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Influence of Stress Triaxiality on Fracture Ductility for Stereolithography

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Scope

Stereolithography (SL) - additive manufacturing process that employs a photopolymer resin and ultraviolet (UV) laser to build the parts[1]

↓

SL - especially popular in biomedical applications - complex parts with better resolution in reasonable time [2,3,4]

↓

Biomedical applications, such as implants, tend to fail due to fracture[3]

↓

Better understand fracture behavior in SL printed specimens for improved part design

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Objective of the current study - Investigate the influence of stress triaxiality on fracture ductility for specimens' printed using SL

[1]. Gibson, I., Rosen, D. W., & Stucker, B. Additive manufacturing technologies. 2010.
[2]. Wong, K. V., & Hernandez, A. (2012). A review of additive manufacturing. ISRN Mechanical Engineering, 2012.
[3]. Melchels, F. P., Feijen, J., & Grijpma, D. W. (2010). A review on stereolithography and its applications in biomedical engineering. Biomaterials, 31(24), 6121-6130.
[4]. Murr, L. E., Gaytan, S. M., Medina, F., Lopez, H., Martinez, E., Machado, B. I., ... & Bracke, J. (2010). Next-generation biomedical implants using additive manufacturing of complex, cellular and functional mesh arrays. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 368(1917), 1999-2032.

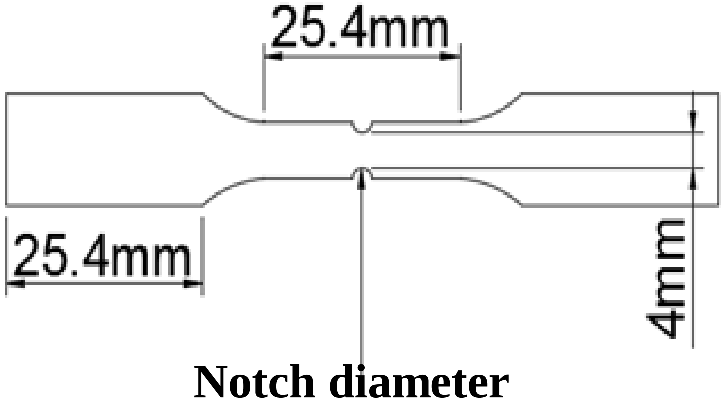
Methods: Preparation and mechanical testing of 3D printed specimens

- Formlabs® Form 2 Desktop SLA 3D printer
- A photopolymer resin - proprietary mix of Methacrylated oligomers, Methacrylated monomer, photo initiators and trace amount of pigments and additives was used for printing the specimens
- Uniaxial tensile tests – Instron® 5566 universal testing machine with a 2kN load cell
- Testing procedure – ASTM D638 specifications[5]
- At room temperature, extension rate: 1mm/minute
- 3 specimens each
- Specimens elongated until failure

[5]. Standard, A. S. T. M. (2010). D638-10, 2010. Standard Test Methods for Tensile Properties of Plastics. ASTM International, West Conshohocken, PA.

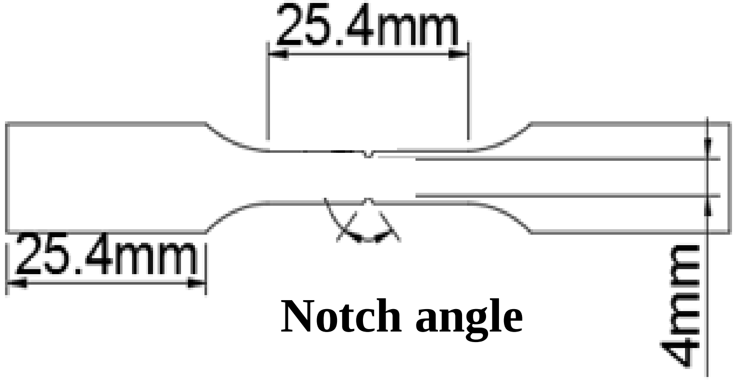
Specimen geometry

Circular notch



Notch diameter (mm)
1
2
2.5

V notch



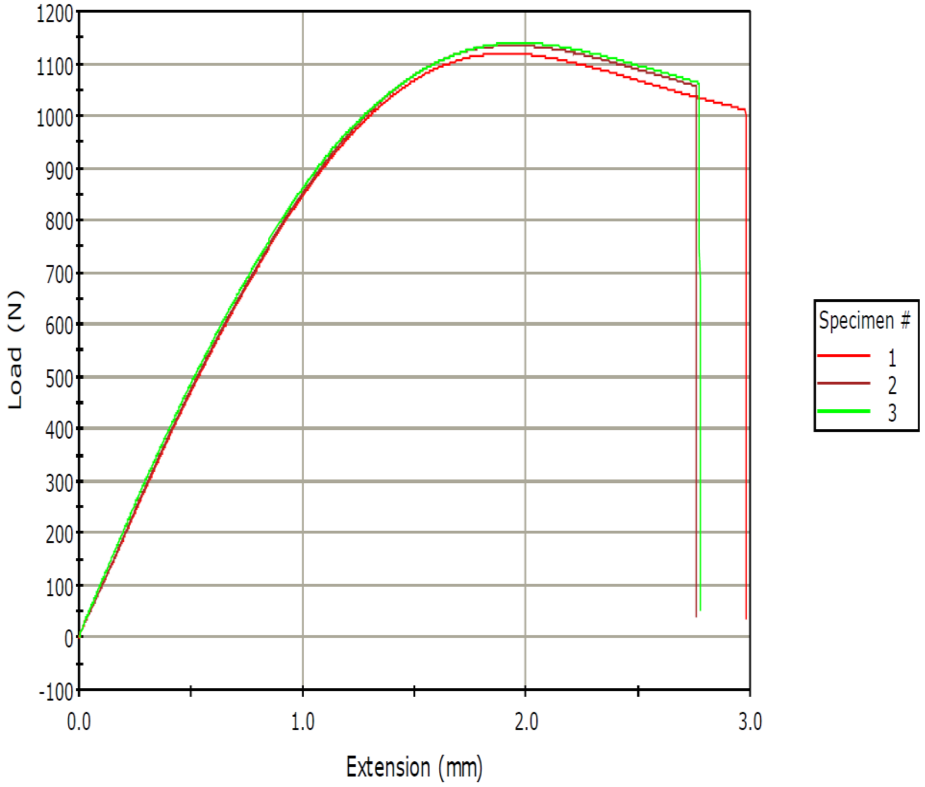
Notch angle (degrees)
15
30
45

Methods: Determination of fracture displacement

Fracture displacements

Specimen type	Specimen 1	Specimen 2	Specimen 3
Circular notch (1mm notch diameter)	1.68 mm	1.61 mm	1.91 mm
Circular notch (2 mm notch diameter)	0.81 mm	1.37 mm	1.17 mm
Circular notch (2.5 mm notch diameter)	1.27 mm	0.87 mm	1.13 mm
V notch (15 degree notch angle)	2.9 mm	2.8 mm	2.7 mm
V notch (30 degree notch angle)	1.32 mm	1.17 mm	1.19 mm
V notch (45 degree notch angle)	1.32 mm	1.30 mm	1.30 mm

Load-displacement curve for v-notch specimen (15 degree notch angle)

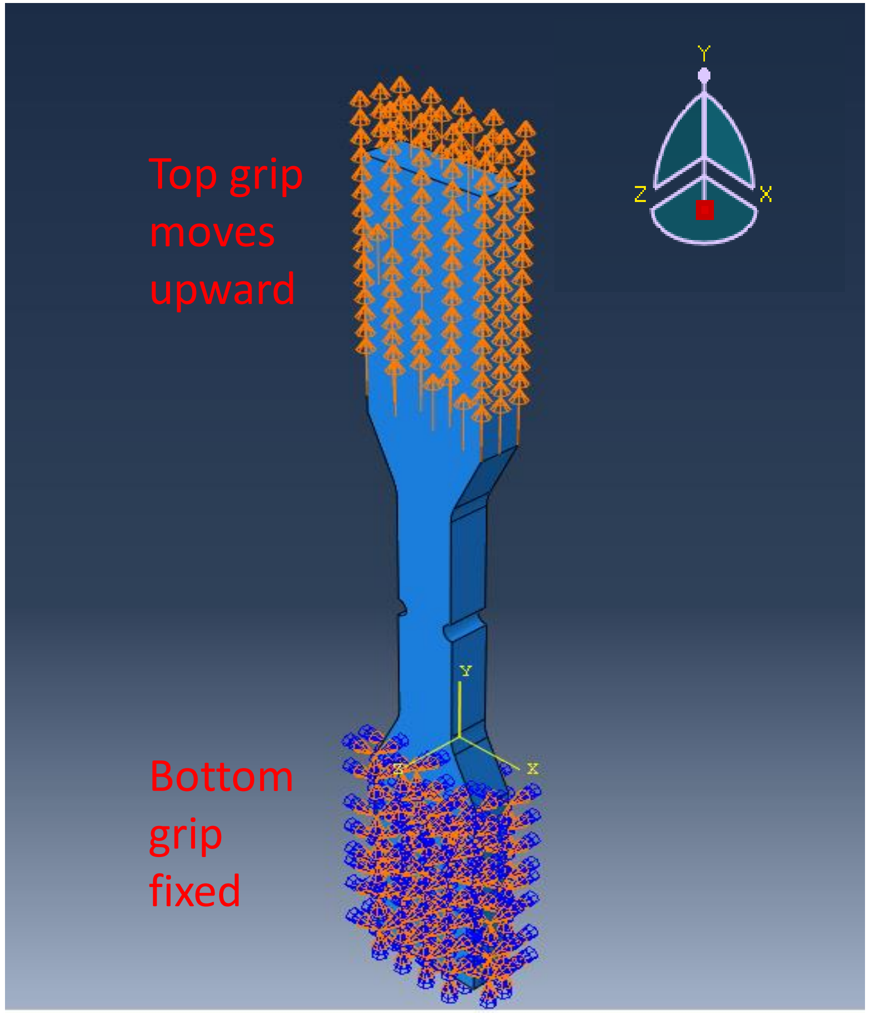


Methods: FE model development - Abaqus

For all specimens tested in this study,

Module	
Material	Linear elastic (automatically replaced by the MCalibration software program)
Step	Static Analysis (including geometric nonlinearities)
History output	For the top grip, concentrated force, reaction force and displacement in the y direction (CF2, RF2 and U2)
Loads and boundary conditions	Displacement controlled loading
Mesh	C3D8R with enhanced hourglass control

FE model in Abaqus



Methods: Material model calibration

- Mcalibration software (version 5.0.1) – Inverse calibrations/Abaqus
- Multiple optimization algorithms used – including Levenberg Marquardt and Nelder-Mead Simplex
- Failure criterion/model – not included in material definition

For all specimens tested in this study

Material model	**Normalized mean absolute difference (or error in model calibration %)**
Yeoh	44.6 ± 10.92
Linear viscoelasticity (Yeoh, 5-term Prony series)	37.1 ± 8.35
Johnson cook	14.8 ± 7.02
BB	13.3 ± 3.91
BB with mullins damage	9.86 ± 2.4
Parallel network model with three networks (Yeoh, power-law flow, yield evolution)	6.11 ± 2.67
Parallel network model with four networks (Yeoh, power-law flow, yield evolution)	5.14 ± 1.86
Parallel network model with five networks (Yeoh, power-law flow, yield evolution)	3.49 ± 1.2
Three network model	2.35 ± 0.78

Methods: Stress triaxiality and equivalent strain definitions

Stress triaxiality = - (hydrostatic pressure)/Von mises equivalent stress[6]

Average stress triaxiality = (sum of stress triaxialities of the elements in fracture region)/number of elements

Equivalent strain[7]

$$\varepsilon_{\mathrm{eq}} = \frac{2}{3}\sqrt{\frac{3\left(e_{xx}^2 + e_{yy}^2 + e_{zz}^2\right)}{2} + \frac{3\left(\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2\right)}{4}}$$

With the deviatoric strains:

$$\begin{aligned} e_{xx} &= +\tfrac{2}{3}\varepsilon_{xx} - \tfrac{1}{3}\varepsilon_{yy} - \tfrac{1}{3}\varepsilon_{zz} \\ e_{yy} &= -\tfrac{1}{3}\varepsilon_{xx} + \tfrac{2}{3}\varepsilon_{yy} - \tfrac{1}{3}\varepsilon_{zz} \\ e_{zz} &= -\tfrac{1}{3}\varepsilon_{xx} - \tfrac{1}{3}\varepsilon_{yy} + \tfrac{2}{3}\varepsilon_{zz} \end{aligned}$$

The engineering strains are defined as:

$$\gamma_{ij} = 2 \times \varepsilon_{ij}$$

For each specimen, chose 1 element in the fracture region,
equivalent strain to fracture = equivalent strain which corresponds to the displacement to fracture[8]

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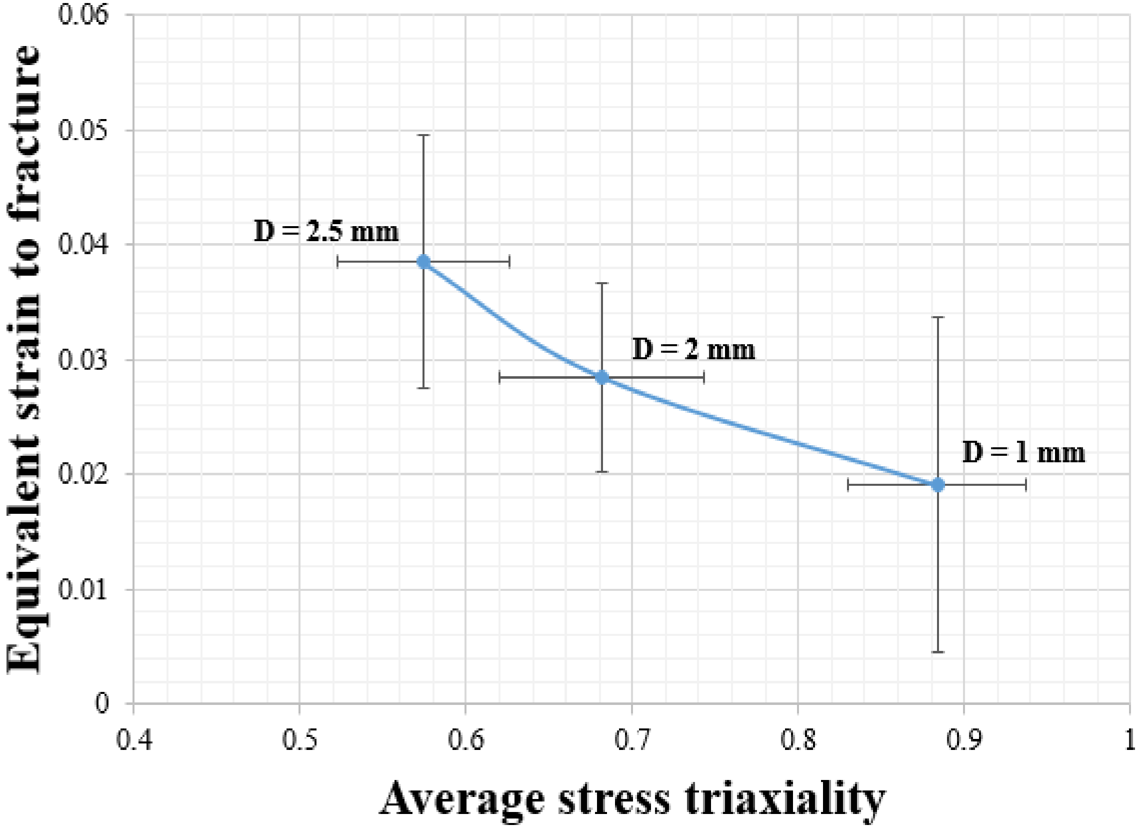
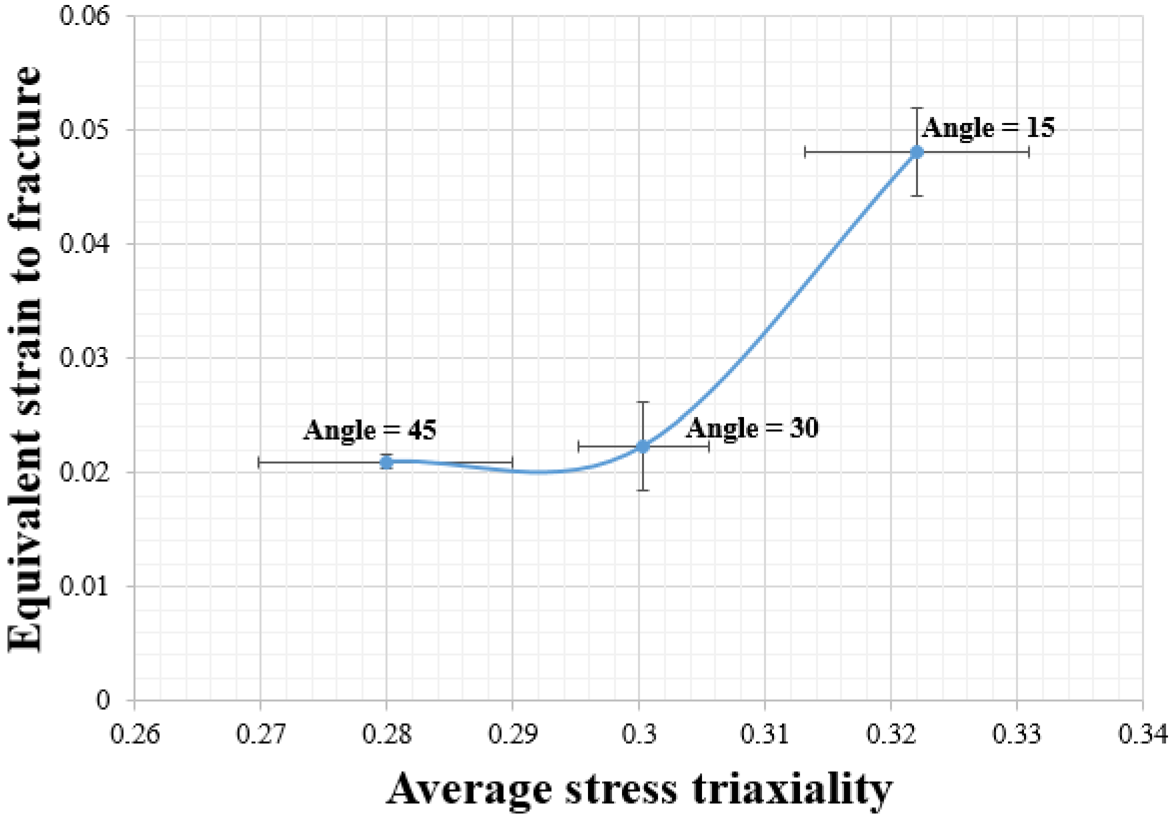
[6]. ABAQUS., ABAQUS User’s Manual, version 6.13, Dassault Systèmes Simulia Corp. Providence, RI, USA, 2014.
[7]. DIANA FEA BV., DIANA FEA BV User’s Manual, version 9.4.4, Delft, Netherlands, 2012.
[8]. Bao, Y., & Wierzbicki, T. (2004). On fracture locus in the equivalent strain and stress triaxiality space. International Journal of Mechanical Sciences, 46(1), 81-98.

Results: Circular notch specimens



Notch diameter	Max. stress triaxiality
1 mm	0.8729 ± 0.106
2 mm	0.6916 ± 0.1199
2.5 mm	0.5961 ± 0.0490

Results: V-notch specimens



Notch angle	Max. stress triaxiality
15 degrees	0.3446 ± 0.0212
30 degrees	0.3202 ± 0.032
45 degrees	0.3225 ± 0.0074

Conclusion

Study objective: Does the stress triaxiality influence fracture ductility for specimens' printed using SL?

Fracture ductility shown to be strongly dependent on stress triaxiality for SL printed specimens

Practical applications: Careful consideration of geometry and location of notches in implant design required to reduce failure due to fracture in specimens printed using stereolithography

Limitations:

1. The results are specific to this material
2. Material calibration limited by a single extension rate

Future work:

1. Investigate the influence of stress triaxiality on fracture ductility for different SL printed materials
2. Calibrate and validate the material for different extension rates
3. Investigate other parameters that affect fracture ductility, such as material thickness, temperature, etc.

Thank you!

Questions?

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