**Graduate students:** Adedotun Banjo, Shreyas Shelke

**Undergraduate students:** Craige LeGrand, Justin Brouillette, Matt Graves, Troy McCay
Our work: structural composites

Characteristics
• High specific strength & stiffness
• Excellent fatigue and corrosion resistance
• Ability to tailor material properties to specific applications

Material life cycle

Design  Manufacturing  Use  Disposal

Design focus
• Multi-functionality
• Autonomous behavior
Manufacturing

Materials processing
• Hand layup
• Resin Transfer Molding (VARTM)
• 3D printing
• Compression molding
• Polymer synthesis

Characterization
• Mechanical and thermomechanical testing (in collaboration with Center for Polymer and Advanced Composites (CPAC))
• *in situ* strain mapping via Digital Image Correlation (DIC)
Material behavior while in use

Focus on autonomous behavior

Patrick et al., *Nature*, 2016
**Strategy:** Damage detection via mechanochemistry

**Mechanochemistry:** Inducing chemical reactions through the use of mechanical energy

**Mechanophores:** Molecules that undergo chemical reactions upon the application of mechanical force

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**Force-sensitive spiropyran (SP) mechanophore**

Davis *Nature*, 2009

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**Spiropyran (SP) activation in bulk polymers**

- Linear SP-PMA
- Cross-linked SP-PMMA
- Linear SP-PMMA

Damage sensing in PMMA

Celestine et al., Polymer, 2014

Scribed SP-PMMA specimen

Fluorescence image of scribed region

SP-PMMA fracture specimen

Fluorescence image showing activation ahead of crack tip

Fluorescence image sequence from rubber toughened SP-PMMA
Strain and stress mapping via mechanochemistry

Celestine et al., Strain, 2019

Predicted strain and stress from intensity results

Fluorescence

Intensity

Scale bars 0.5 mm

Equivalent Strain

Equivalent Stress

\[ \Delta a = 0.4 \text{ mm} \]
Self-sensing: Moving forward

• Demonstrate mechanophore-driven self-sensing in diverse material systems
  ➢ in fiber reinforced composite matrices e.g. epoxy, vinyl esters, nylon
  ➢ in 3D printing filament for strain mapping during printing
  ➢ in nanoparticles

![SEM image of SP-linked rubber nanoparticles](image)
Avg diam: 350 ± 10 nm

• Demonstrate repeatable self-sensing
  • explore new mechanophores with more efficient responses
**Goal:** Repair damage and restore structural integrity without human intervention

Healing efficiency evaluated based on the recovery of strength, stiffness, fracture toughness or even electrical resistance!
Damage repair via solvent-filled microcapsules

Solvent released into crack plane
Solvent diffuses into and swells matrix
Crack heals as polymer chains move across crack plane

Material System:
PMMA with PMMA-anisole microcapsules

Fracture plane of self-healing PMMA specimen

* Error bars: upper and lower bounds of each variable
Self-healing: *Moving forward*

- **Demonstrate repeatable self-healing via**
  - robust healing material
  - capsule-channel configurations
  - regenerative materials

- **Integrate self-healing and self-sensing**

- **Self-healing 3D printing filament**
  - coat filament with microcapsules
  - load filament with microcapsules

*Collaboration with Beckingham Lab, Chemical Engineering*

Controlled degradation

**Strategy:**

- Understand degradation from a mechanics perspective
- Modify composite architecture and material properties to initiate degradation on demand

Collaboration: Agrawal Lab, Aerospace Engineering
Degradation behavior

Mechanical response of nylon composites soaked in DI water

- Significant decreases in strength and modulus
- Contributing factors:
  - time
  - temperature
  - architecture
  - fiber type

Celestine et al., OTC Proceedings, 2018
Controlled degradation: *Moving forward*

- **Investigate effect of**
  - fluid type (e.g. brine, sea water)
  - composite architecture
  - thermal and/or mechanical cycling
  - other external stimuli (e.g. UV) on degradation behavior

- **Model degradation using Continuum Damage Mechanics**
• Recycle old desktop printers for 3D printing

Collected printers are ground to pellet size

Material extruded into filament

Samples printed from recycled material

• Characterize mechanical properties of recycled material

*Collaboration: Triggs Lab, Aerospace Engineering*
Path forward

Closing the loop

➢ Adaptive composite design by incorporating modeling with experiments

➢ Integrated autonomous systems e.g. SELF-SENSING-HEALING-DEGRADING

➢ 3D printing of self-healing and self-sensing material

➢ Repurposing end-of-lifetime and degraded material

➢ Efficient and sustainable composites and composites manufacturing
Thank you!

Questions?

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