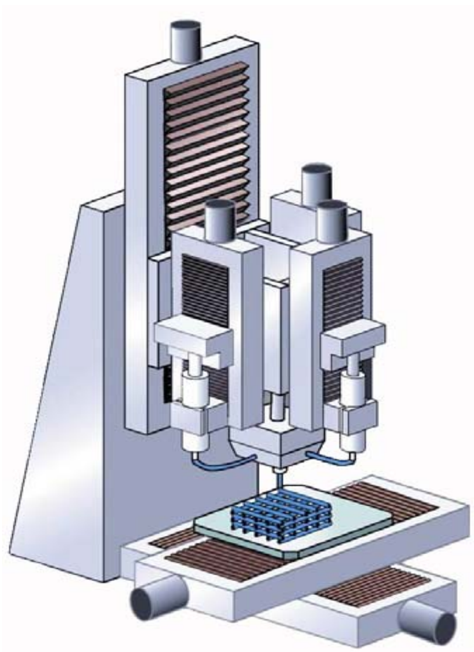
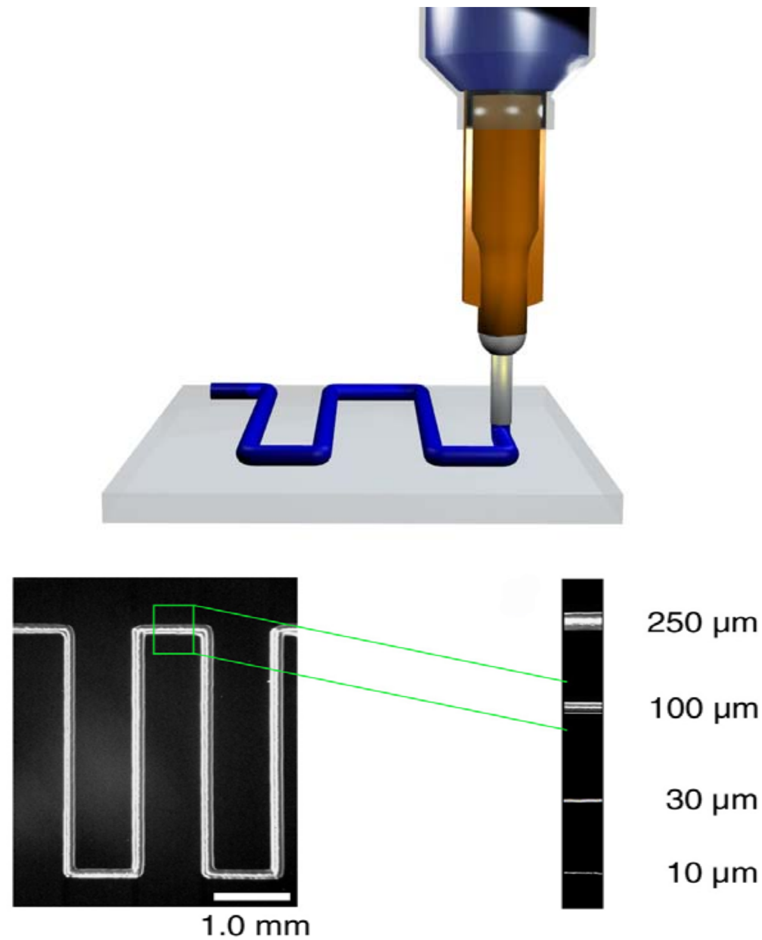
Directed Assembly of 3-D Microvascular Networks



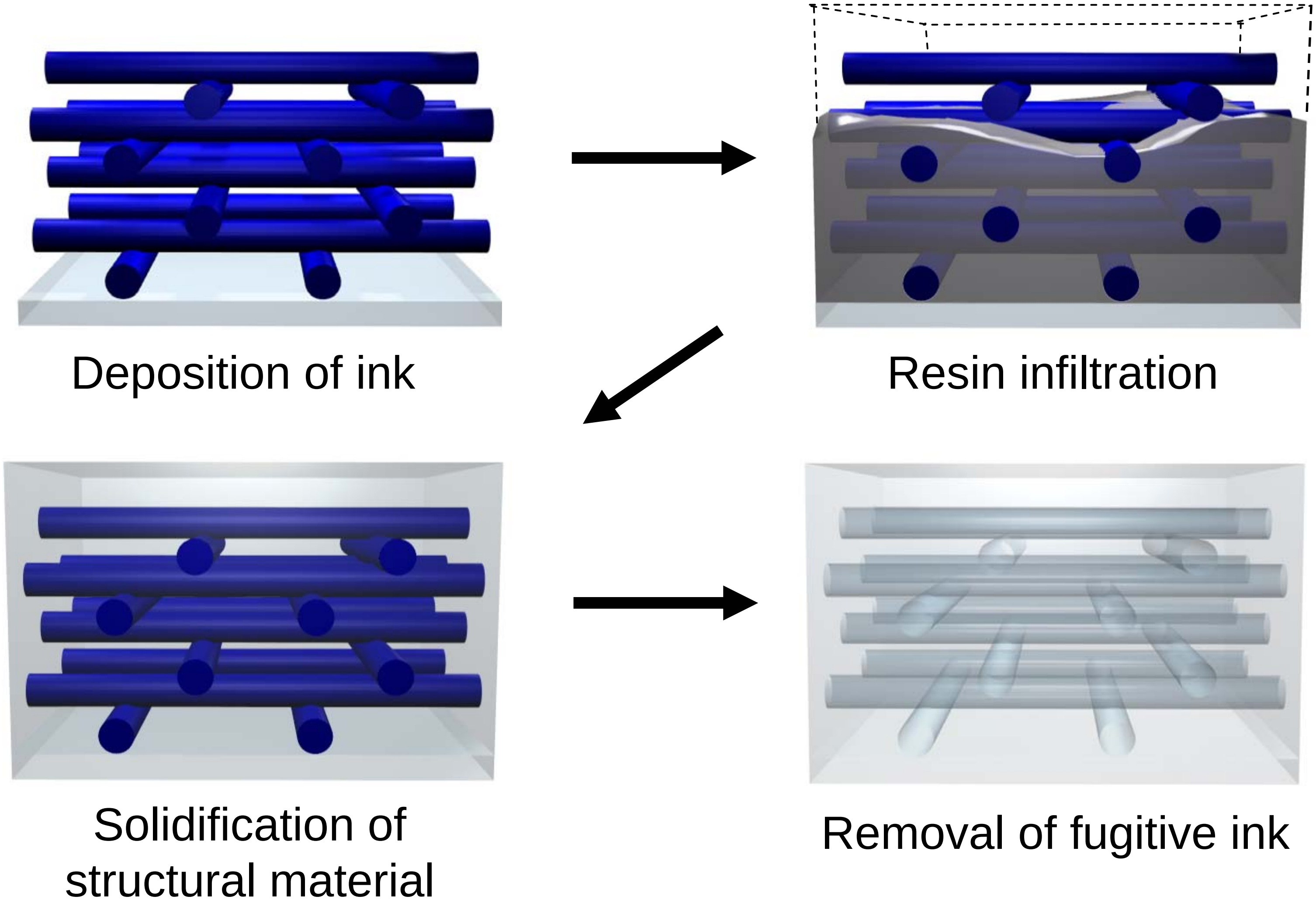
Robotically controlled deposition (RCD) machine*



*Cesarano, J., “Freeforming objects with low-binder slurry,” US patent no. 6,027326.

*Software developed by Smay, J. (now at Oklahoma St. University)

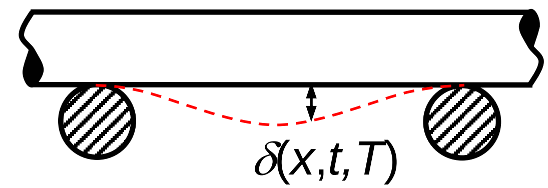
Microvascular Network Fabrication



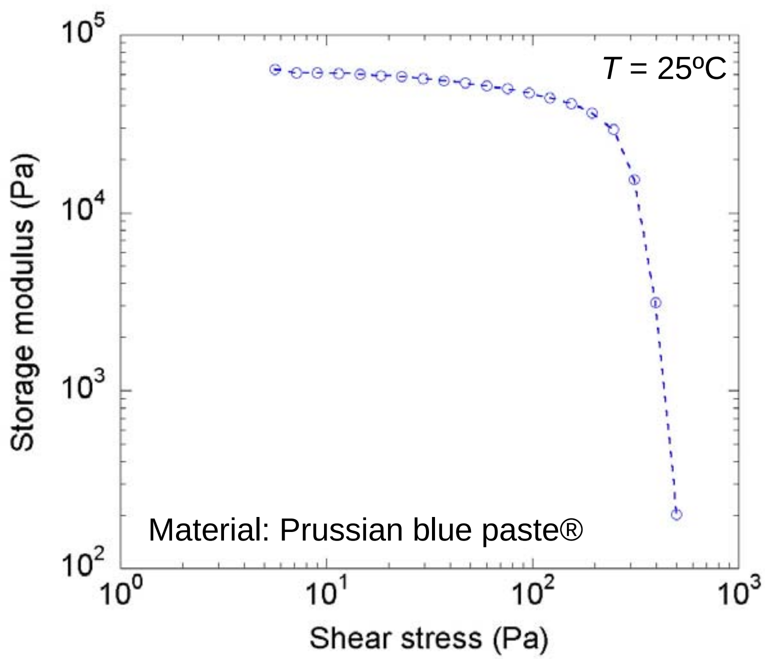
Design of Fugitive Organic Inks

Criteria for organic inks

- Exhibit thixotropic viscoelastic response
  - Flow through a deposition nozzle
  - Subsequently "set" immediately after exiting nozzle to retain shape
- Maintain architecture during resin infiltration and curing
- Offer a solid-to-liquid phase transition at moderate temperature for removal from final structure



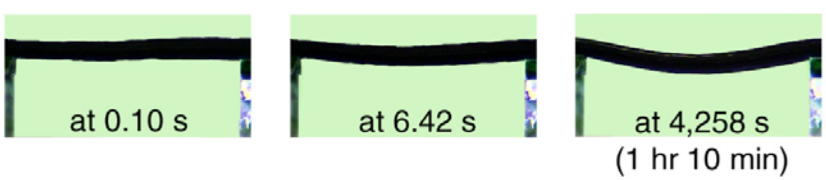
Deformation (δ) of spanning filament



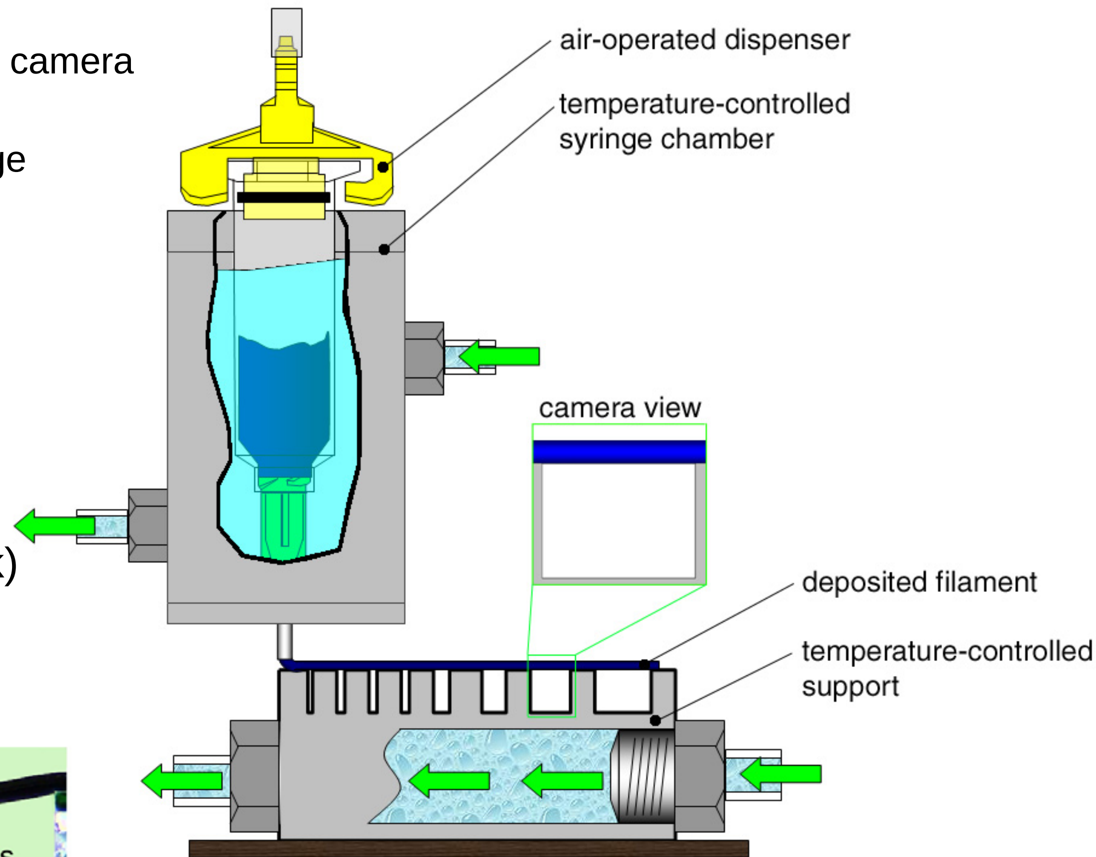
Viscoelastic Deformation of Polymeric Scaffolds

- Deposition of single spanning filament under controlled temperature
  - Deflection profile recorded with video camera (s-video, 30 frames/s)
  - Mid-span deflection obtained by image processing

- Experimental parameters
  - d = 0.2 – 1.5 mm
  - L = 0.25 – 10 mm
  - T = 15 – 25ºC
  - t = 0.033 – 1x10^6 s (1 week)



Deformation history of 430-μm filament



Spanning filament experimental setup

Viscoelastic Beam Models

- **Euler-Bernouilli theory (EBT)**
  - No transverse shear deformation
  - Recommended for slender beams
    - $L/d > 10$

$$\rho A \frac{\partial^2 w}{\partial t^2} + \frac{\partial^2 \left(E(t) I \frac{\partial^2 w}{\partial x^2} \right)}{\partial x^2} = f(x)$$

  - Quasi-static solution

$$w(t) = \frac{C_1 q L^4}{384 I} J(t)$$

C_1 = 5 (simply supported) and 1 (clamped)

- **Timoshenko beam theory (TBT)**
  - Considers rotatory inertia
  - Recommended for thick beams
    - $L/d < 10$

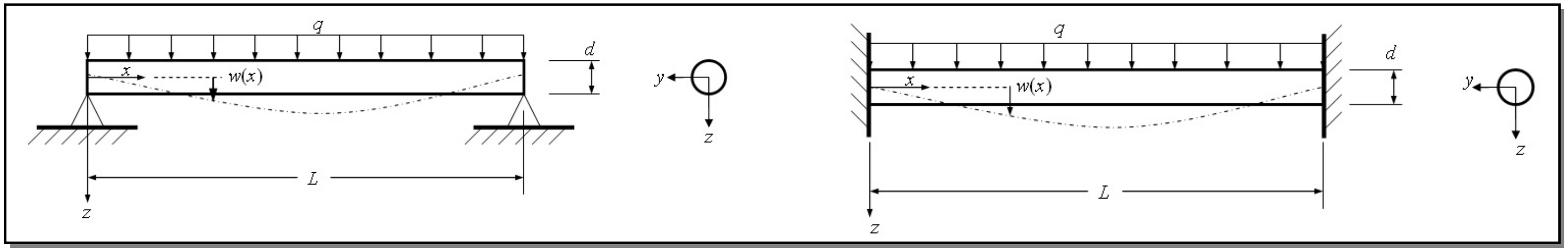
$$-\frac{\partial}{\partial t}\left(\rho A \frac{\partial w}{\partial t} \right) + \frac{\partial}{\partial x}\left[\left(kG(t) A \right) \left(\frac{\partial w}{\partial t} - \psi \right) \right] + q = 0$$

$$-\frac{\partial}{\partial t}\left(\rho I \frac{\partial \psi}{\partial t} \right) \frac{\partial}{\partial x}\left(E(t) I \frac{\partial \psi}{\partial x} \right) + \left(kG(t) A \right) \left(\frac{\partial w}{\partial x} - \psi \right) = 0$$

  - Quasi-static solution

$$w(t) = \frac{C_1 q L^4}{384 I} \left[1 + C_2 \frac{1+\upsilon}{k} \left(\frac{d}{L} \right)^2 \right] J(t)$$

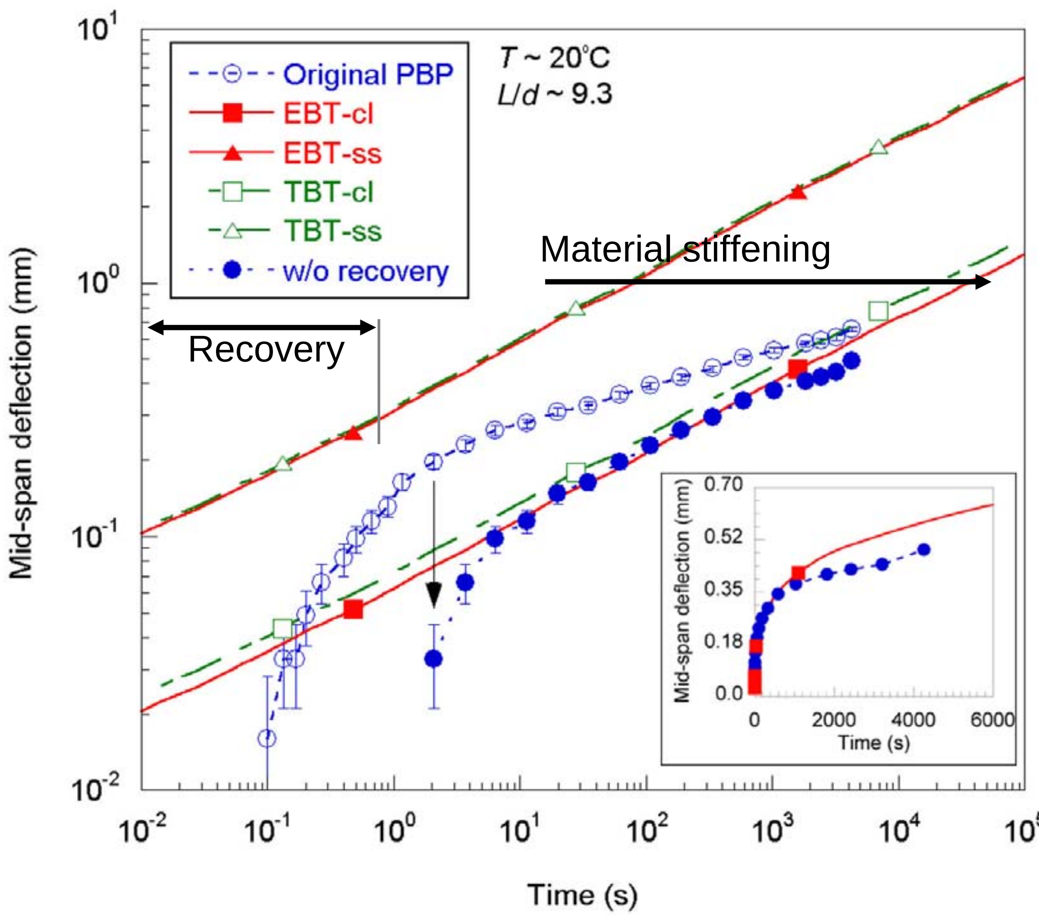
C_1 = 5 (simply supported) and 1 (clamped)
C_2 = 1.6 (simply supported) and 8 (clamped)



Viscoelastic Beam Models and Experiments

Time-dependent mid-span deflection of Prussian blue paste®

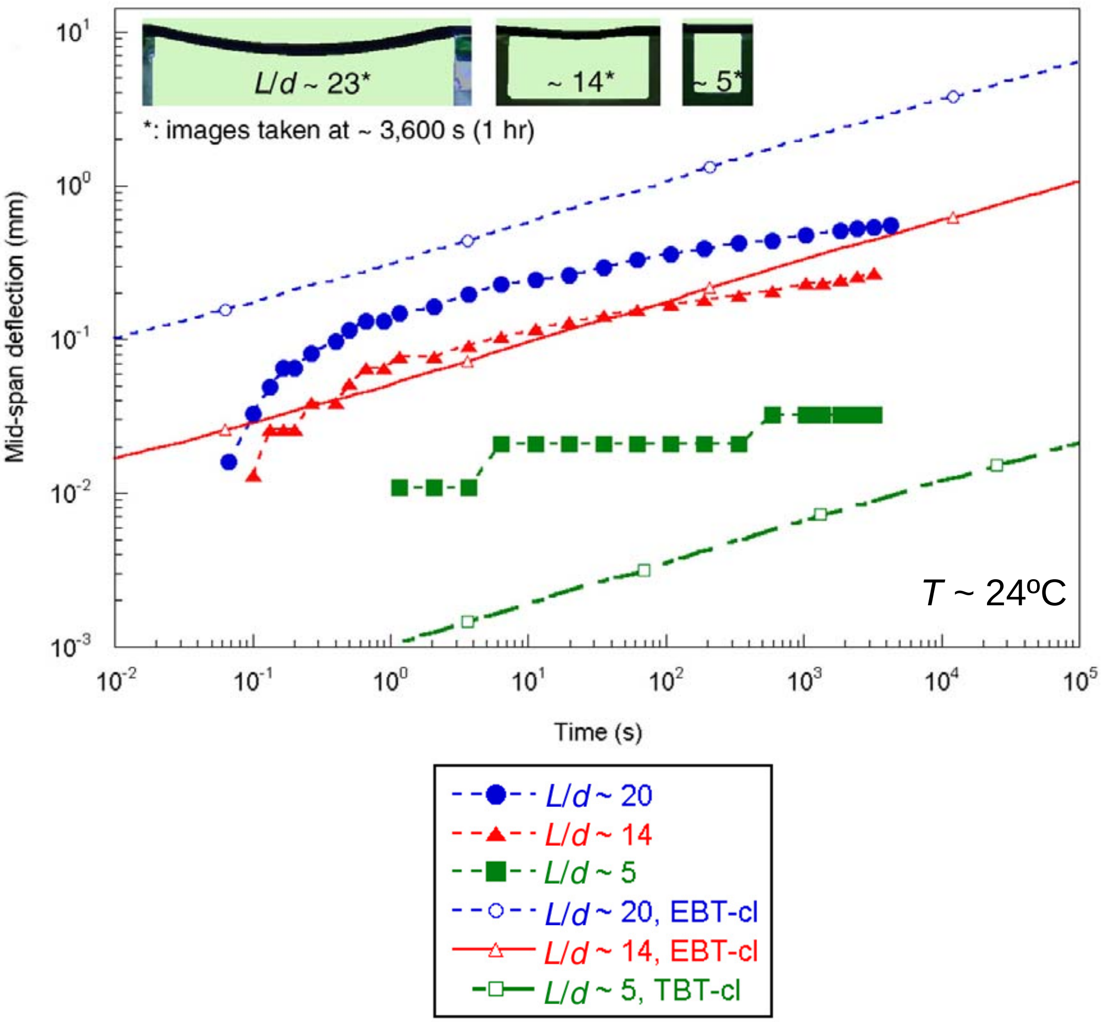
- 0 < t < 1 s: viscoelastic recovery after shearing inside micronozzle during deposition
- t > 1 s: deflection rate slows down due to material stiffening



Deformation history of 430-μm filament

Viscoelastic Beam Models and Experiments

Effects of aspect ratio on experimental data and model predictions



- *L*/*d* ~ 23: Overestimation due to high degree of stretching during deposition
- *L*/*d* ~ 14: Good correlation with EBT predictions with clamped conditions
- *L*/*d* ~ 5: Underestimated due to localized deformation of filament near supports