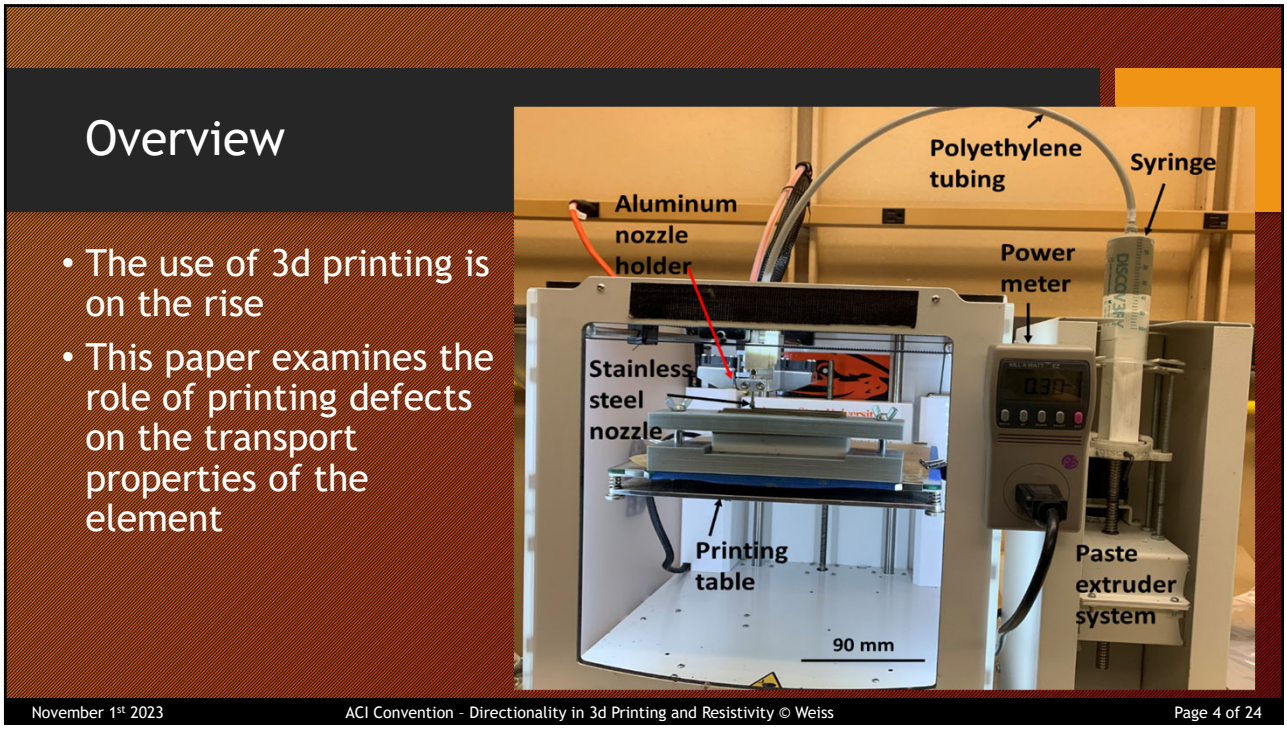
Abstract

• This presentation examines the use of electrical resistivity to evaluate the degree of anisotropy associated with 3D-printed elements. The presentation will begin by describing the system being measured and the measurement procedure used. Experimental measures will be used to compute the formation factor in three orthogonal directions. An equivalent circuit model is used to relate oriented porosity to the measured changes in resistivity. These results indicate the potential use of this approach in quality control/quality assurance.


Oregon State University
PRINCETON UNIVERSITY
Using Electrical Measurements to Categorize Material Anisotropy and Defects
November 1st 2023
Rita M. Ghantous, Anastasiia Evseeva, Brandon Dickey, Shashank Gupta, Arjun Prihar, Hadi S. Esmaeeli, Reza Moini, W. Jason Weiss


Overview
• The use of 3d printing is on the rise
• This paper examines the role of printing defects on the transport properties of the element
Polyethylene tubing
Syringe
Aluminum nozzle holder
Power meter
Stainless steel nozzle
Printing table
Paste extruder system
90 mm
November 1st 2023
ACI Convention – Directionality in 3d Printing and Resistivity © Weiss
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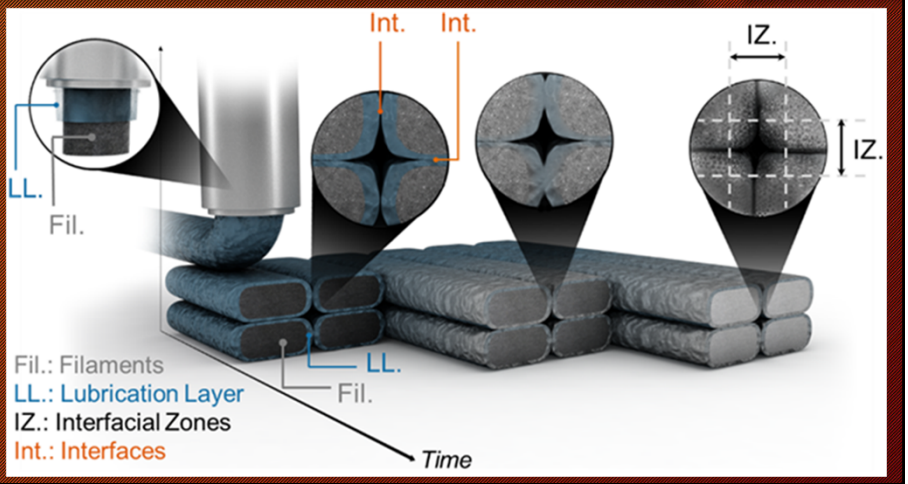
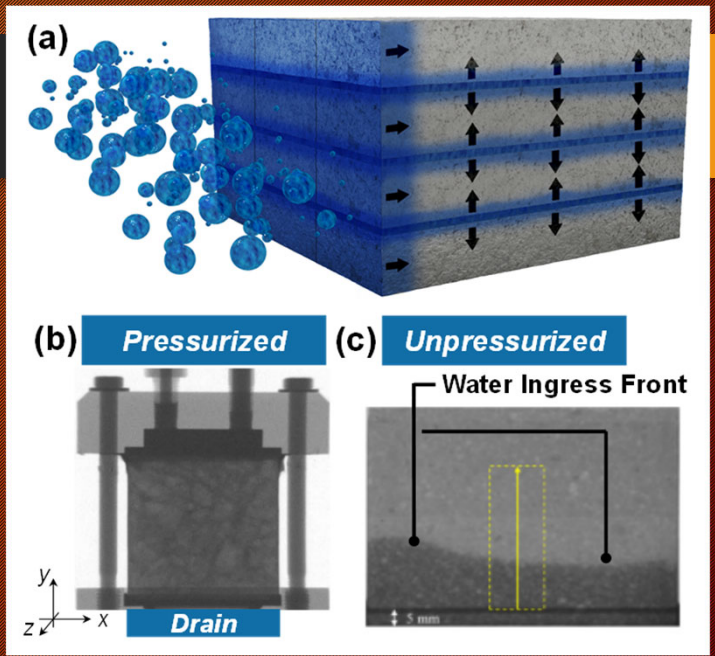
Printed Elements and Interfaces

- Many of the 3d printing approaches use printed filaments that 'ideally fuse together'
- What happens if this does not happen?
- Role of interfaces on transport and anisotropy.

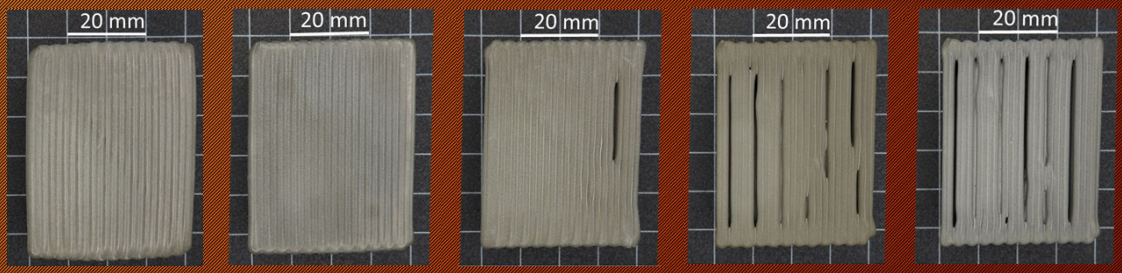


Transport

- The hypothesis is that the interfacial channels lead to water absorption, permeation, ionic diffusion
- These channels can then accelerate saturation levels or high concentration levels
- These channels can lead to anisotropy
- How prevalent are these channels

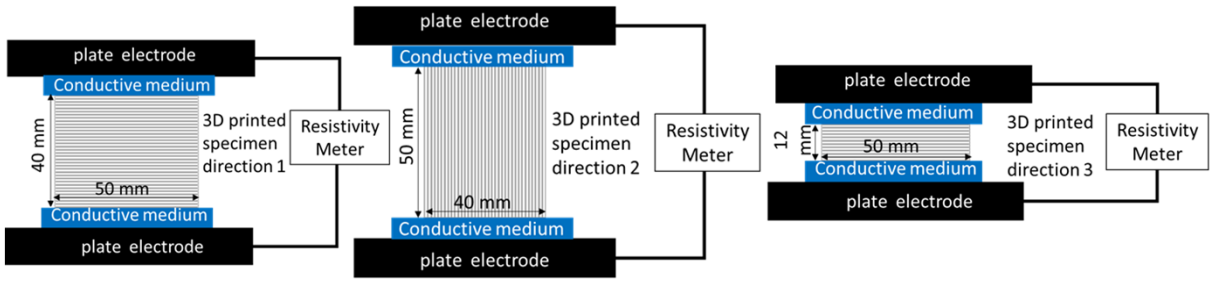


Elements Printed with Defects



- The 'extrusion multiplier' was changed 1.2, 1.1, 1.0, 0.95, 0.90 (Left to Right)
- Extrusion multiplier (flow rate) – extrusion width/average wall thickness
- Over extrusion - Too much material is extruded (flow is too high).
- Under extrusion - Not enough material is extruded (flow is too low). Gaps

Measuring Properties with Orientation



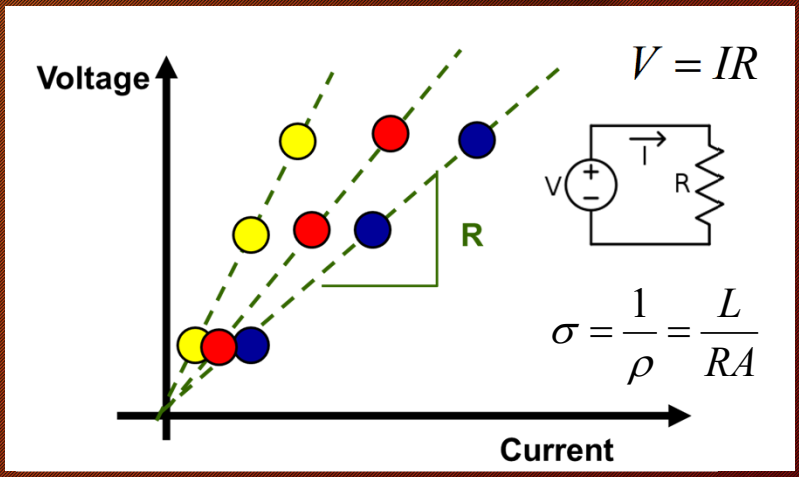
Direction 1
Perpendicular
Filaments

Direction 2
Parallel
Filaments

Direction 3
Transverse

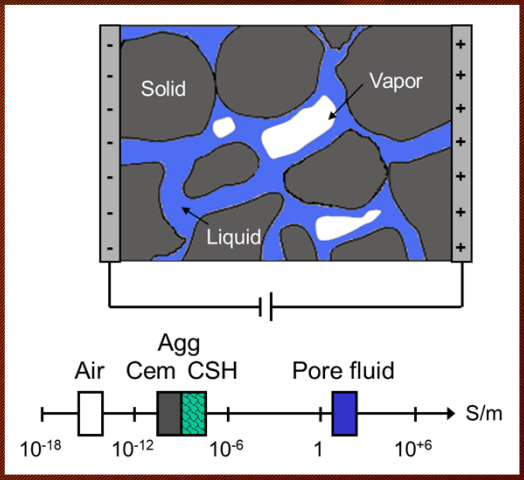
Electrical Properties

- Generally applied to electrical circuits
- "The current between two points is directly proportional to the potential difference (voltage drop or voltage) across two points and inversely proportional to the resistance between then"

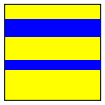


Measurement in Cementitious Systems

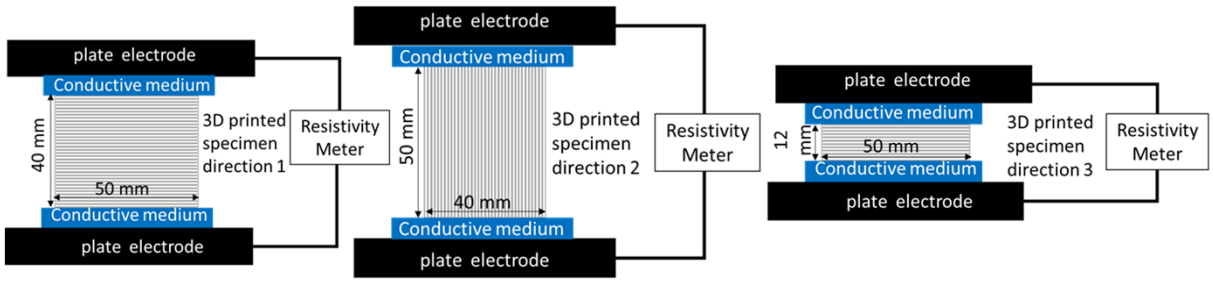
- Concrete is a composite:
- Solid phase (unhyd Cement, CSH, CH,…); $\sigma_{sol} \approx$ 10-9 S/m
- Liquid phase (pore solution); $\sigma_{liq} \approx$ 1 S/m to 20 S/m
- Vapor phase (air voids, emptied pores); $\sigma_{vap} \approx$ 10-15 S/m



Simple Composite Models

NAME	FORMULA	MICROSTRUCTURE
Parallel	$D_{bulk} = D_1\phi_1 + D_2\phi_2$	
Series	$1/D_{bulk} = (\phi_1 / D_1) + (\phi_2 / D_2)$	
Modified Parallel	$D_{bulk} = D_1\phi_1\beta_1 + D_2\phi_2\beta_2$	

Measuring Properties with Orientation



Direction 1
Perpendicular
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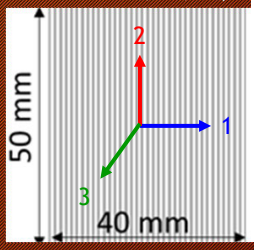
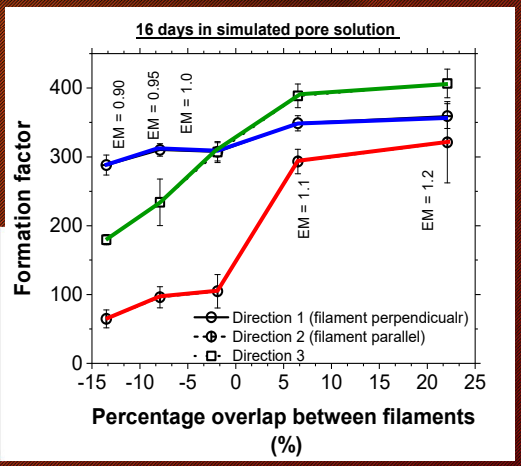
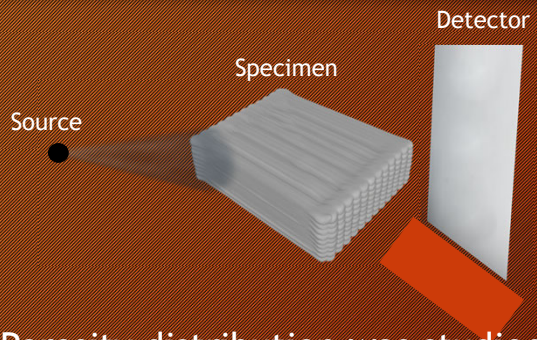
Measured Resistivity

- When the Extrusion Multiplier is lower (i.e., there are gaps between filaments) the Formation Factor is lower
- The pore volume increases with a decreasing EM (however the same 1, 2, 3)
- The connectivity of the samples is very different
- This results in a large difference in electrical response

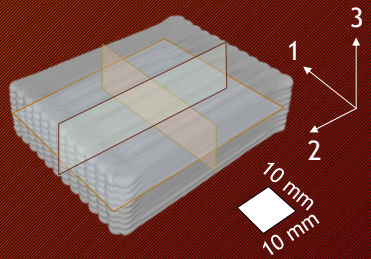




Micro-Computed Tomography of 3D-Printed Specimens

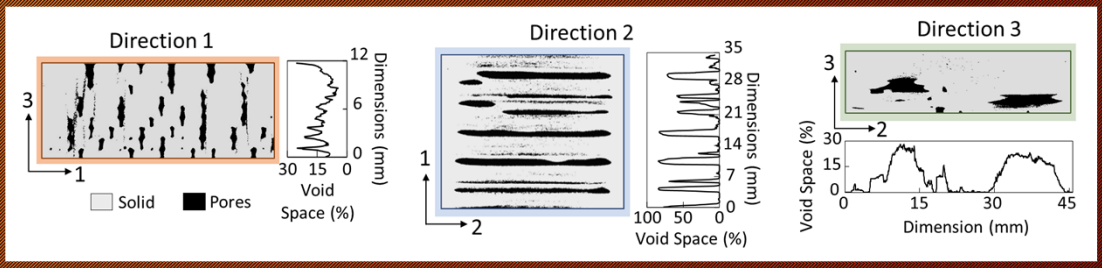


- 0.4X Magnification
- Resolution of 50.3 - 54.8 µm/pixel
- Beam energy of 80 - 110 keV
- Power of 7 - 10 W
- Exposure periods of 1.5 - 6.0 s

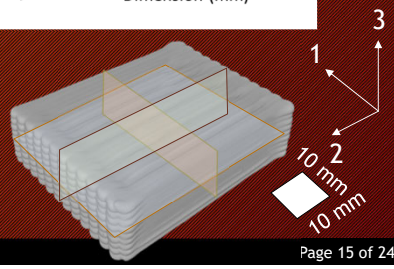


- Porosity distribution was studied with Micro-CT
- 2D slices were binary segmented using tangent-slope method

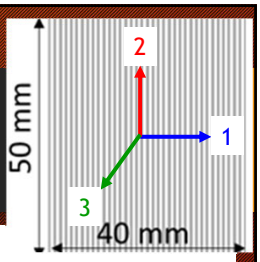
Generation of Cumulative Frequency Plots



- Spatial distribution of void space was evaluated in three perpendicular directions
- Cumulative frequency plots generated using void space data from 2D-slices in one direction

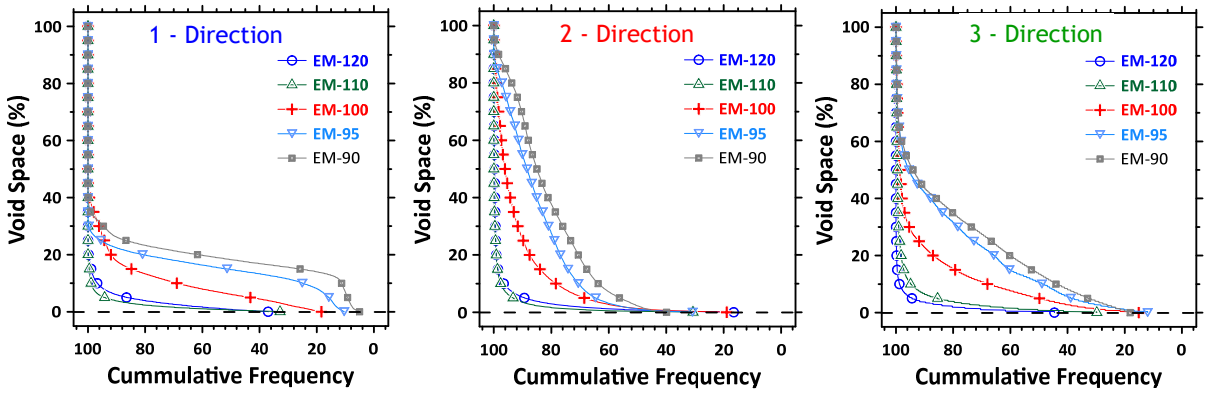


Measured Void Space Per Filament

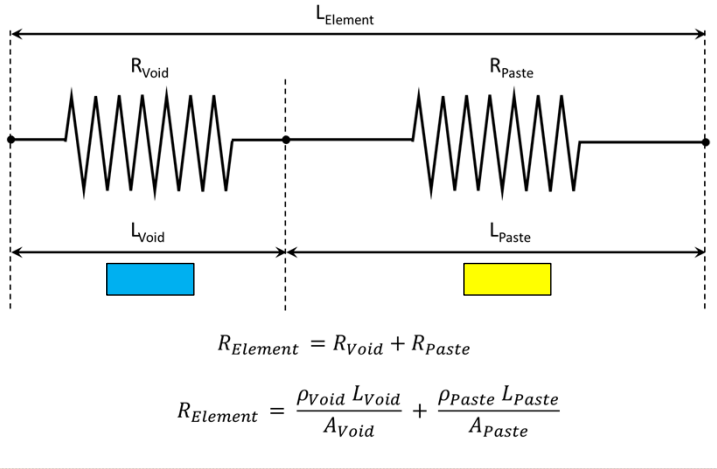


Longer Paths - Connected Pores

Shorter Paths - Disconnected Pores

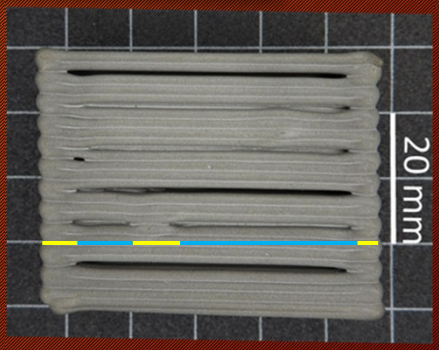


Conceptual Model – Single Filament



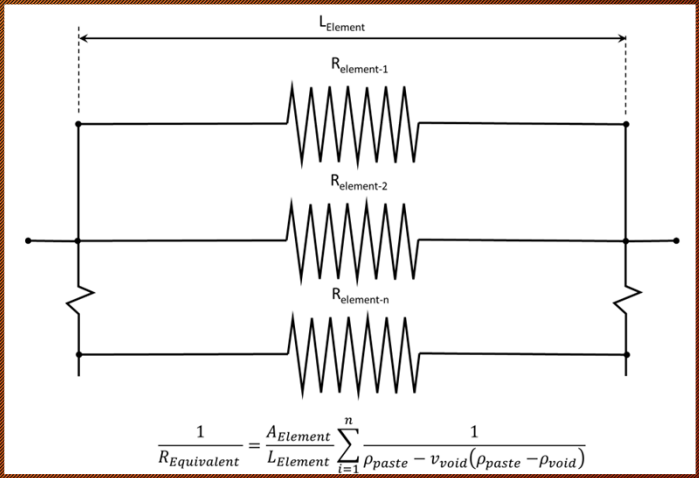
$$R_{Element} = R_{Void} + R_{Paste}$$

$$R_{Element} = \frac{\rho_{Void}\, L_{Void}}{A_{Void}} + \frac{\rho_{Paste}\, L_{Paste}}{A_{Paste}}$$



- A series model is used to describe the role of voids and paste here

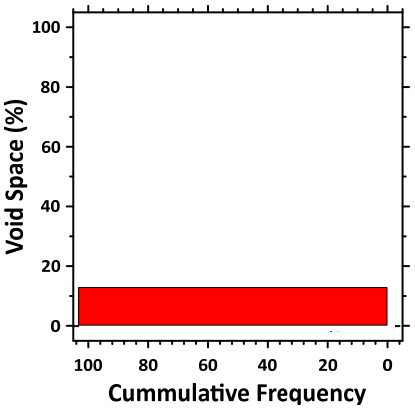
Conceptual Model – All Filaments

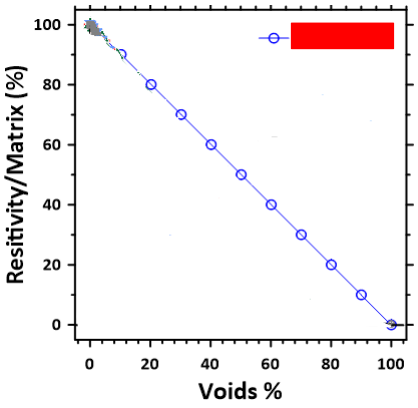


$$\frac{1}{R_{Equivalent}} = \frac{A_{Element}}{L_{Element}} \sum_{i=1}^{n} \frac{1}{\rho_{paste} - v_{void}(\rho_{paste} - \rho_{void})}$$

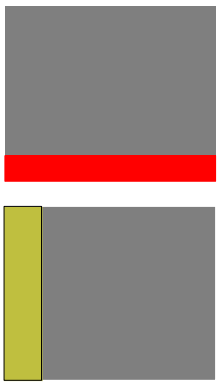
- The series model is then combined with a parallel model
- The parallel model brings all the filaments together

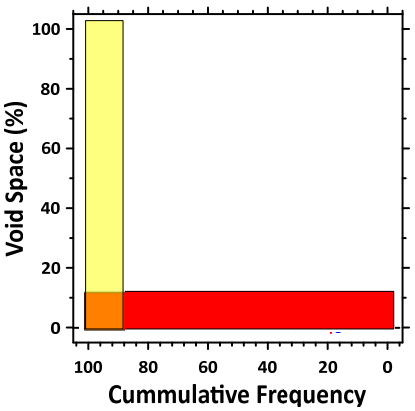
Idealized Model (10% Porosity)

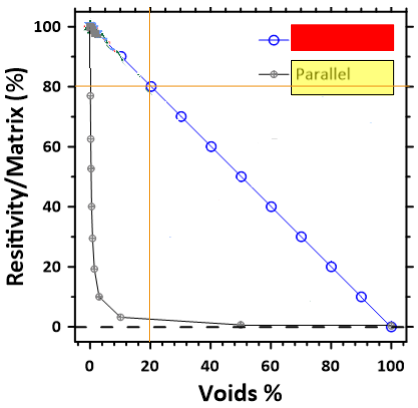




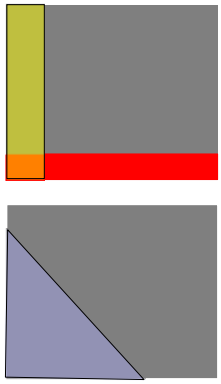
Idealized Model (10% Porosity)

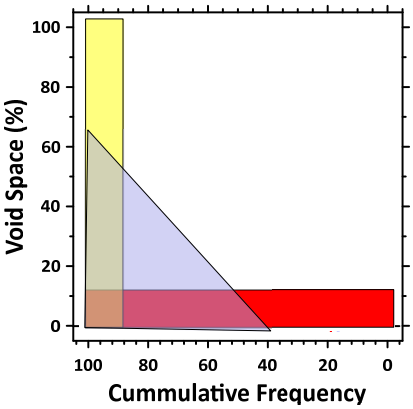


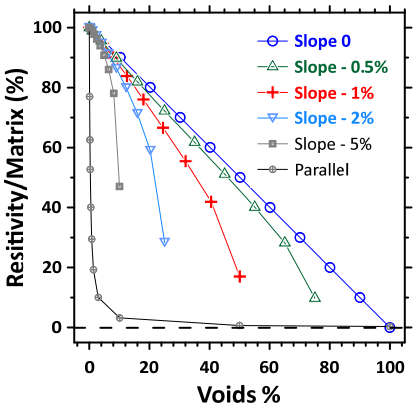




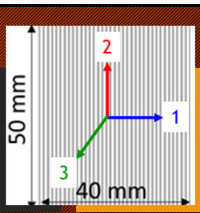
Idealized Model (10% Porosity) Distribution



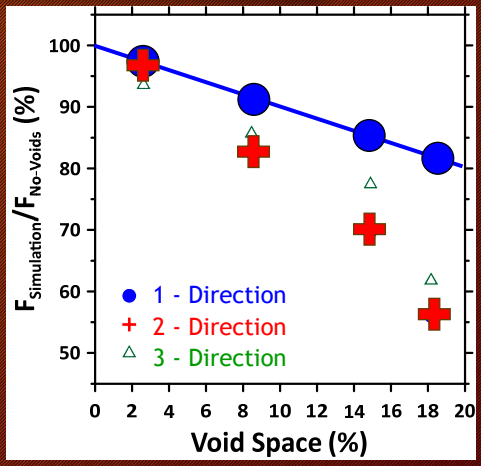




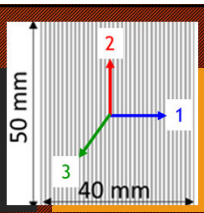
Predicted Results – F Values (beta fixed)



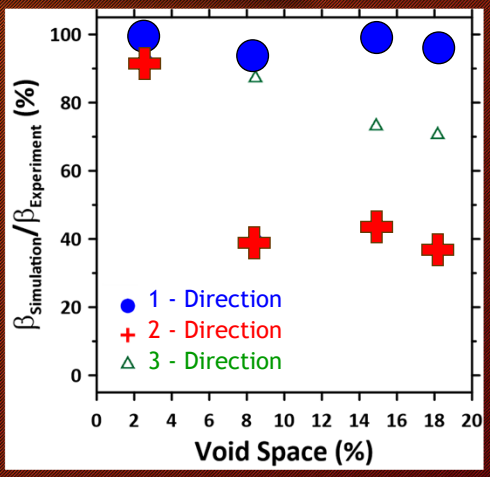
- Predicted expression is powerful
- Does very well for the 2 direction as anticipated
- Struggles more in the 1 and 3 directions due to lateral connectivity
- Due primarily to out of plane connectivity



Predicted Results (Beta Modification)



- For the y direction fitted connectivity values are nearly 100%
- However, you can noticed that in the x and z directions the connectivity needs to be changed due to lateral connectivity
- This is logical as those pores are connected both in the filament and across filaments



Summary

- The electrical resistivity of 3D-printed elements was measured for systems where the 3d printing defects were placed and measured
- The formation factor was measured in three orthogonal directions.
- An equivalent circuit model was used to relate oriented porosity to the measured changes in resistivity.
- Disconnected pores are well predicted
- Connected pores (connected in 3d) are not well caputed in the simple model however this occur

Using Electrical Measurements to Categorize Material Anisotropy and Defects
Presented by Jason Weiss