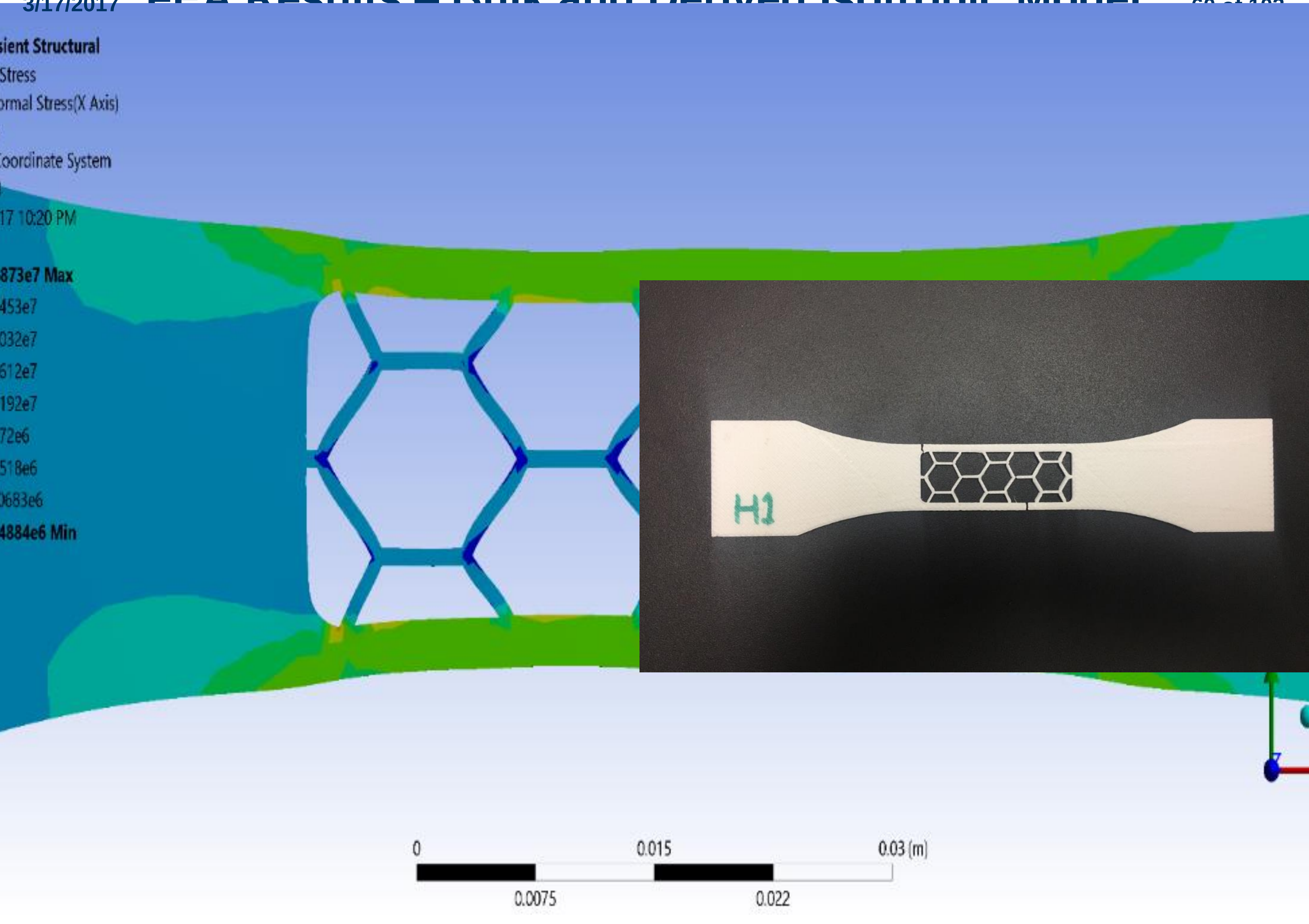
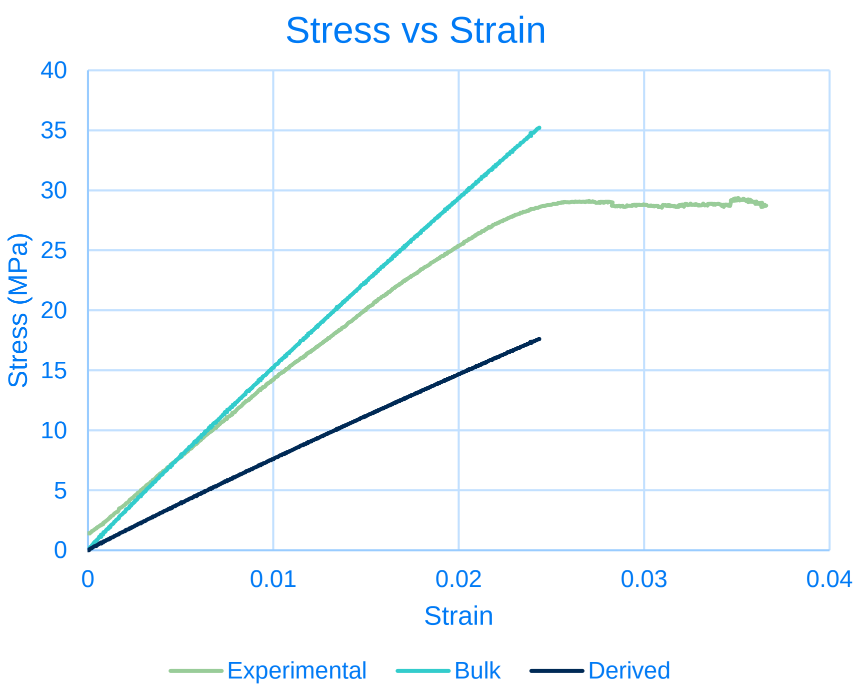
FEA Results – Bulk and Derived Isotropic Model



FEA Results – Bulk and Derived Isotropic Model

Hilbert Infill



	Error	
	Bulk Model	Derived Model
Stress at 2% strain	16%	42%
Stress at 1% strain	8%	45%

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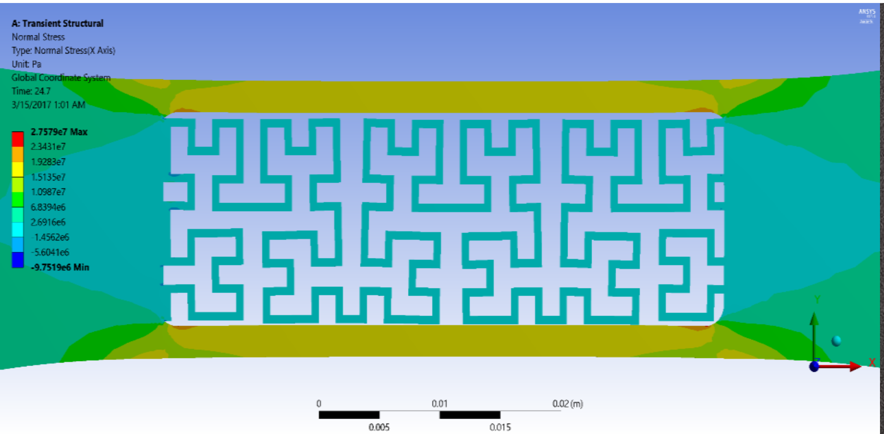
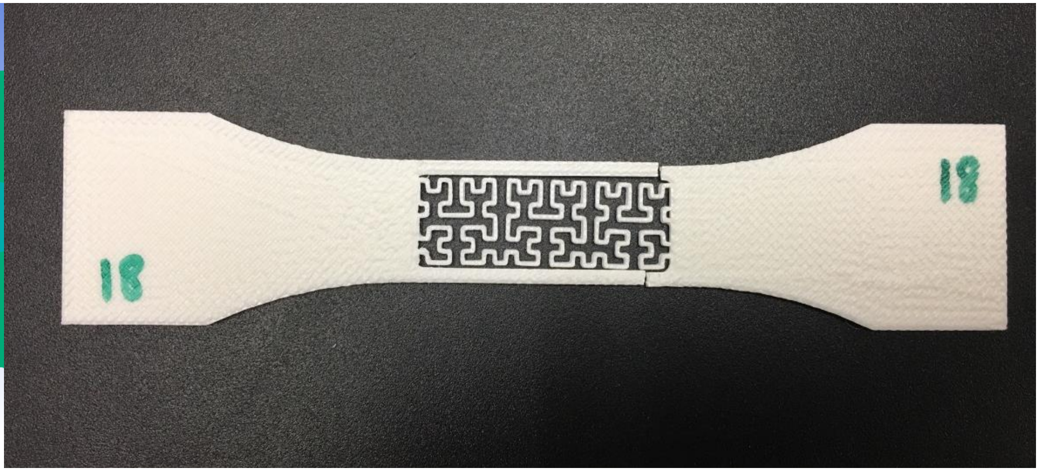
FEA Results – Bulk and Derived Isotropic Model

Hilbert Infill





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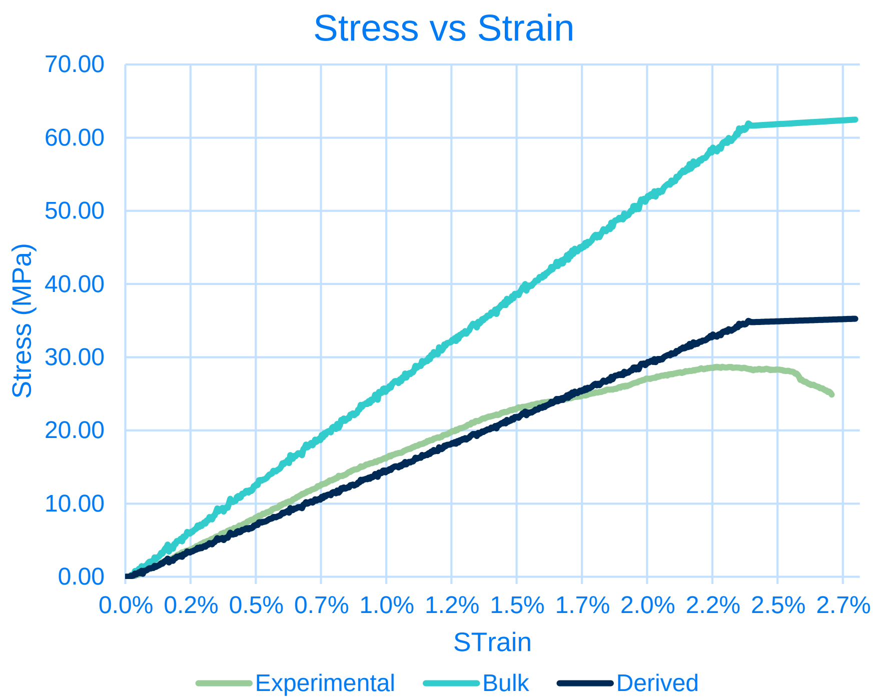
FEA Results – Bulk and Derived Isotropic Model

Circular Straight Infill



	Error	
	Bulk Model	Derived Model
Stress at 2% strain	42%	7%
Stress at 1% strain	60%	6%

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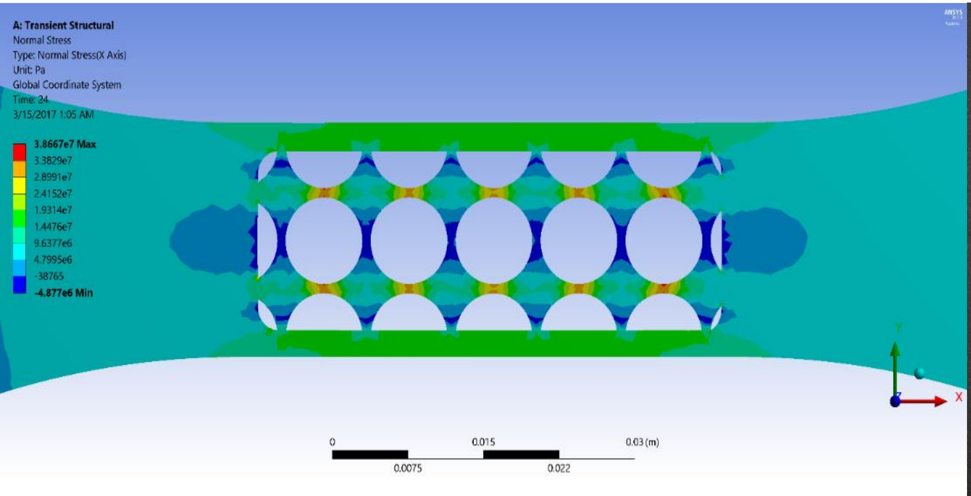
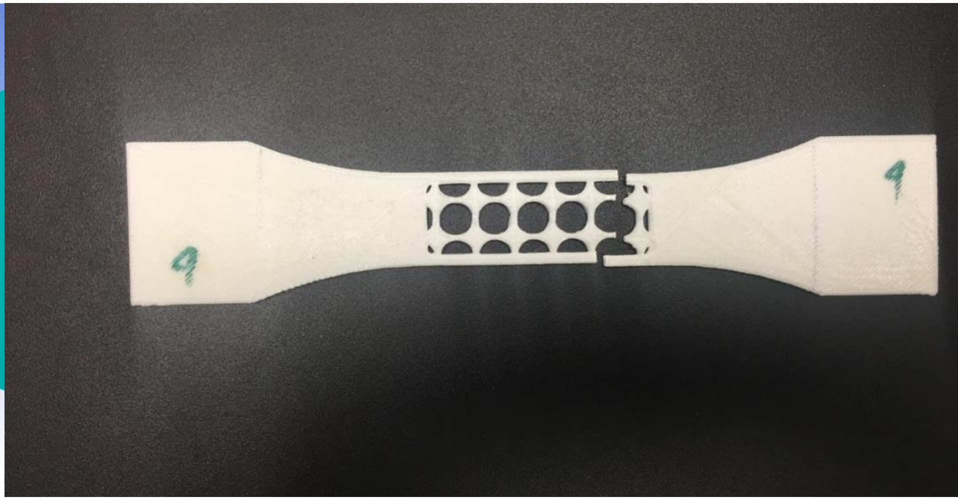
Circular Straight Infill





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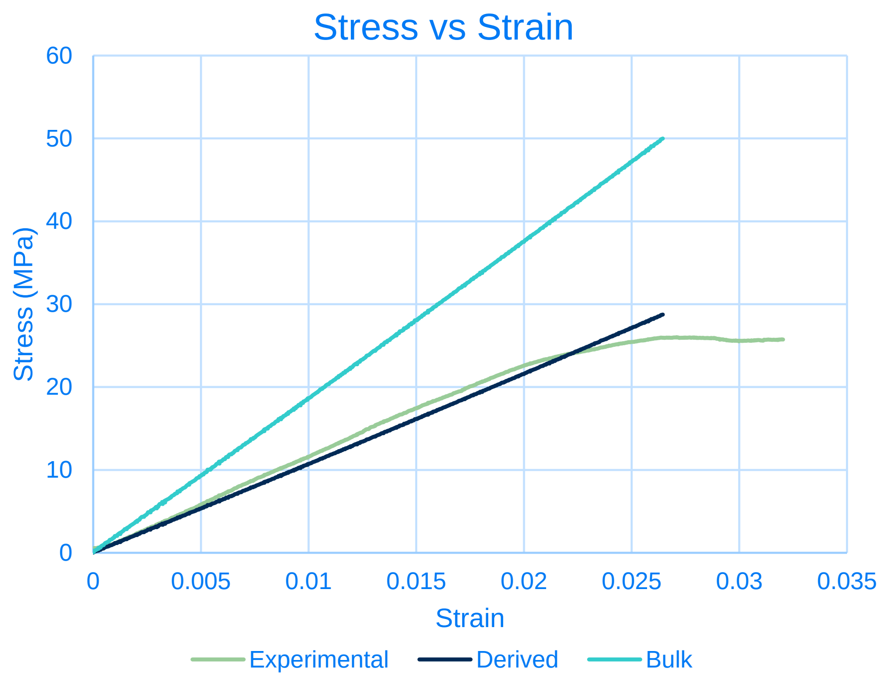
FEA Results – Bulk and Derived Isotropic Model

Circular Packed Infill



	Error	
	Bulk Model	Derived Model
Stress at 2% strain	42%	4%
Stress at 1% strain	60%	7%

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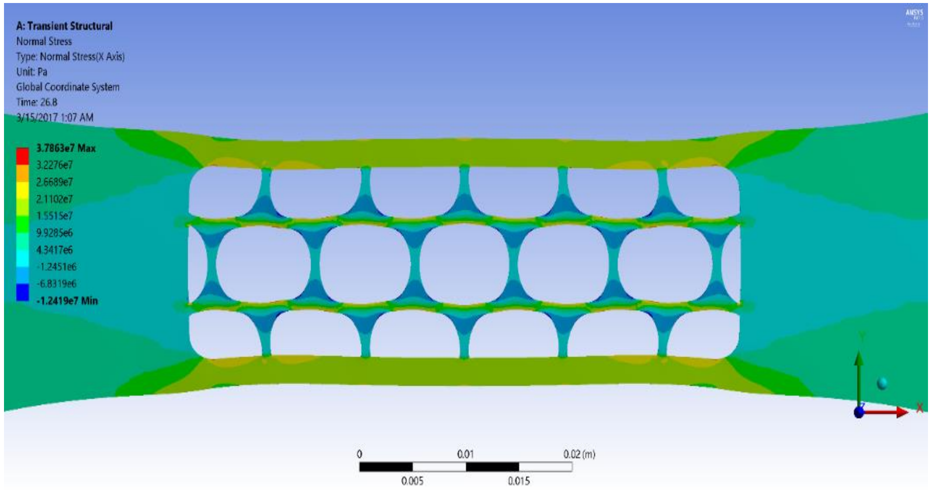
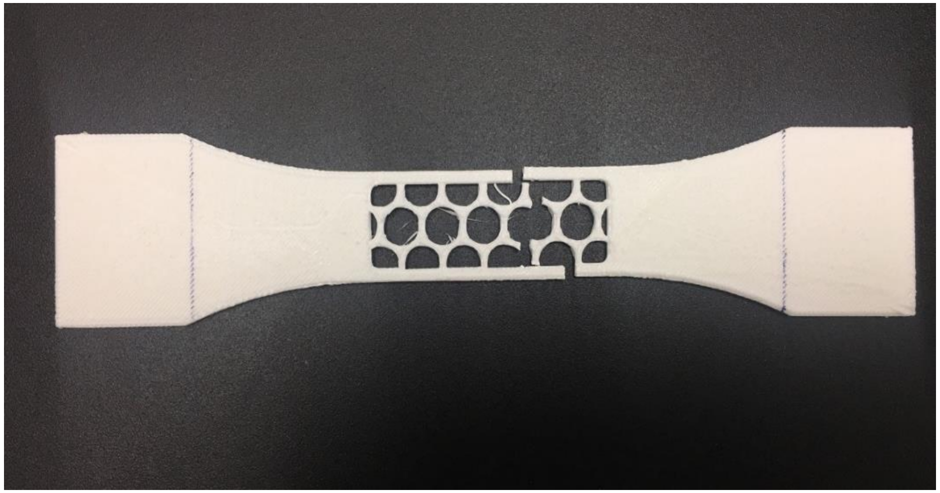
FEA Results – Bulk and Derived Isotropic Model

Circular Packed Infill





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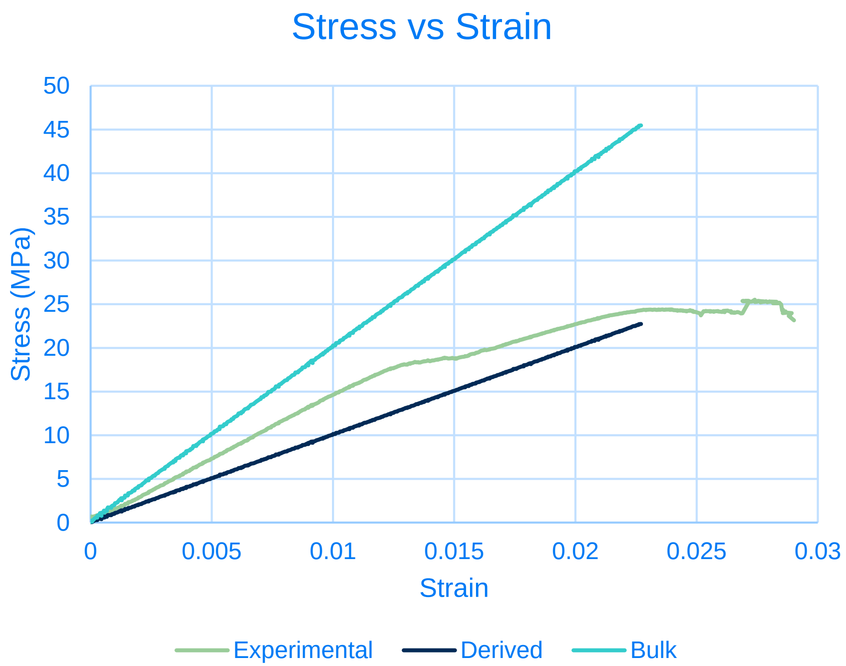
Linear Straight Infill



	Error	
	Bulk Model	Derived Model
Stress at 2% strain	75%	11%
Stress at 1% strain	38%	30%

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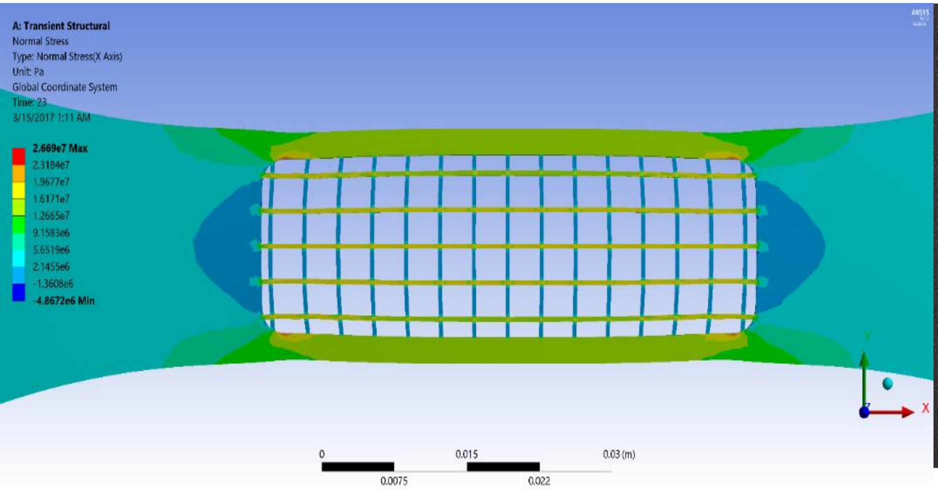
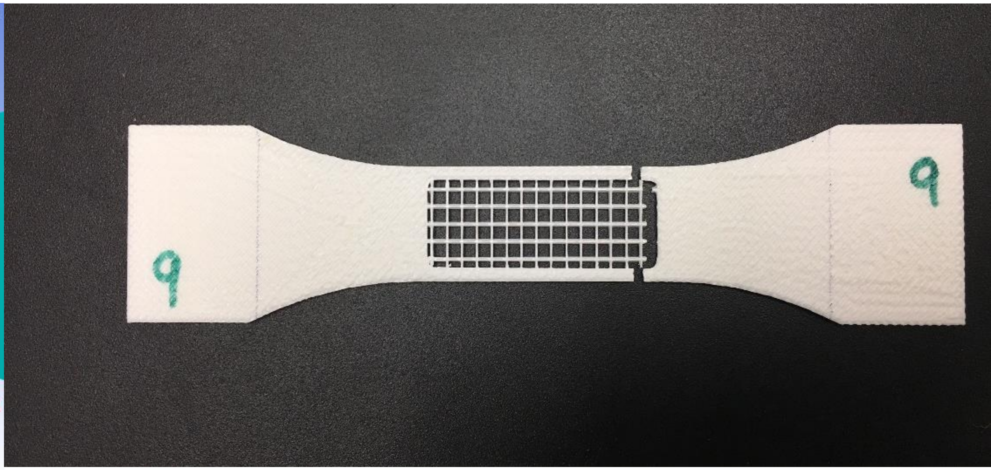
FEA Results – Bulk and Derived Isotropic Model

Linear Straight Infill





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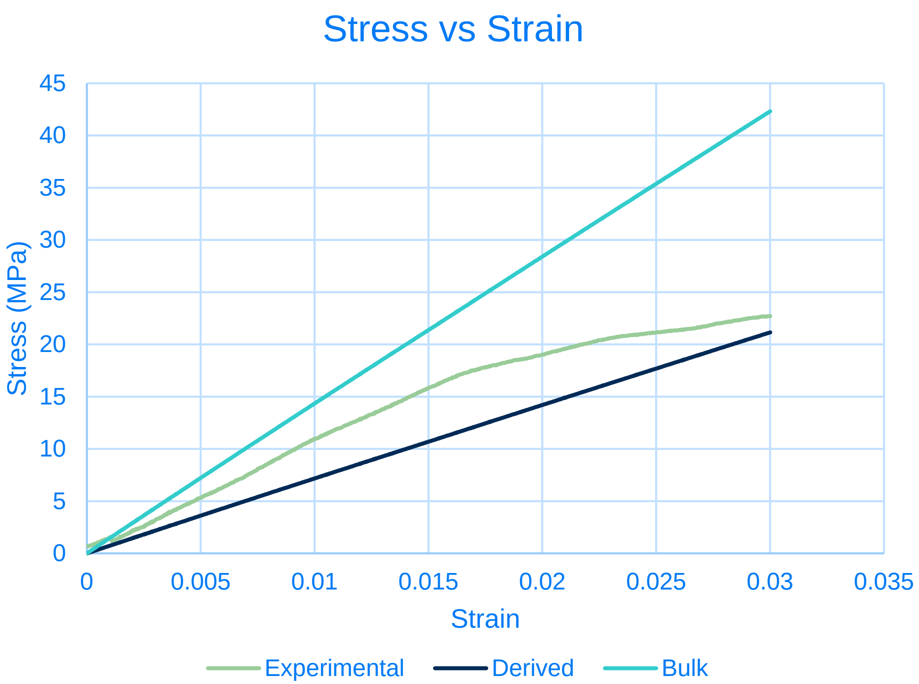
FEA Results – Bulk and Derived Isotropic Model

Linear CrossHatch Infill



	Error	
	Bulk Model	Derived Model
Stress at 2% strain	45%	26%
Stress at 1% strain	30%	35%

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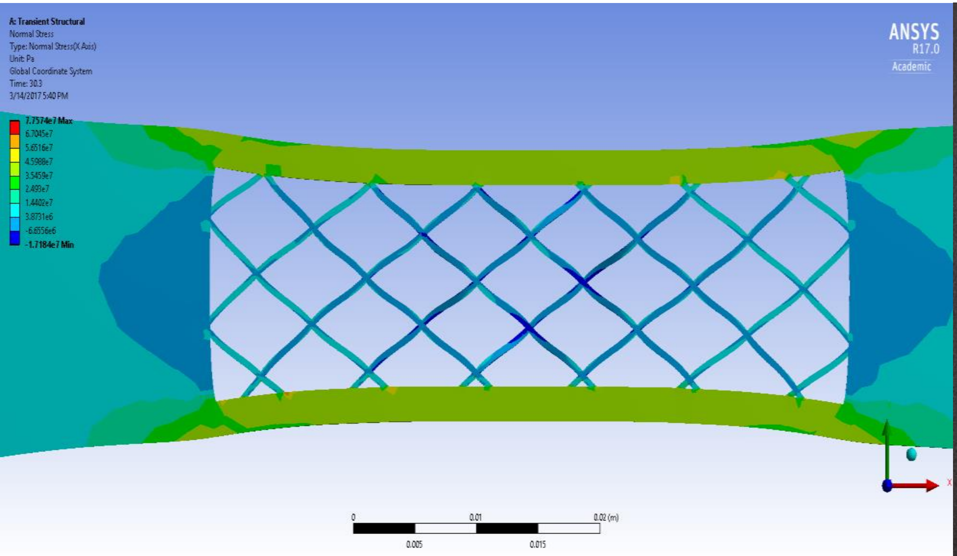
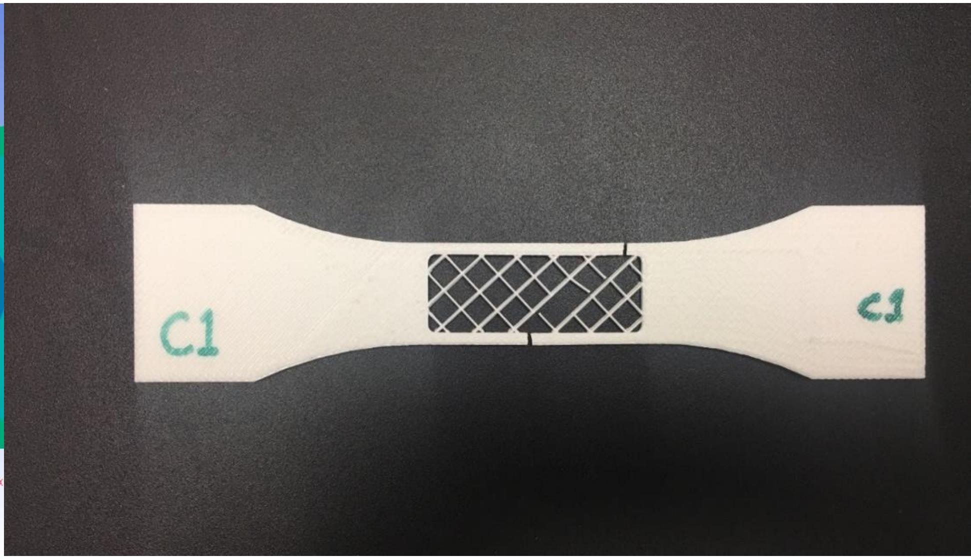
FEA Results – Bulk and Derived Isotropic Model

Linear CrossHatch Infill





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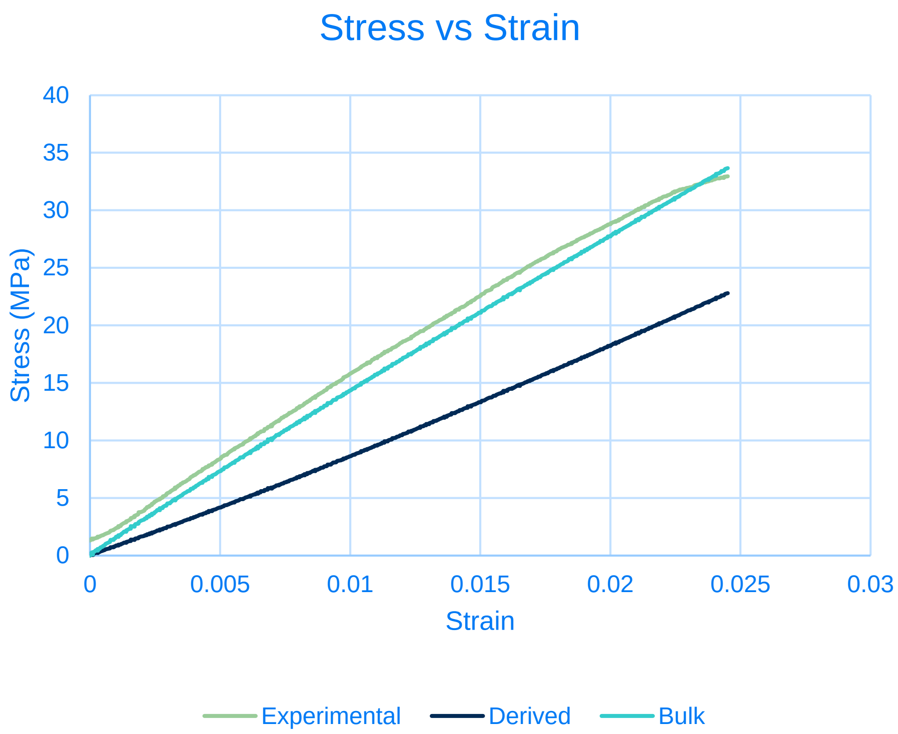
FEA Results – Bulk and Derived Isotropic Model

Infill-less



	Error	
	Bulk Model	Derived Model
Stress at 2% strain	4%	35%
Stress at 1% strain	9%	43%

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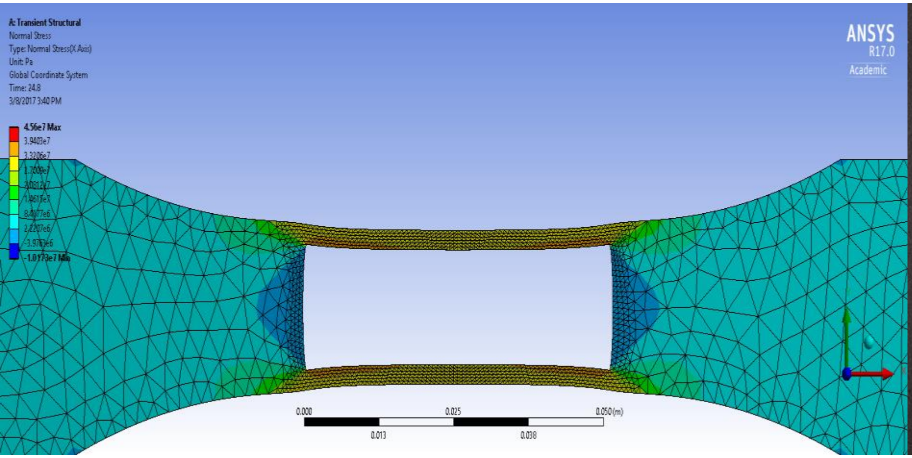
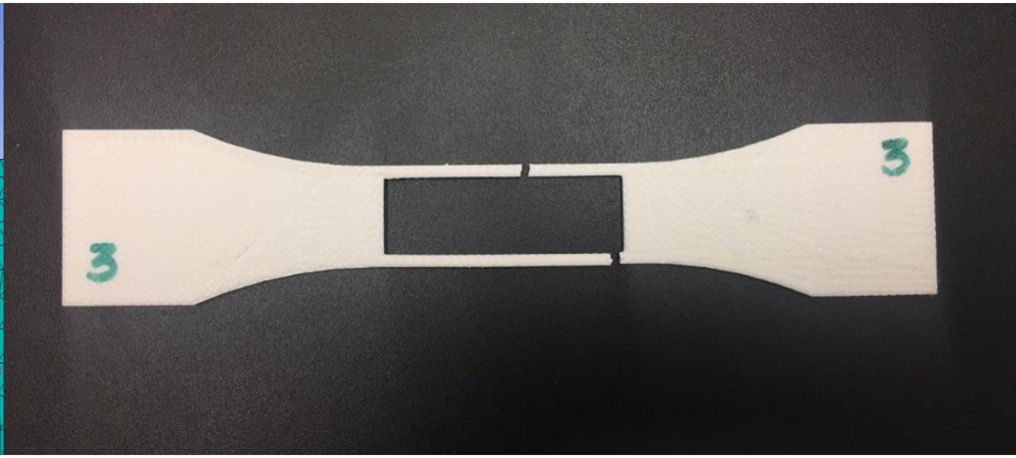
FEA Results – Bulk and Derived Isotropic Model

Infill-less





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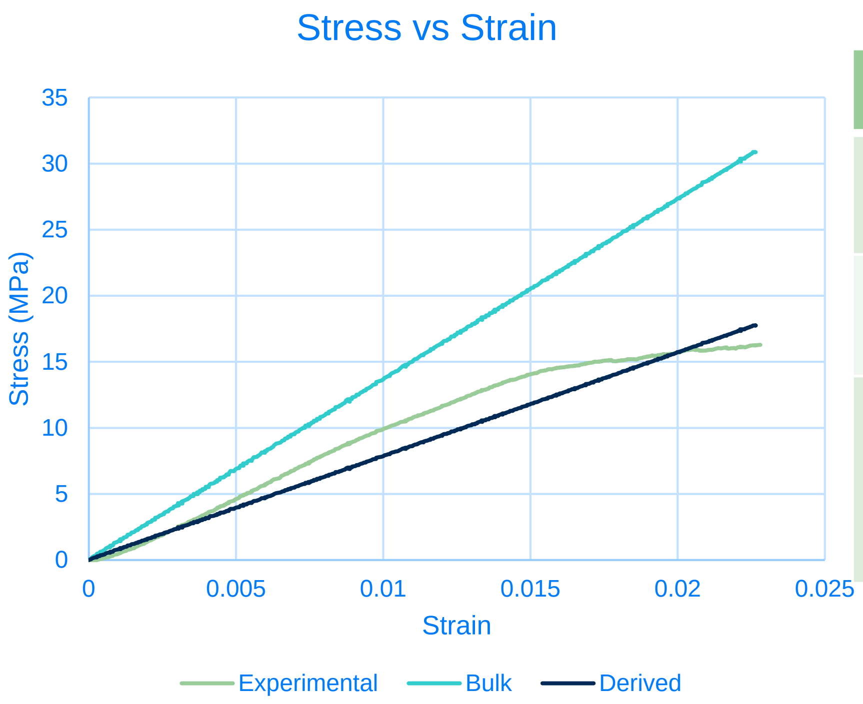
FEA Results – Bulk and Derived Isotropic Model

Continuous



	Error	
	Bulk Model	Derived Model
Stress at 2% strain	11%	0%
Stress at 1% strain	30%	20%

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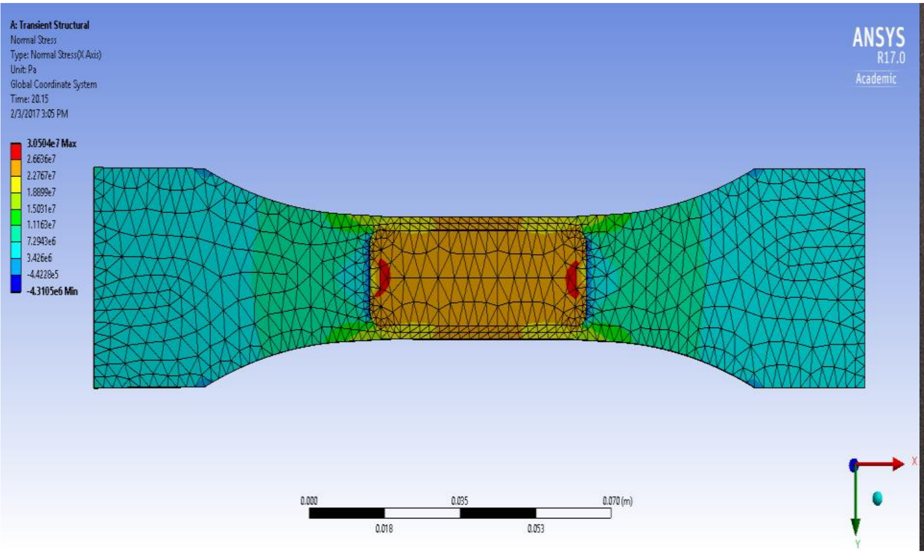
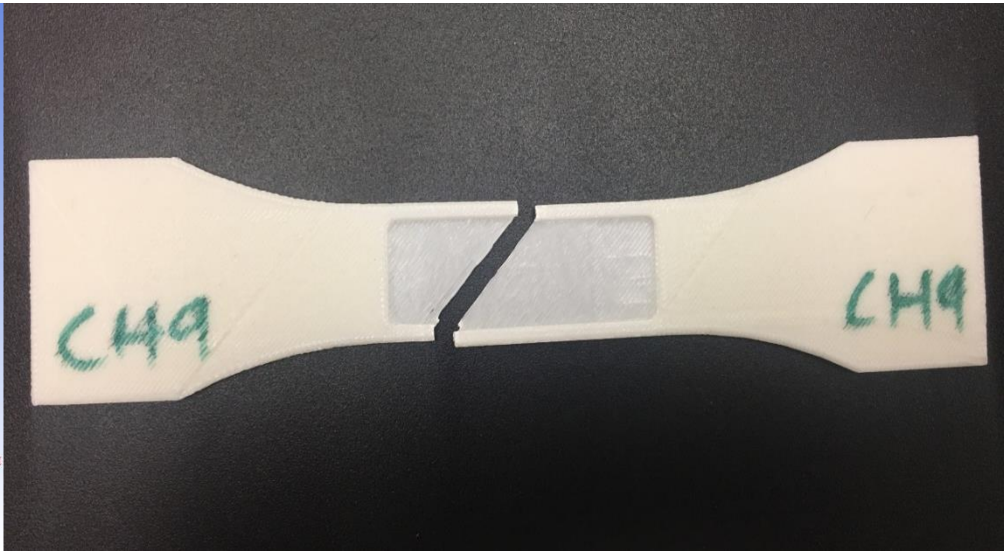
FEA Results – Bulk and Derived Isotropic Model

Continuous





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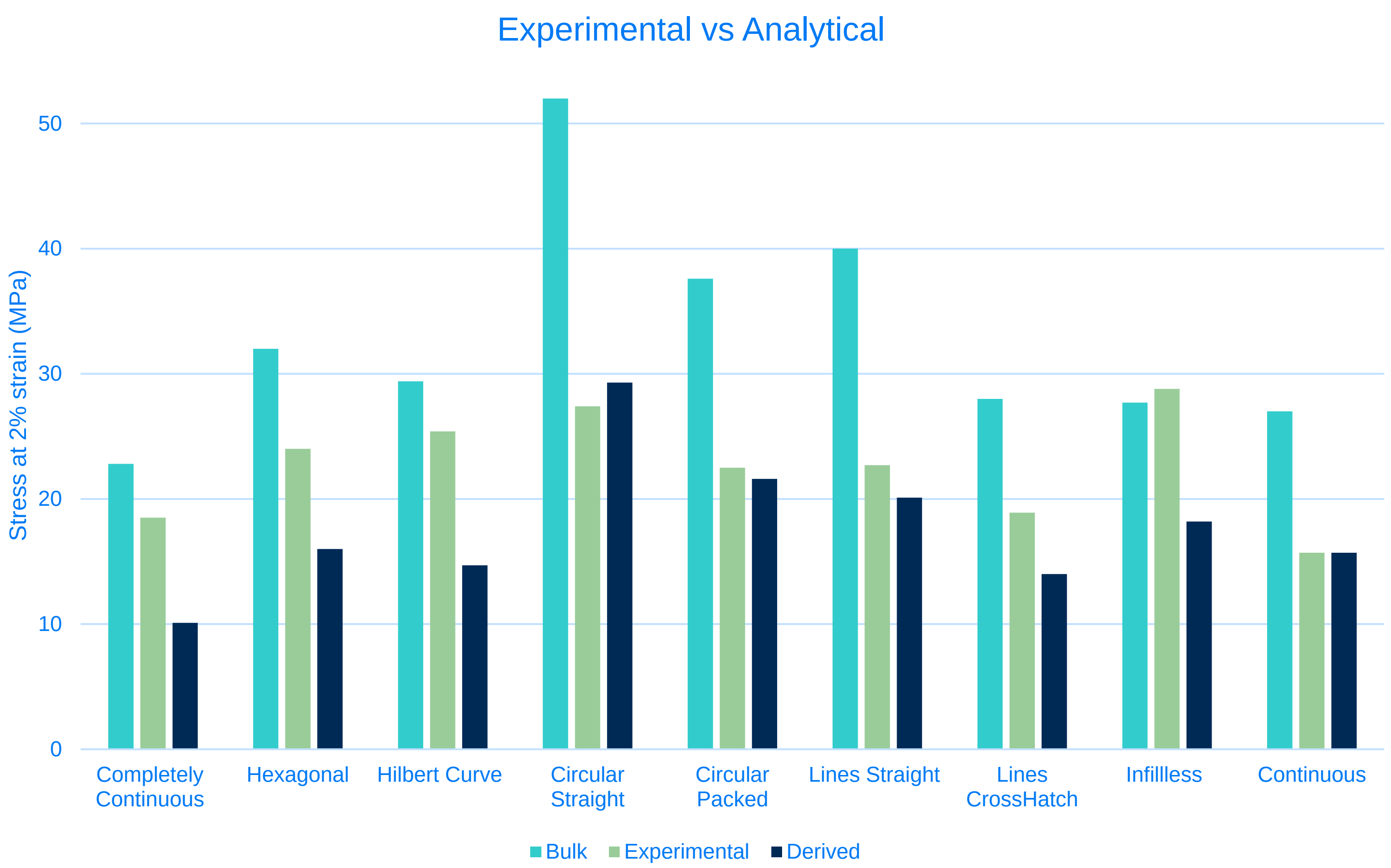
Results – Summary &Comparison



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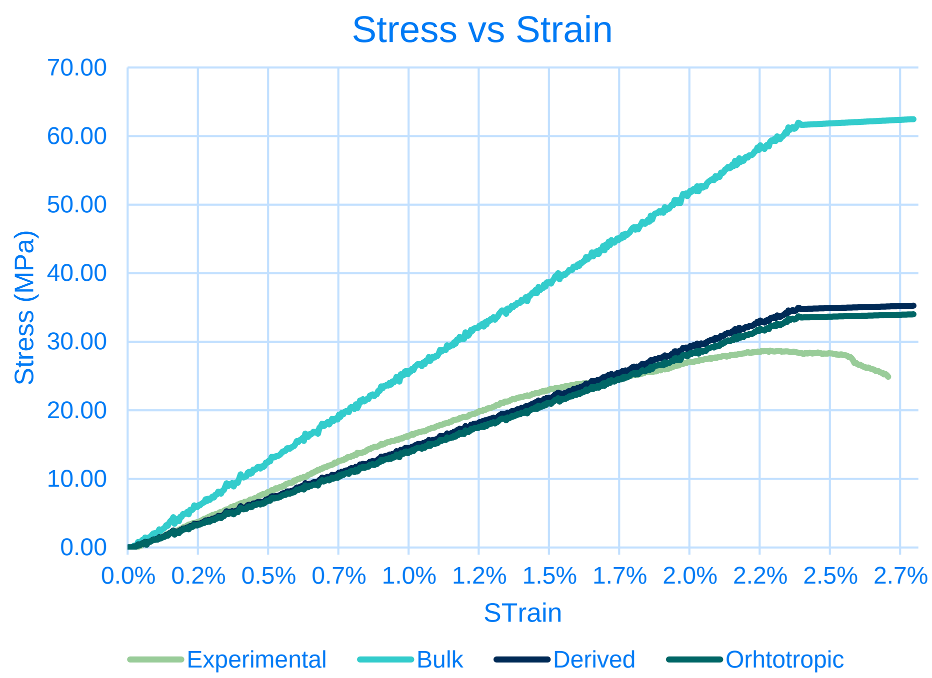
FEA Results – Orthotropic Properties Model

Circular Straight Infill



	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	28.3	33.5		
Yield Strain	0.024	0.024		
Stress at 2%	27.2	28.3		3.5%
Stress at 1%	16.4	14.5		8%

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Results – Summary

- Bulk properties over predicted results.
- Derived properties under predicted results.
- Better representation of FDM part is needed.
- Accurate material model is needed.
- Circular Pattern showed consistent results with derived properties.
- Pattern with continuous thick infill showed consistent results.
- FEA stress plots of patterns with continuous areas is consistent with experimental data.
- Stress plots of intricate infills like Hexagon fail to predict actual fracture.

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Conclusions from current work.

- The FEA models used above are not reliable for analyzing FDM parts.
- Lack of an accurate material model leads to errors.
- Representation of FDM parts as solid continuous parts produces inconsistencies.
- Higher fidelity models require long times and are computationally intensive.
- Current FEA model can be used as a visual aid to predict fracture in case of patterns having continuous geometry.

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Work to be completed

- Evaluate orthotropic properties.
- Analyze using orthotropic material model.
- Analyze using a composite layup.
- Compare and discuss.

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Future Work

- Better representation for actual structure of FDM parts.
- Better Material Model using an extensive anisotropic model formulation.
- Higher fidelity FEA models.
- Compare with different AM technologies.
- Discrete Element Analysis.

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THANK YOU.

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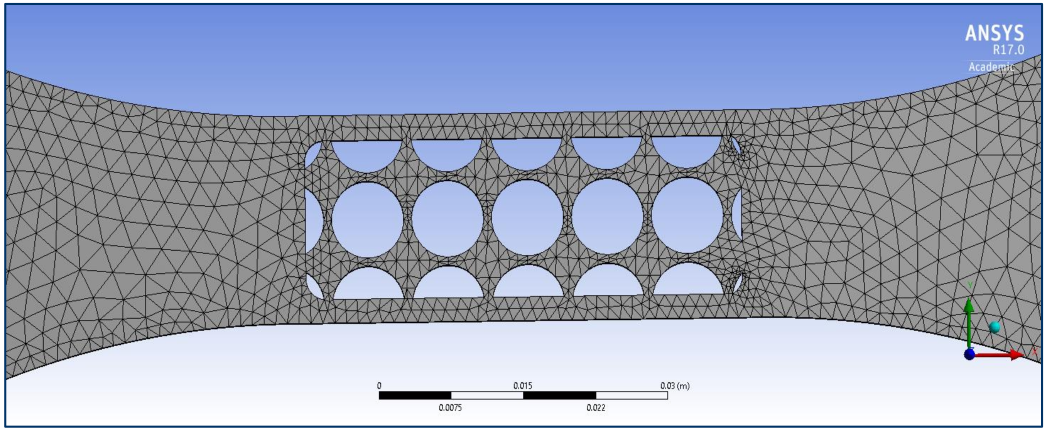
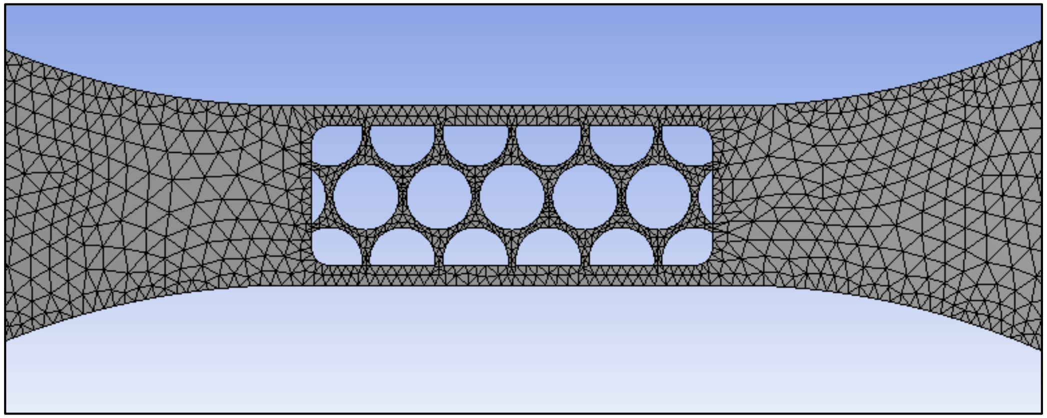
Meshed Part

Circular Straight Infill



Circular Packed Infill



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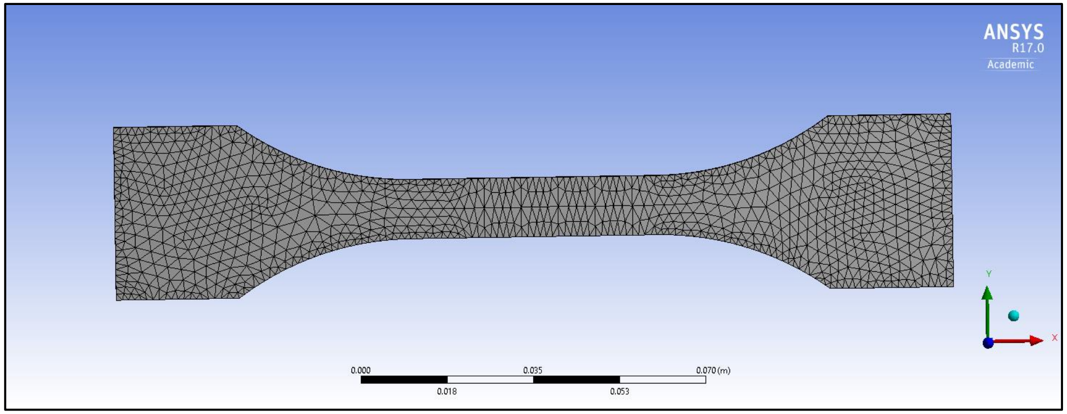
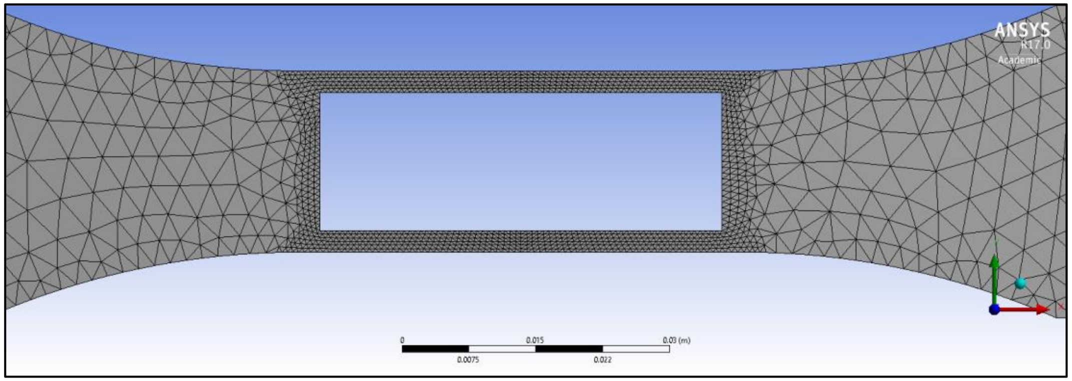
Meshed Part

Linear Straight Infill



Linear CrossHatch Infill



Mesh Statistics

	ANSYS©			Abaqus©		
	Type	Nodes	Elements	Type	Nodes	Elements
Continuous (C)	Tetrahedral	15209	7344	Tetrahedral	2400	1092
Hexagonal Infill (HI)	Tetrahedral	19522	9397	Tetrahedral	103885	62493
Hexagonal Continuous (HC)	Tetrahedral	13341	6582	Tetrahedral	18765	9667
Circular Straight Infill (CI)	Tetrahedral	26840	13026	Tetrahedral	44840	13026
Circular Continuous (CC)	Tetrahedral	13280	6515	Tetrahedral	17520	9572
Circular Packed Infill	Tetrahedral	237364	147796	Tetrahedral	325621	153625
Linear Straight Infill	Tetrahedral	321630	152453	Tetrahedral	123154	76545
Linear CrossHatch Infill	Tetrahedral	212544	121456	Tetrahedral	213514	142123
Hilbert Curve Infill	Tetrahedral	424719	212611	Tetrahedral	345334	121442
Infill-less	Tetrahedral	60437	36631	Tetrahedral	85463	45311

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Analysis using Orthotropic Material Properties

- Solve for Stress and Strain plots for given displacement and compare with experimental values.
- The compliance matrix for orthotropic model.

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{zx}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix}$$

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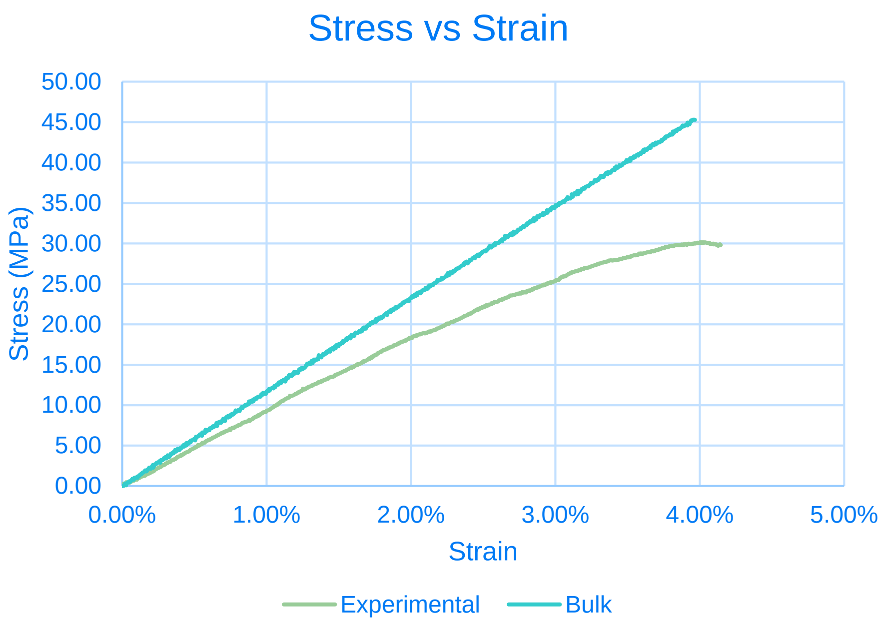
FEA Results – Bulk Isotropic Properties Model

Completely Continuous



	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	30.2	45.1	43	
Yield Strain	0.04	0.042	0.042	
Stress at 2%	18.1	22.8	22	25%
Stress at 1%	9.6	12	11.9	25%

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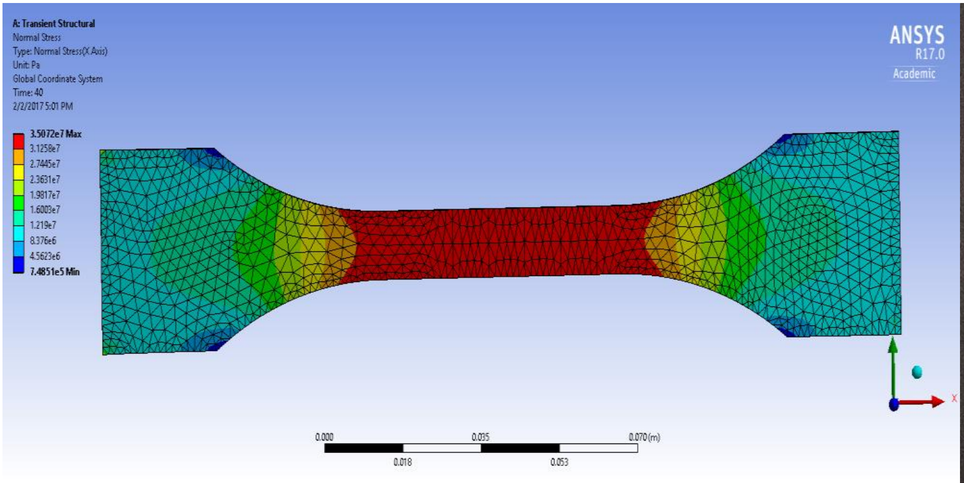
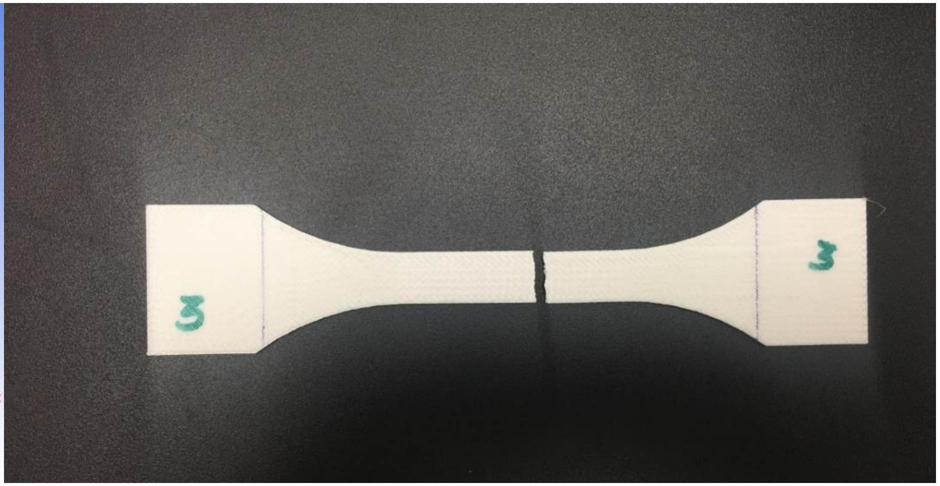
FEA Results – Bulk Isotropic Properties Model

Completely Continuous – Stress Plot





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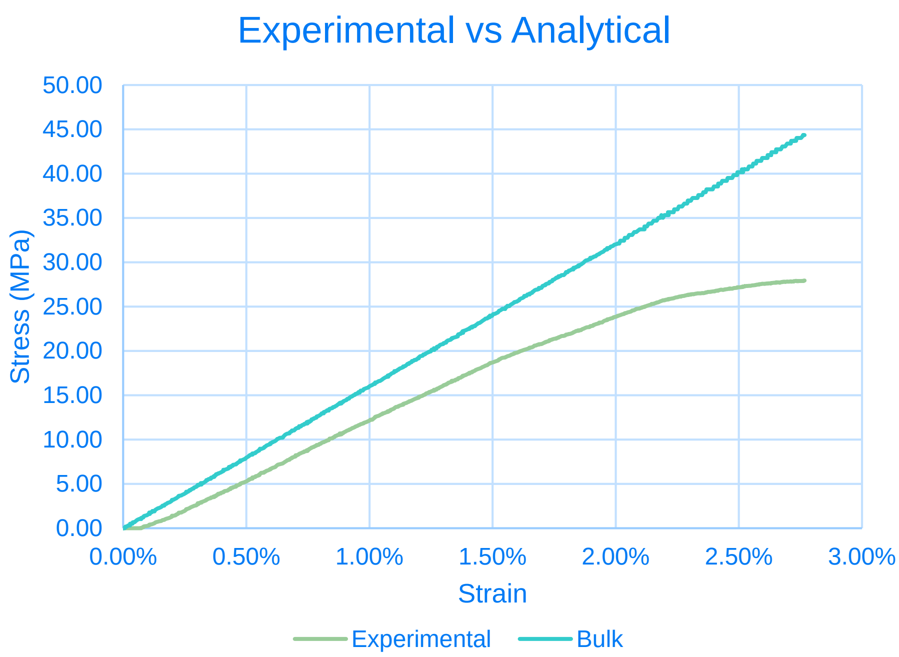
FEA Results – Bulk Isotropic Properties Model

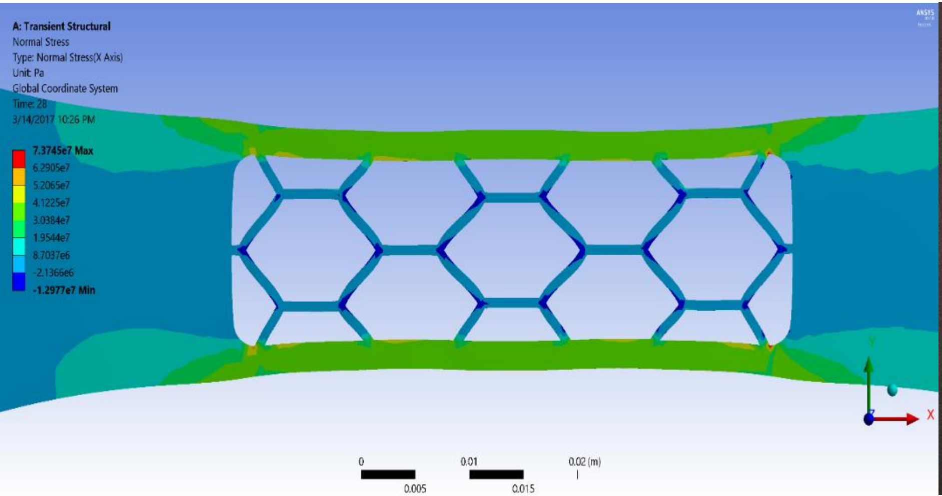
Hexagonal Infill

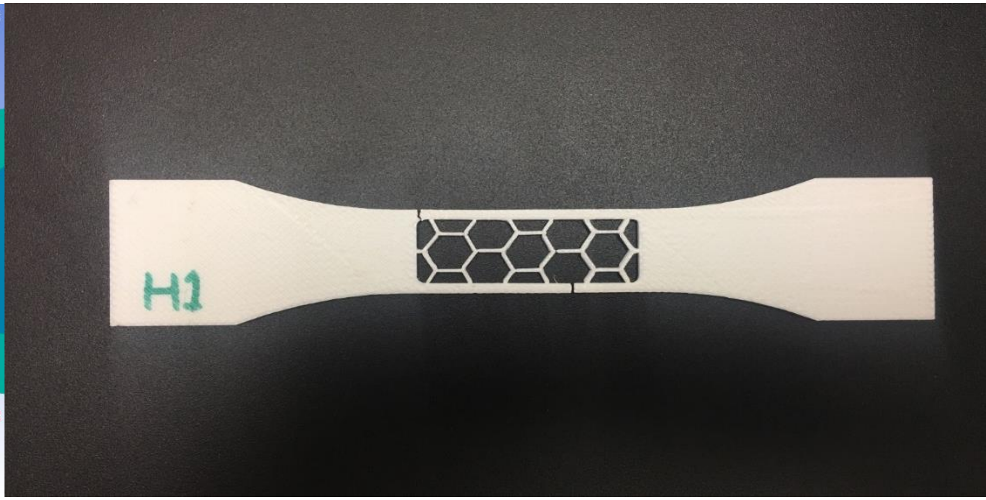


	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	27.9	44.4	43	
Yield Strain	0.028	0.023	0.022	
Stress at 2%	24	32	32	33%
Stress at 1%	12.1	15.9	16	30%

FEA Results – Bulk Isotropic Properties Model

Hexagonal Infill





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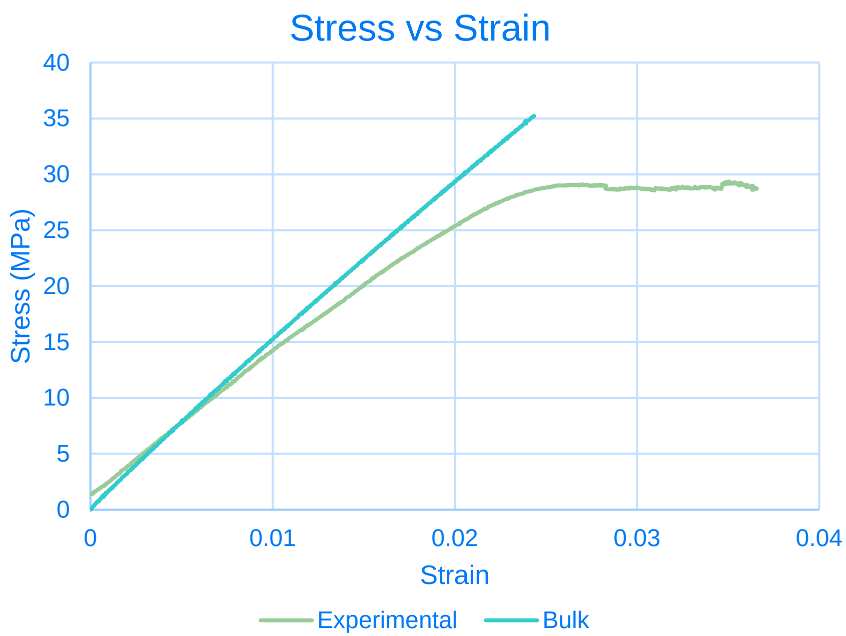
FEA Results – Bulk Isotropic Properties Model

Hilbert Infill



	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	28.6	35.2	35	
Yield Strain	0.024	0.023	0.023	
Stress at 2%	25.4	29.4	30	16%
Stress at 1%	14.2	15.2	15.5	7% - 8%

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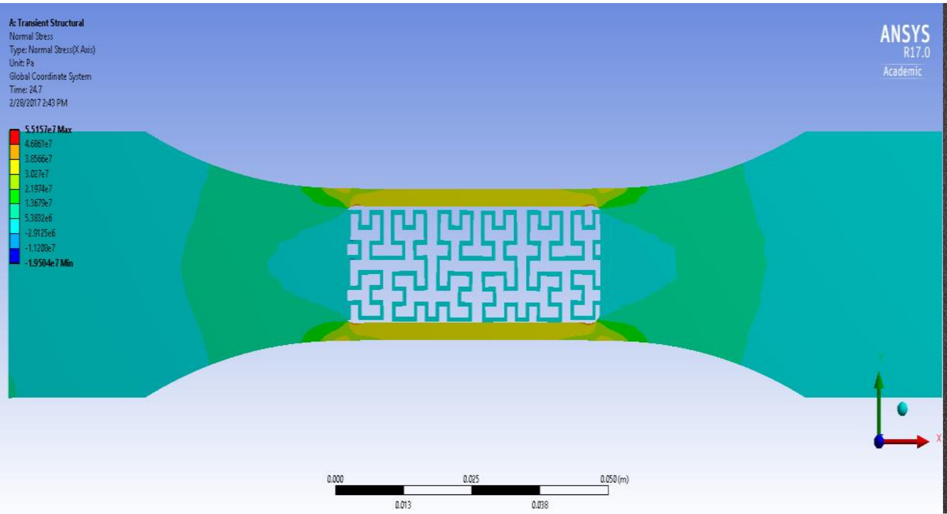
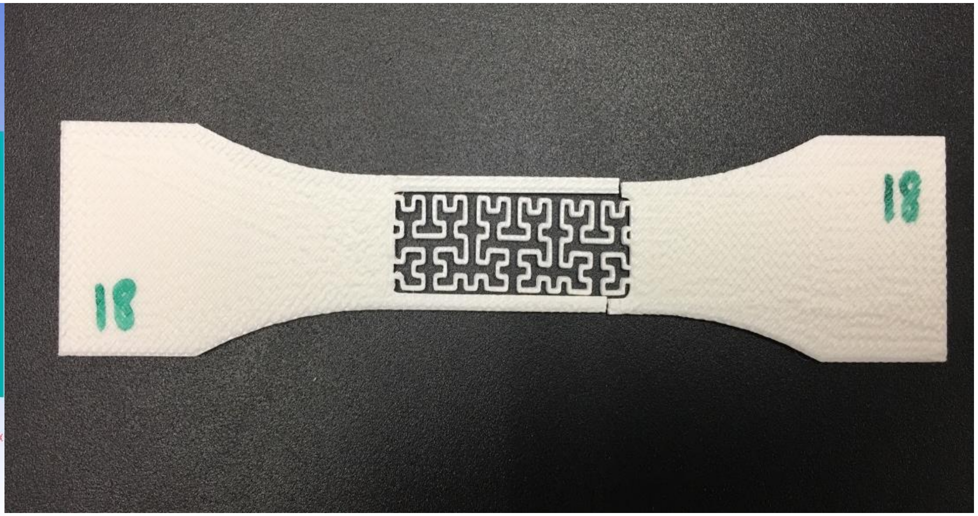
FEA Results – Bulk Isotropic Properties Model

Hilbert Infill





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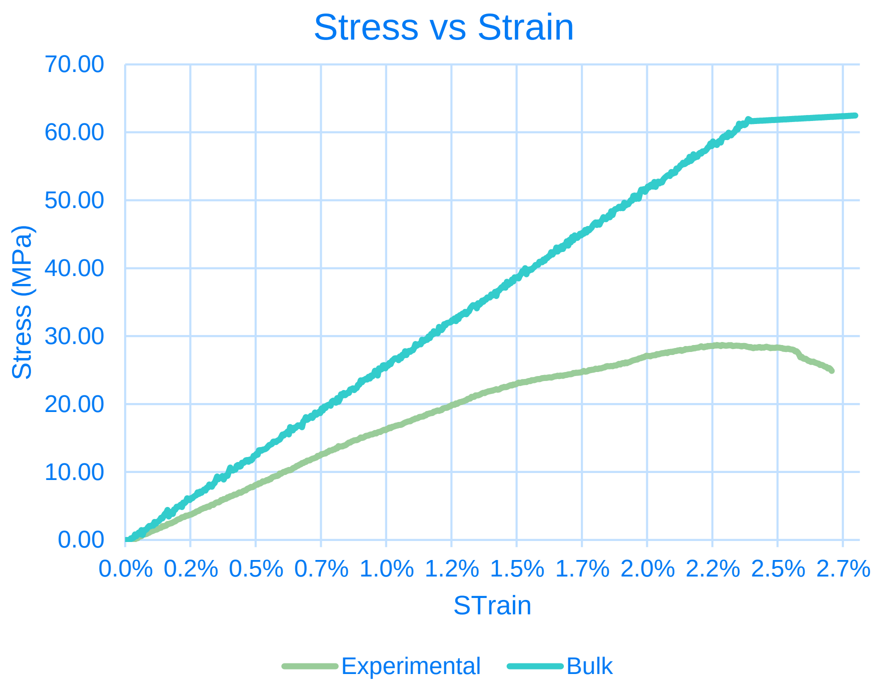
FEA Results – Bulk Isotropic Properties Model

Circular Straight Infill



	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	28.3	64.7	65	
Yield Strain	0.026	0.027	0.027	
Stress at 2%	27.2	52	51	42%
Stress at 1%	16.4	26.7	25.8	60%

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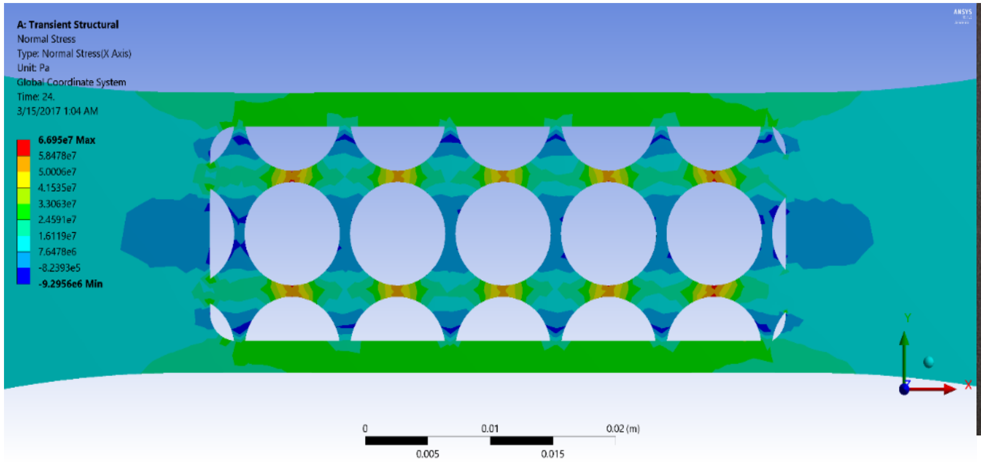
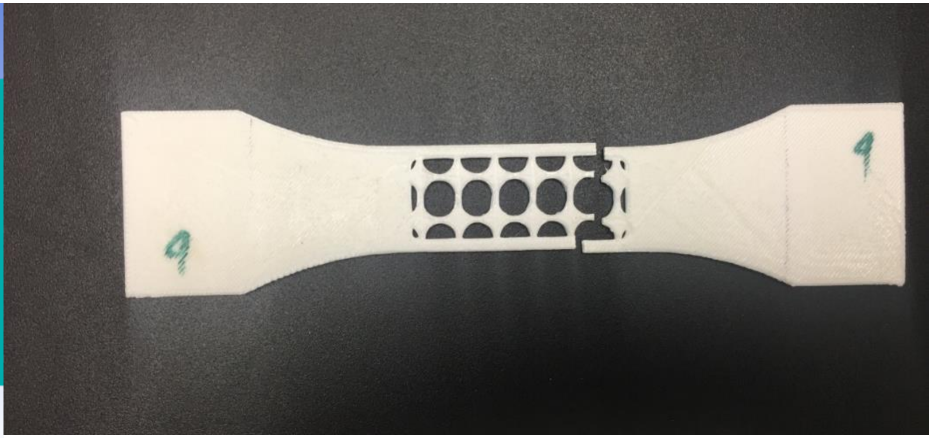
FEA Results – Bulk Isotropic Properties Model

Circular Straight Infill





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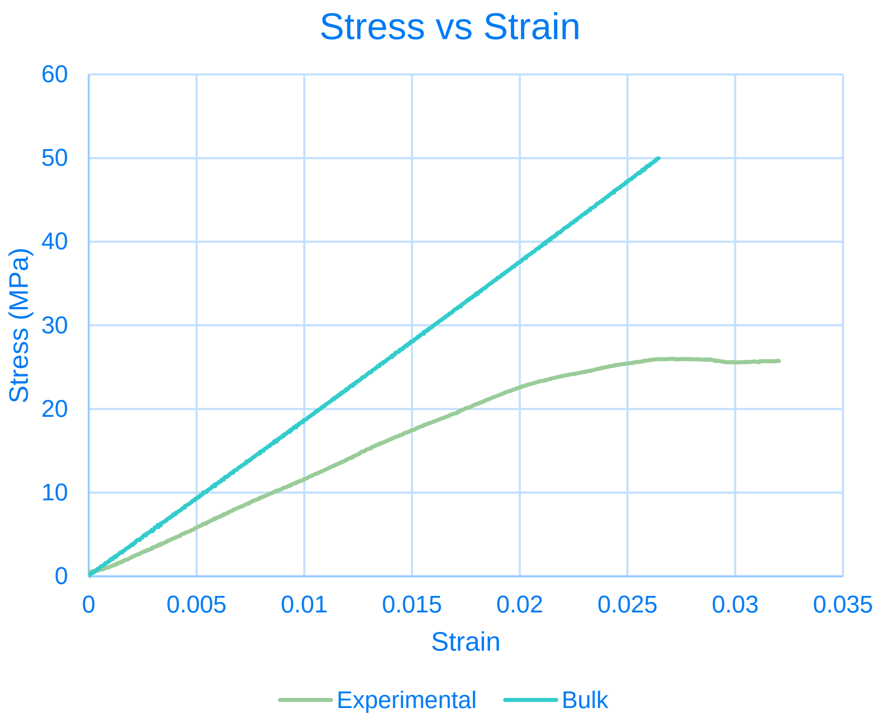
FEA Results – Bulk Isotropic Properties Model

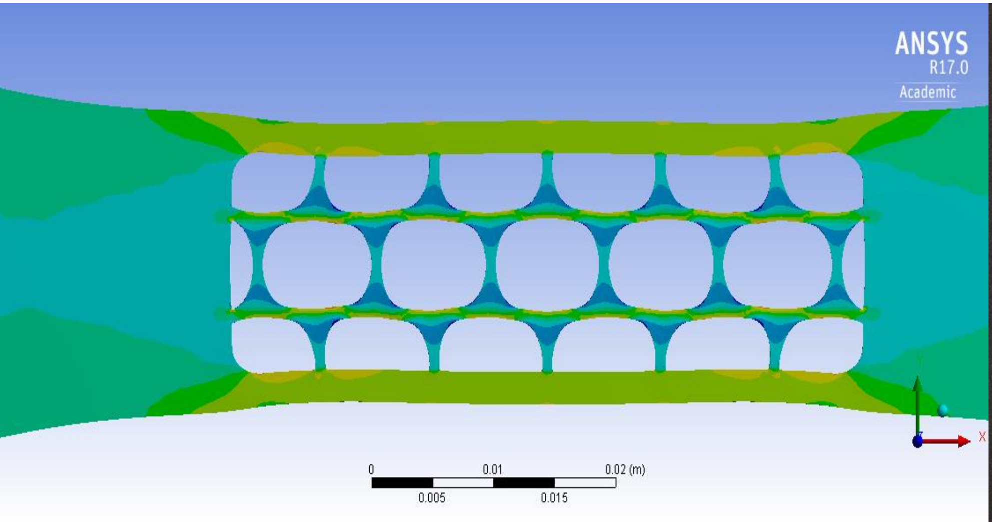
Circular Packed Infill

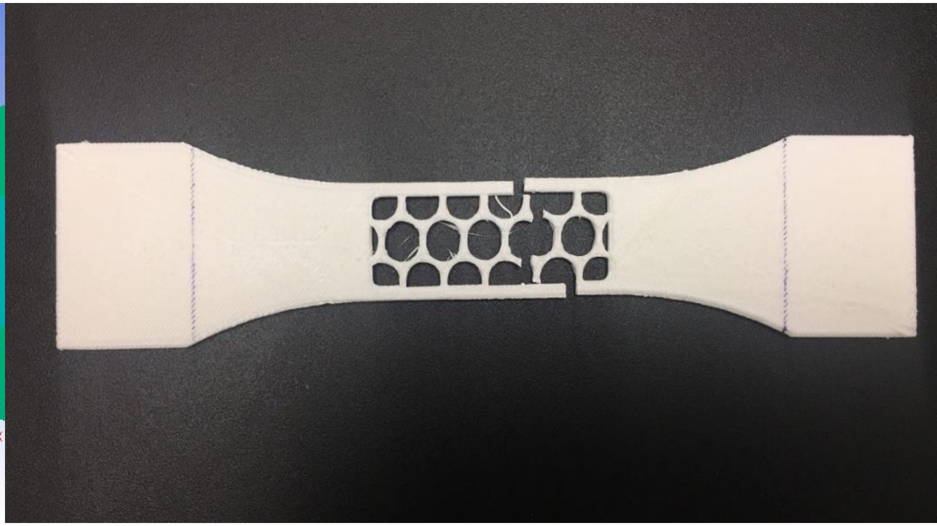


	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	25.9	50	51	
Yield Strain	0.026	0.026	0.26	
Stress at 2%	22.6	37.6	38	42%
Stress at 1%	11.6	18.7	19.5	60%

FEA Results – Bulk Isotropic Properties Model

Circular Packed Infill





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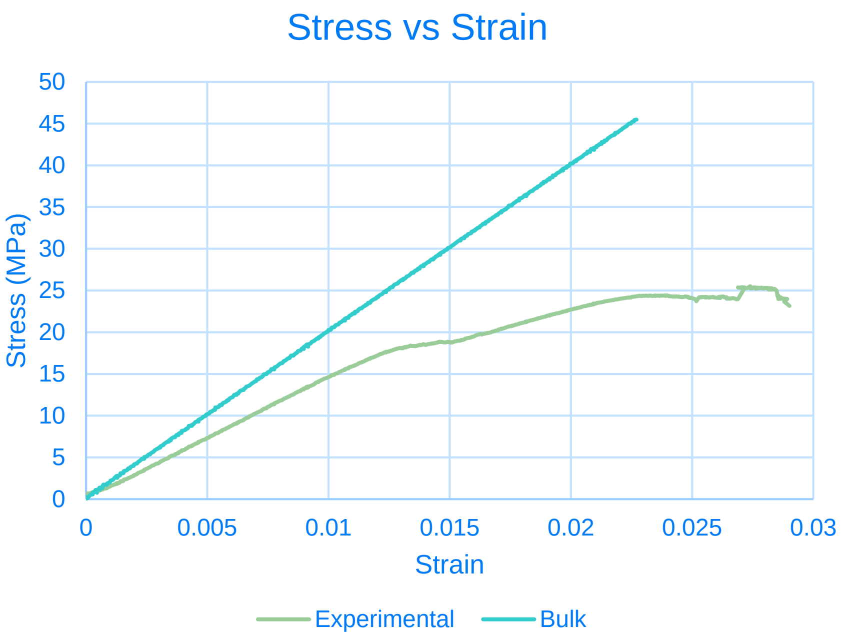
FEA Results – Bulk Isotropic Properties Model

Linear Straight Infill



	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	24.3	45.5	44.2	
Yield Strain	0.025	0.022	0.022	
Stress at 2%	22.7	40	41.5	75%
Stress at 1%	14.7	20.3	21.2	38%

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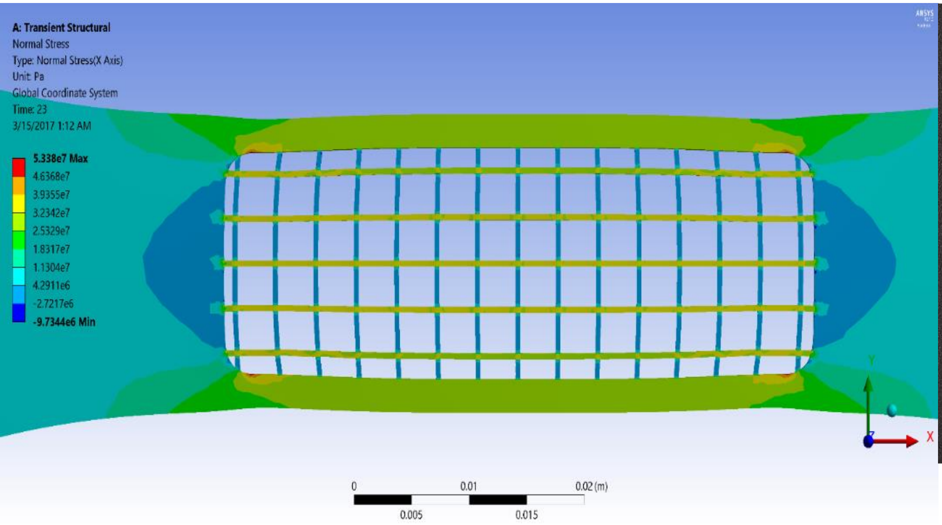
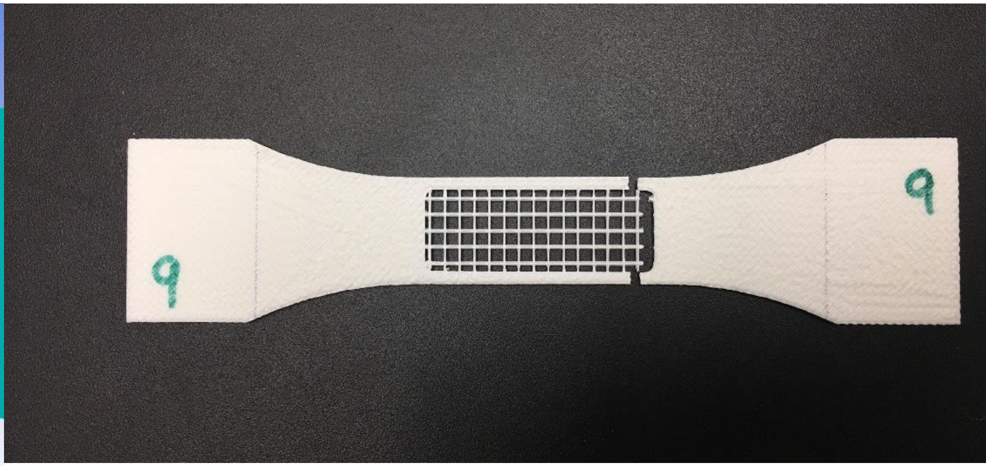
FEA Results – Bulk Isotropic Properties Model

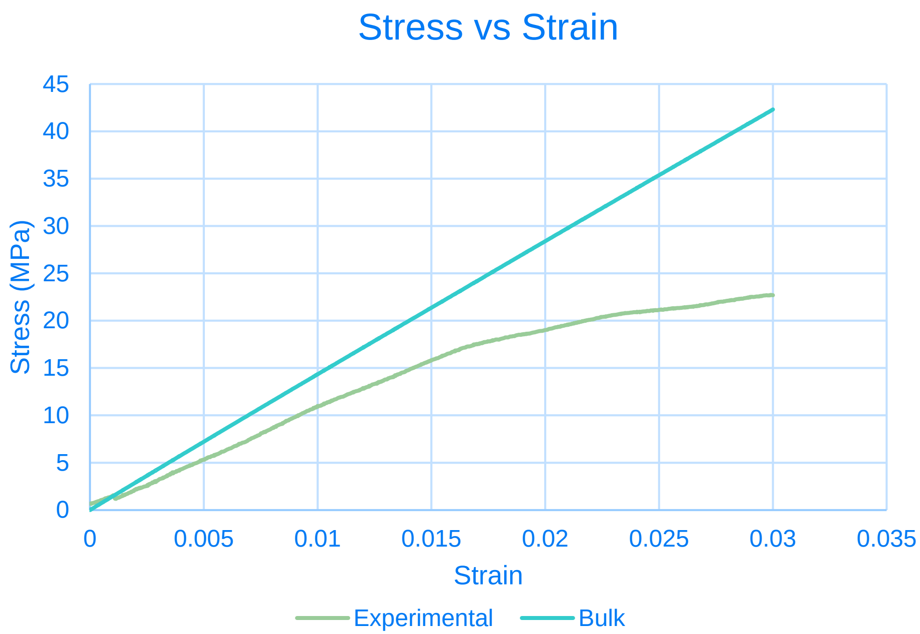
Linear Straight Infill





FEA Results – Bulk Isotropic Properties Model

Linear CrossHatch Infill



	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	22.7	42	43	
Yield Strain	0.032	0.03	0.3	
Stress at 2%	19	28	28.8	45%
Stress at 1%	11	14.3	15	30%

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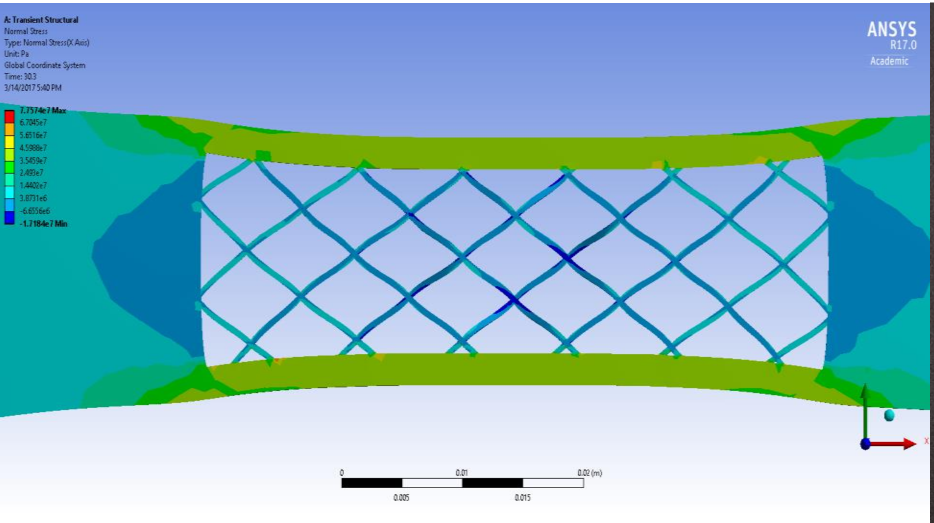
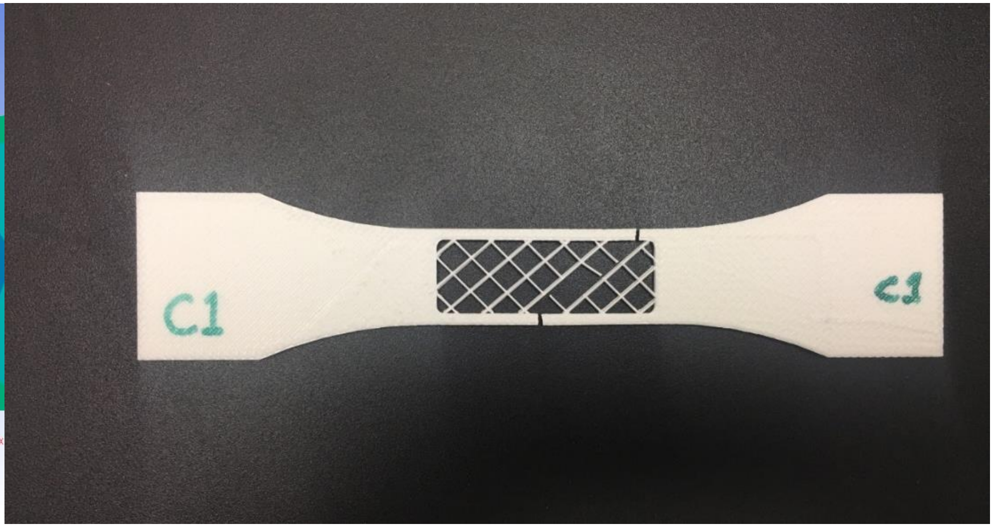
FEA Results – Bulk Isotropic Properties Model

Linear Cross-Hatch Infill





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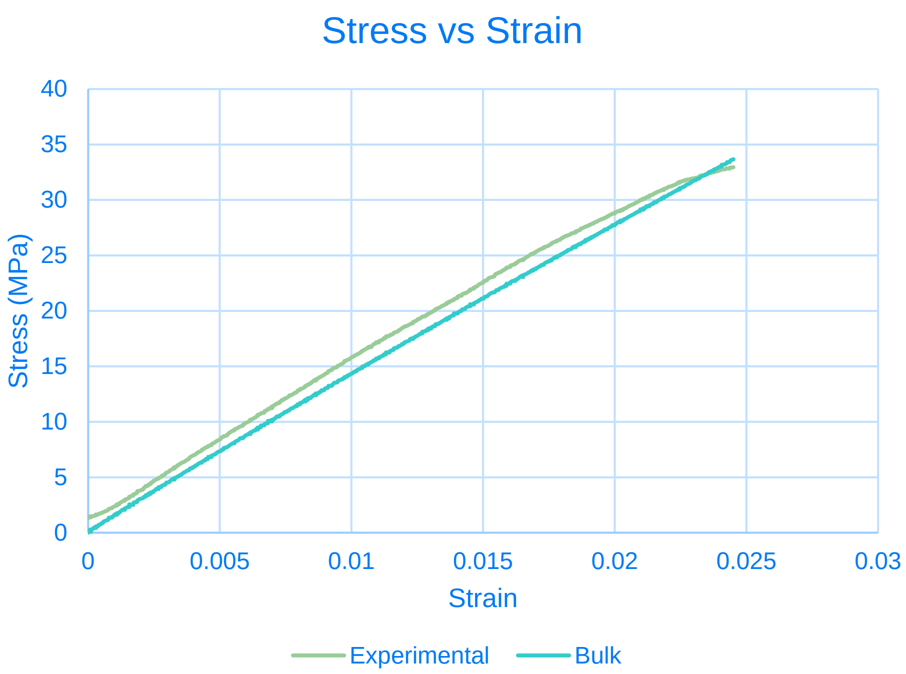
FEA Results – Bulk Isotropic Properties Model

Infill-less



	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	32.9	33.7	34.8	
Yield Strain	0.025	0.024	0.024	
Stress at 2%	28.8	27.7	28	4%
Stress at 1%	15.8	14.3	14	9%

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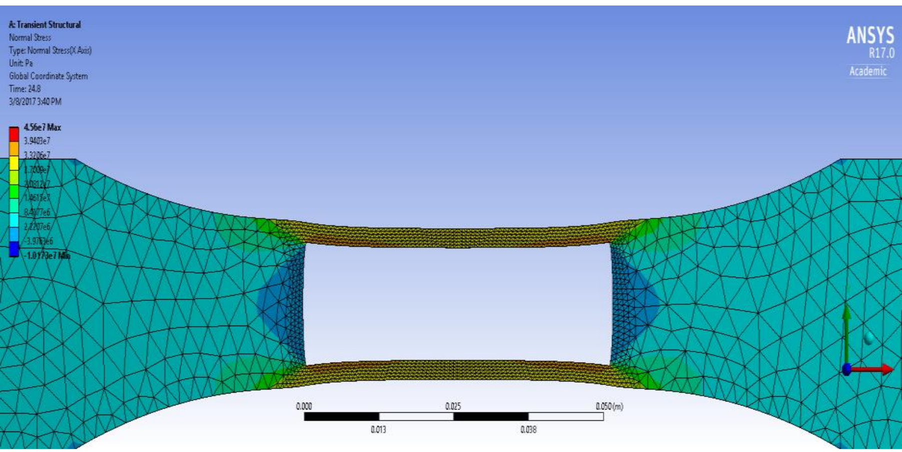
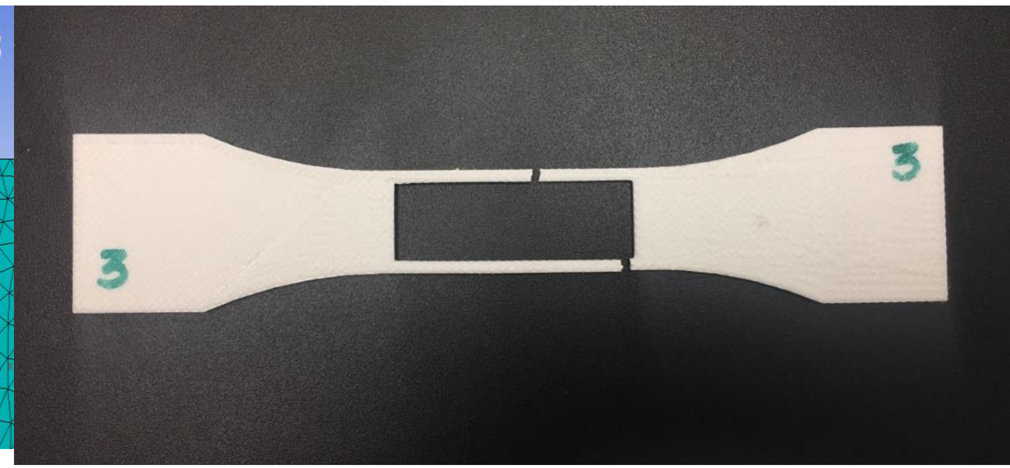
FEA Results – Bulk Isotropic Properties Model

Infill-less





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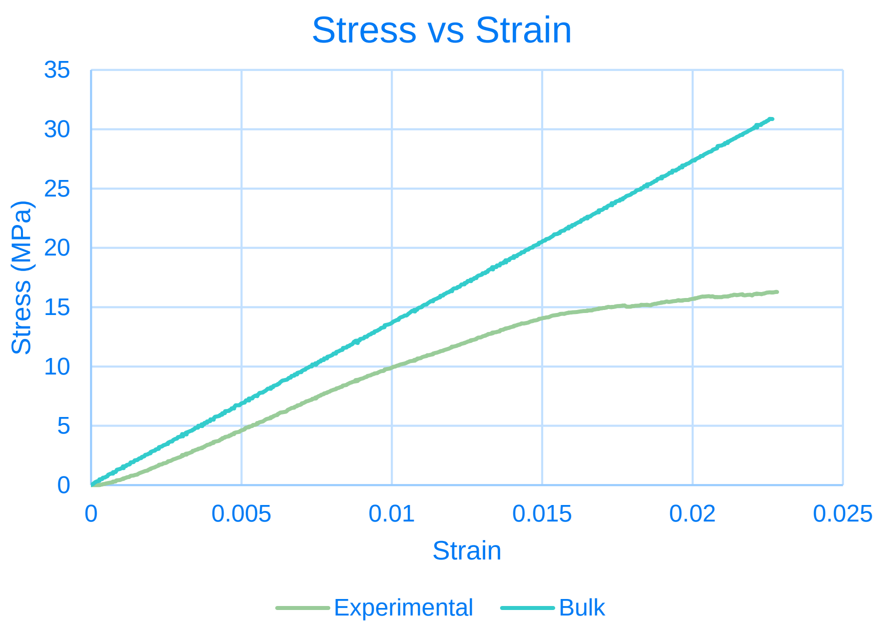
FEA Results – Bulk Isotropic Properties Model

Continuous



	Experimental	Analytical		Error
		ANSYS	Abaqus	
Yield Stress	16.2	30.8	31.5	
Yield Strain	0.022	0.023	0.023	
Stress at 2%	15.7	27	28	11%
Stress at 1%	9.9	13.8	14.2	30%

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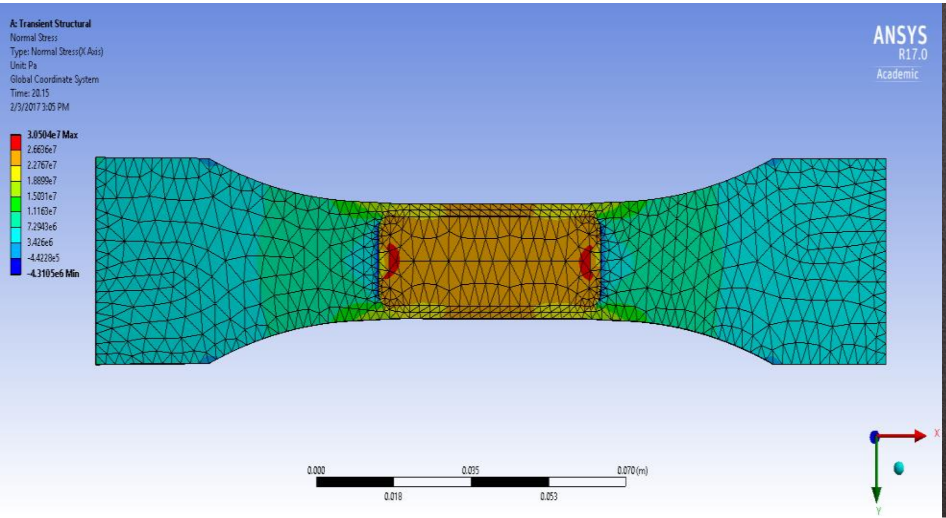
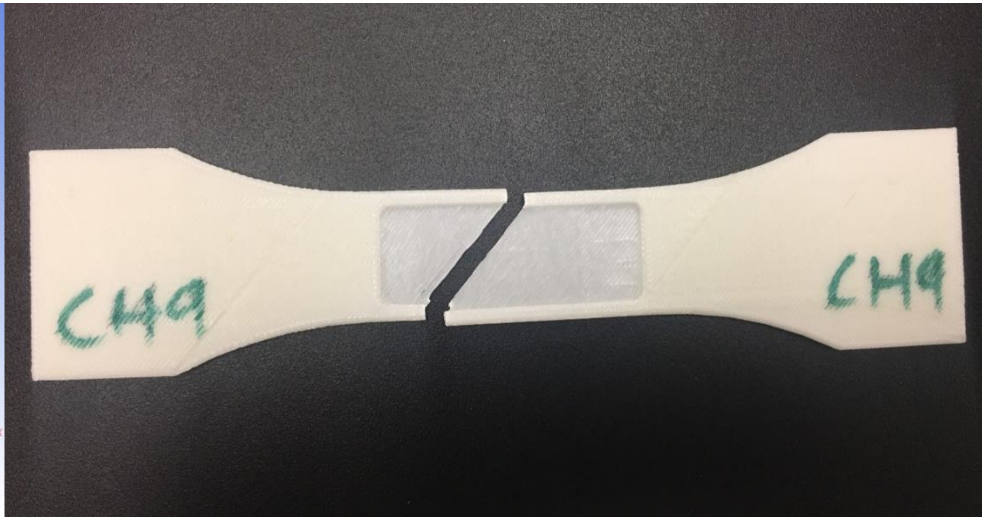
FEA Results – Bulk Isotropic Properties Model

Continuous





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