SAND2022-7729C

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High Strain Rate Compressive Behavior of 3D Printed Liquid Crystal Elastomers

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Liquid Crystal Elastomers (LCE) Background

Liquid Crystals

- State of matter with properties between liquids and solid crystals
  - LCDs, soap + detergents, clays

Liquid Crystal Elastomers

- LCs covalently bonded into flexible polymer network → LCEs
- Unique properties:
  - Reversible actuation
  - Anisotropic responses (mechanical and optical)
  - Auxetic in some cases
  - *Soft elasticity*

Liquid Crystal Elastomers (LCE) Background

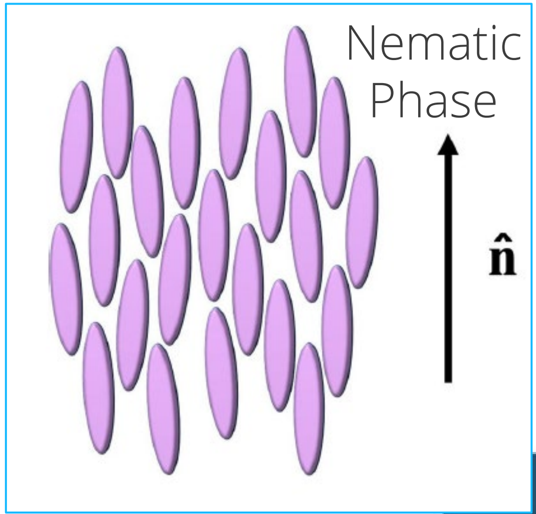
Liquid Crystal Elastomers

- Thermoset polymer with LC phases

Composed of **rigid** molecules called ***mesogens***

- Anisotropic, elongated shape which encourages organization
- Mesogens can be linked to the polymer backbone at ends or sides, leading to different phases (nematic, smectic)
- **Flexible ends** allow mesogens to reorient while flowing
- Nematic phase: mesogens exhibit long-range orientation

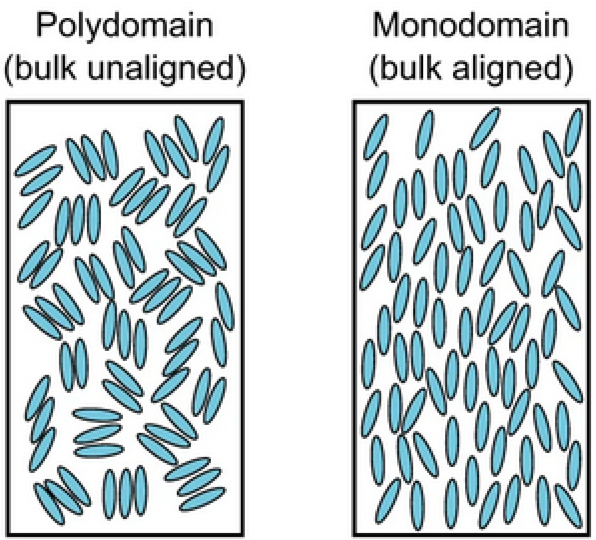
Mesogens may undergo **reorientation/phase transition** during mechanical loading, offering improved **energy dissipation** over conventional polymers

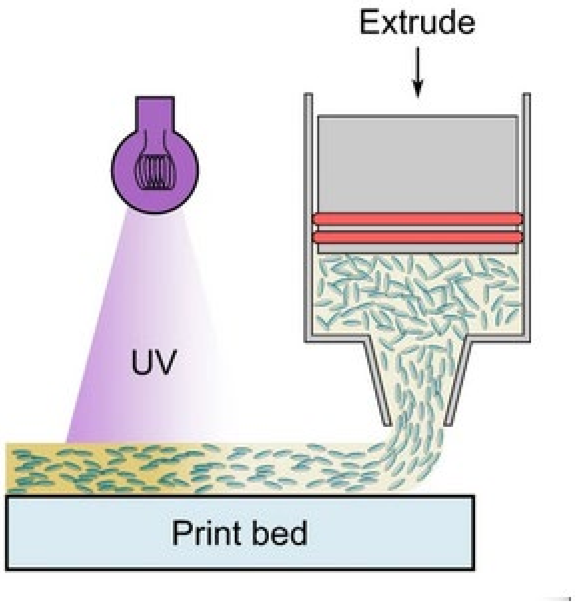


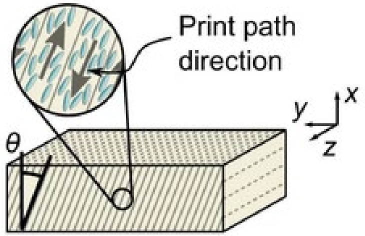
Ula et al. "Liquid crystal elastomers: an introduction and review of emerging technologies." Liquid Crystals Review, 2018 6 (1): 78-107

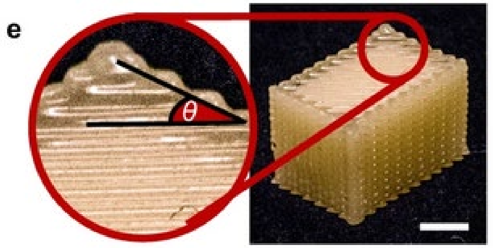
3D Printing LCEs

- Taking advantage of phase transition has been difficult due to processing
- Direct ink write (DIW) allows alignment of mesogens in finished material
- This can be tailored, allows complex geometries and configurations such as “foam-like” materials or lattice structures for mechanical protection of assets in impact or vibration situations







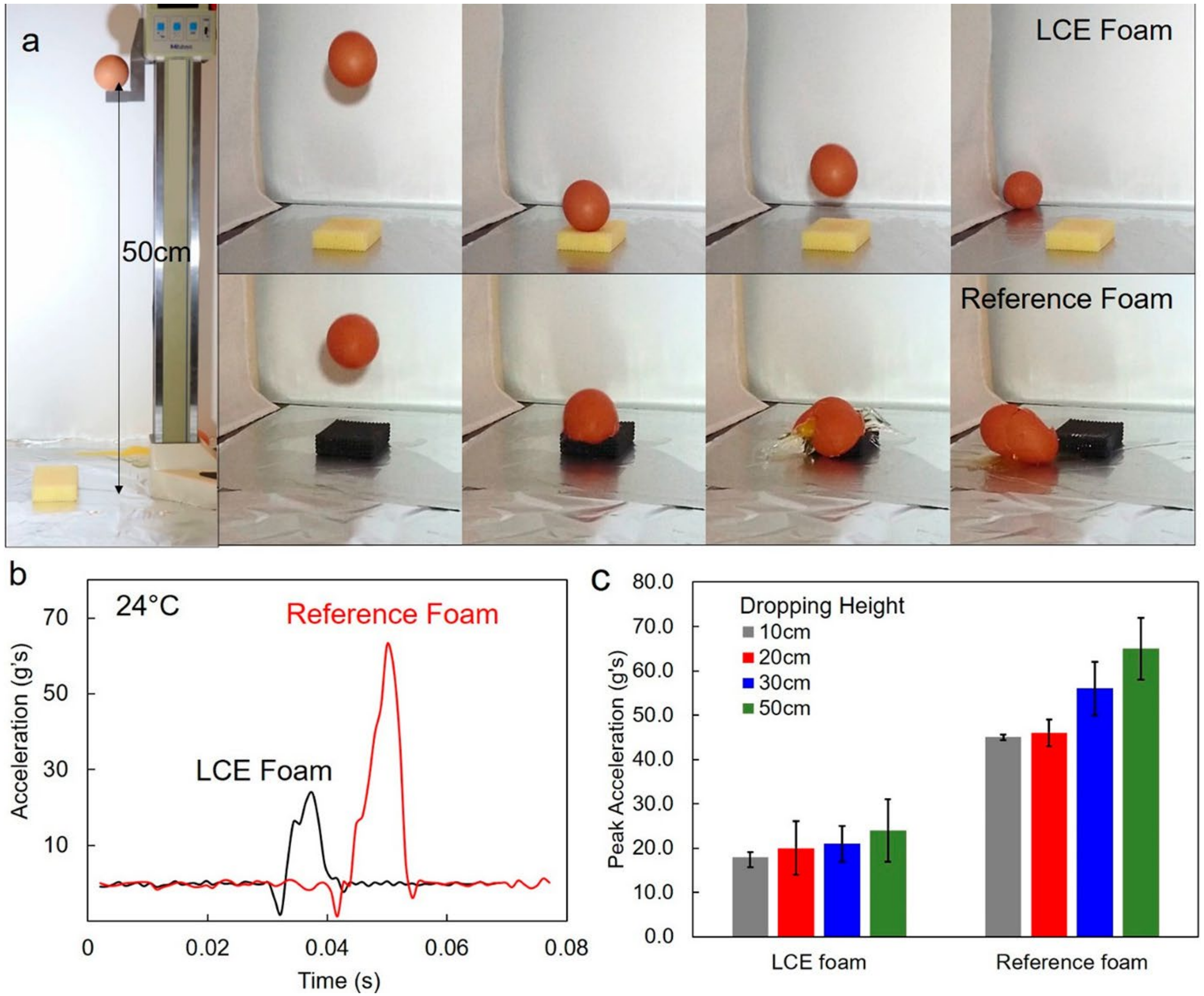


Mistry et al. “Soft elasticity optimses dissipation in 3D-printed liquid crystal elastomers.” Nature Communications, 2021, 12 , Article 6677

Motivation

- **LCE** lattice was shown to protect a chicken egg during a drop test from 50 cm
- Equivalent conventional polymer (bisphenol-A (**BPA**)) resulted in a broken egg
- Impact velocity ~3.1 m/s
- Loading rate at impact ~6000 s^{-1}

How do the constituent materials behave at high strain rates?



Luo et al. "3D Printing of liquid crystal elastomer foams for enhanced energy dissipation under mechanical insult." ACS Applied Materials and Interfaces, 2020, 13, 11, 12698-12708

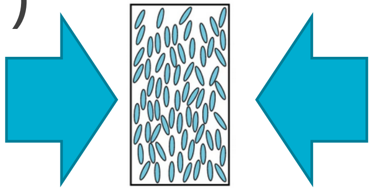
Overview of Experiments

Materials (DIW 3D printing)

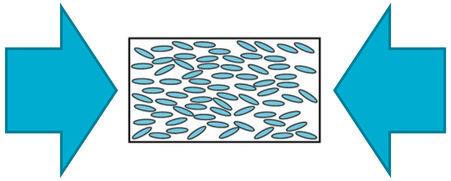
- **BPA 90°** orientation relative to loading direction (perpendicular)
- **BPA 0°** orientation relative to loading direction (parallel)

Should be equivalent

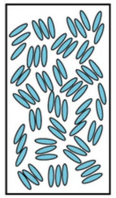
- **Monodomain** LCE with **90°** orientation (perpendicular)

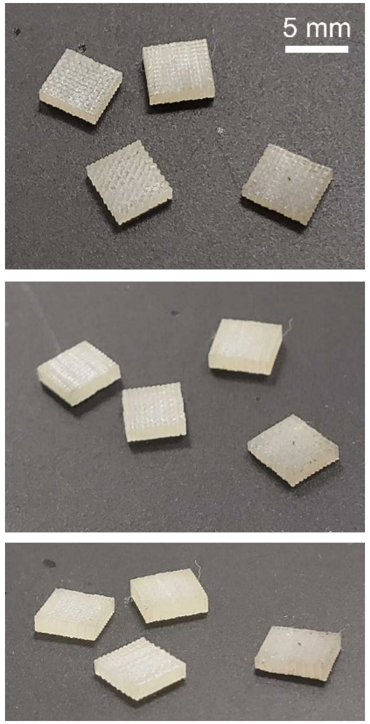


- **Monodomain** LCE with **0°** orientation (parallel)



- **Polydomain** LCE bulk synthesis





- **Sorbothane** commercial shock/vibe damping material

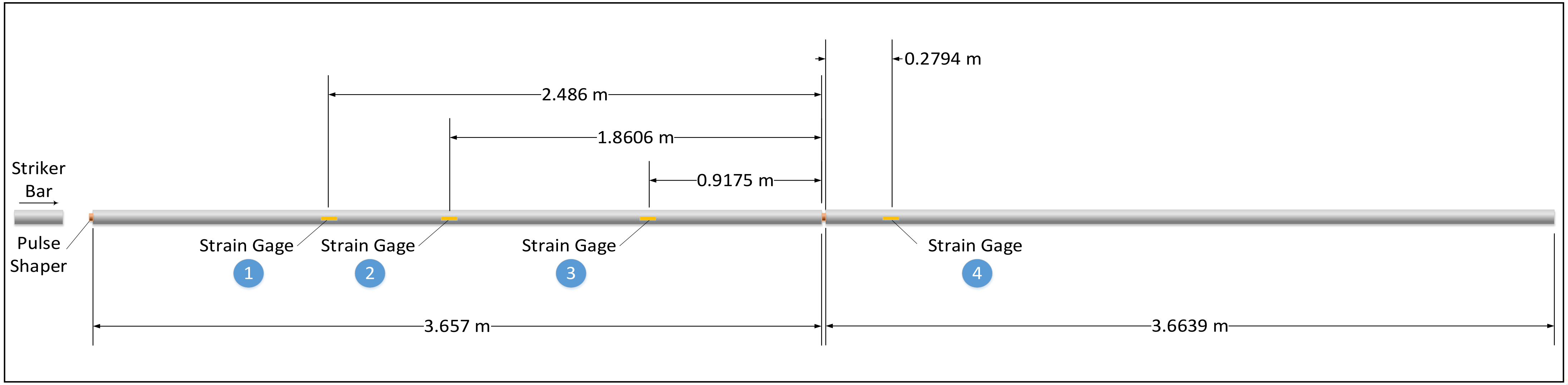
Experiments

Kolsky Compression bar experiments

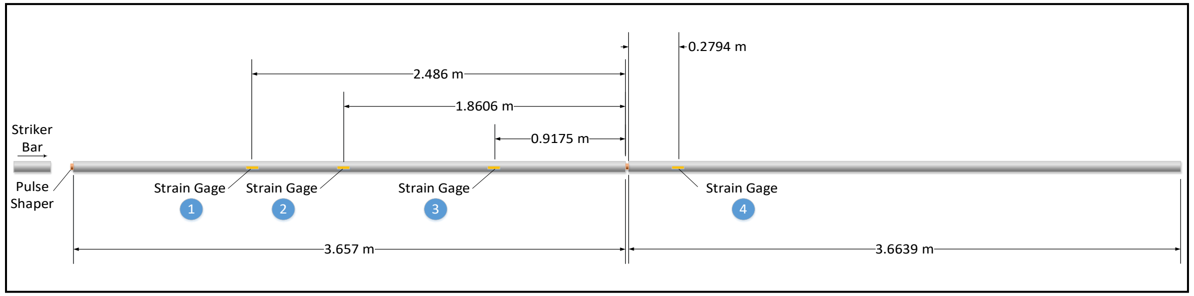
- 800, 1600, and 3000 s^{-1}
  - Quasi-static rates also conducted by CU Denver collaborators
- > 50% engineering strain
- Six materials, three repeats at each condition

Bar configuration

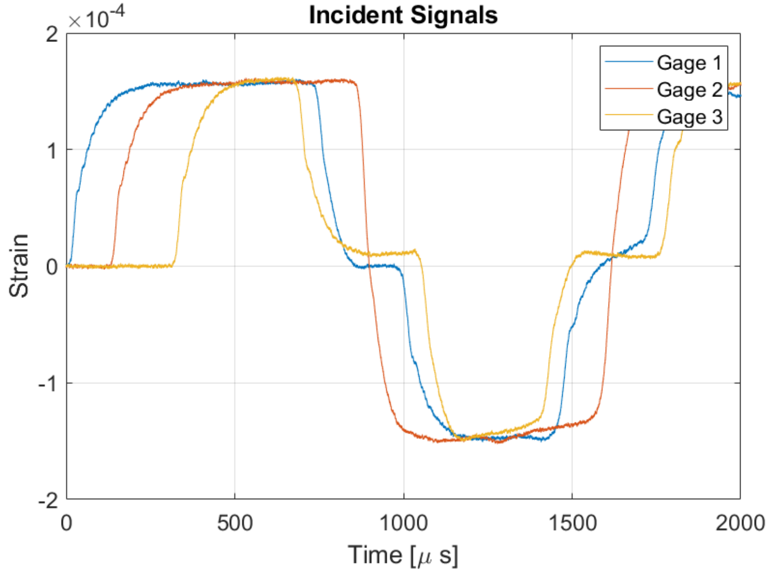
- 12’ long incident and transmission bars (aluminum 1” diameter)
- Quartz crystal force transducers installed at bar ends (force equilibrium check)

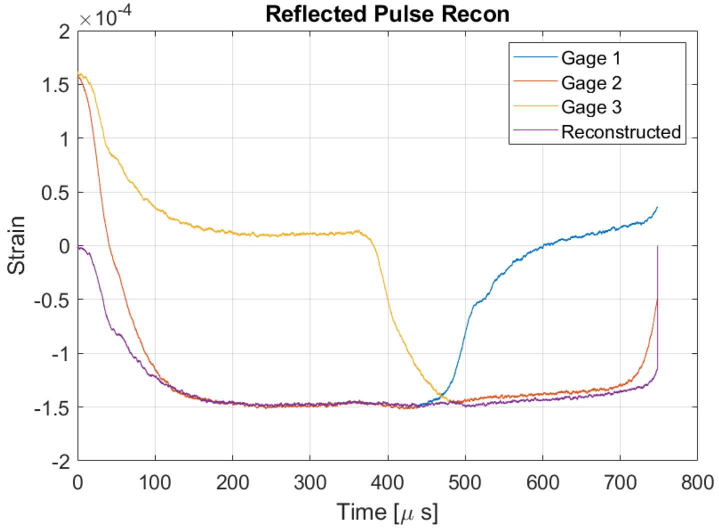


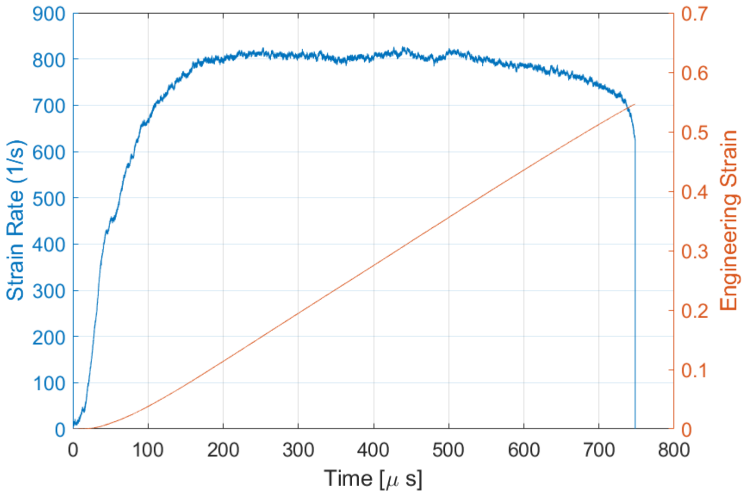
Reflected Pulse 800 s^{-1}



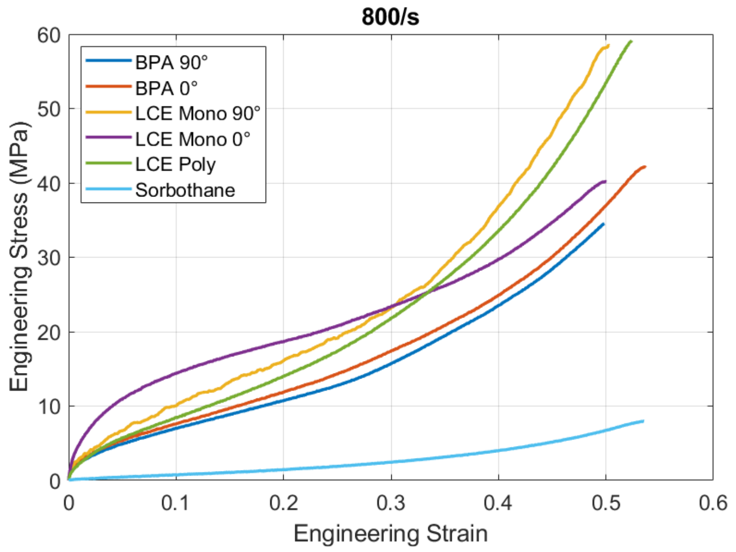
- Constraint of 50% minimum strain at 800 s^{-1} required the use of 6' long striker bar
- Due to wave overlap that occurs with a single set of strain gages, three sets of gages were used
- Gages were time shifted and the reflected pulse was "reconstructed " or spliced together

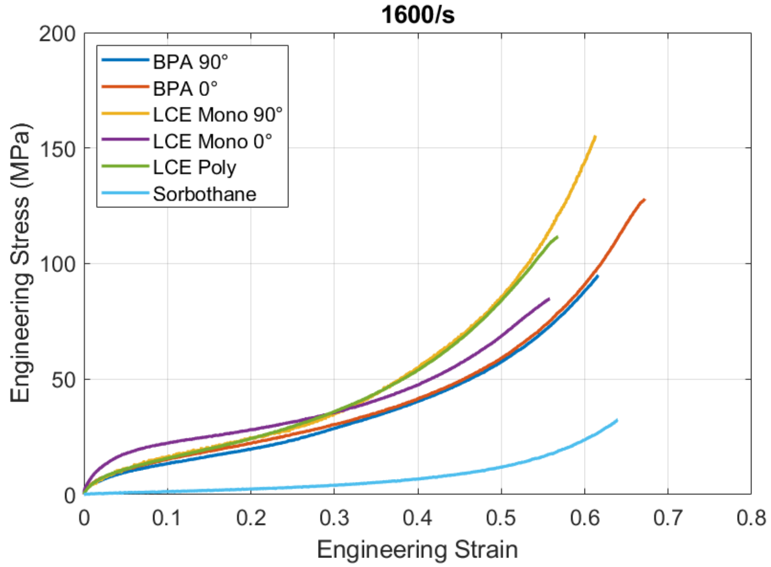


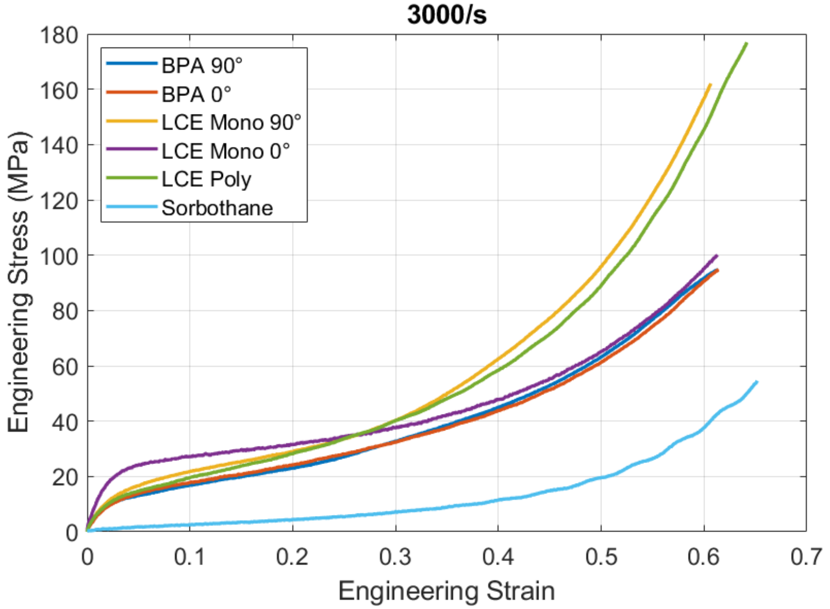




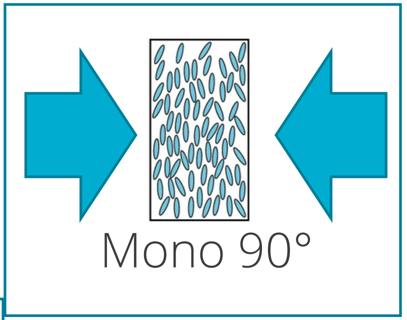
Results

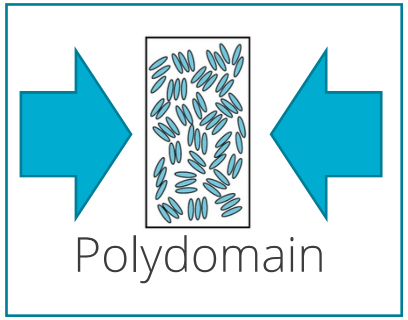


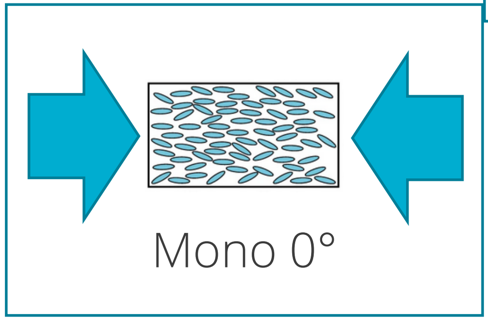




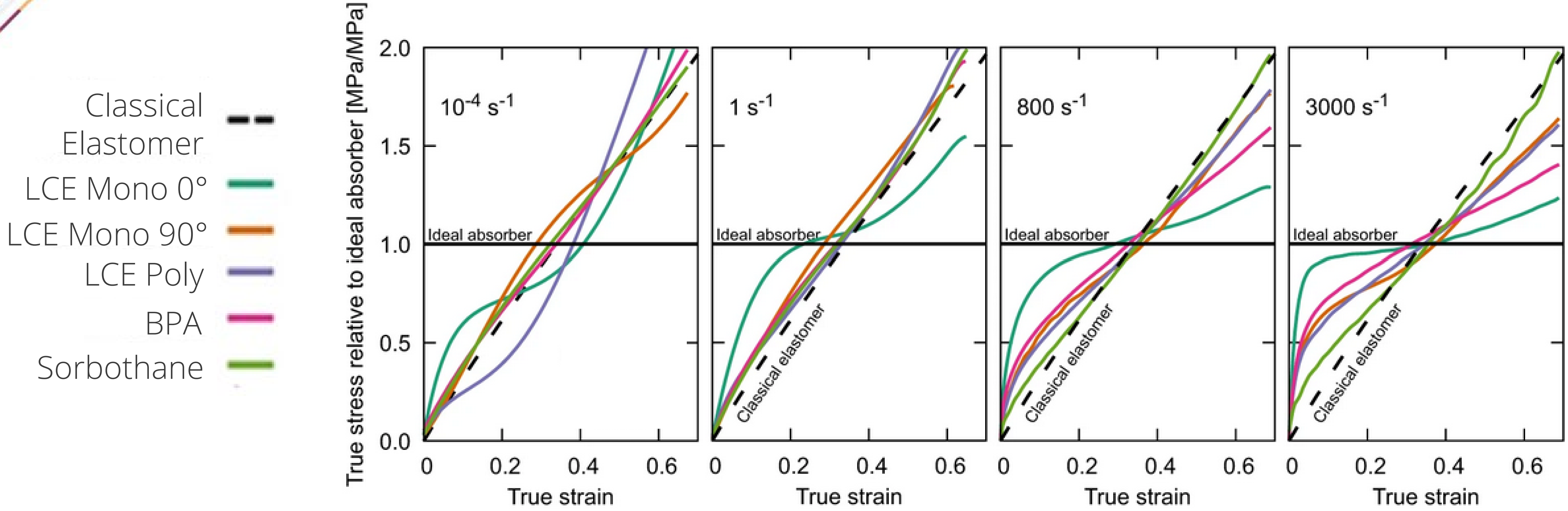
- BPA 0 and 90° had nearly identical behavior
- LCE Monodomain 90° and Polydomain behaved similarly
- LCE Monodomain 0° displayed a plateau behavior suggesting mesogen rotation may have occurred
- Sorbothane behaved like a classical elastomer/soft rubber







Strain Energy Absorption



- Stress-strain curves were normalized and compared to an ideal strain energy absorber
- Quasi-static LCE behaves like classical elastomer, with some soft elasticity by polydomain, mesogen rotation in LCE 0°
- At 1 s^{-1} materials except LCE 0° behave like a classical elastomers. LCE 0° responds closest to ideal absorber (rate effect)
- High strain rates show improved response of all materials. LCE 0° converges towards ideal response (not a foam)
- LCE 0° can more quickly accumulate more strain energy at small strains

Conclusions and Future Work

- Measured stress-strain response for LCE, BPA, and classical elastomer materials
- Monodomain LCE materials have unique energy absorption capacity due to mesogen rotation, behaving similarly to a foam-like “ideal absorber” despite being a solid polymer
- Conventional polymers (BPA, Sorbothane) did not show this absorber behavior
- This mechanism can be exploited with 3D printing to design new absorbing lattices for protection schemes

Future work

- Investigate behavior at intermediate rates
- Expand energy analysis to include unloading
- Measure and quantify mesogen rotation during deformation