# Mechanical and Vibration Testing of Carbon Fiber Composite Material with Embedded Piezoelectric Sensors

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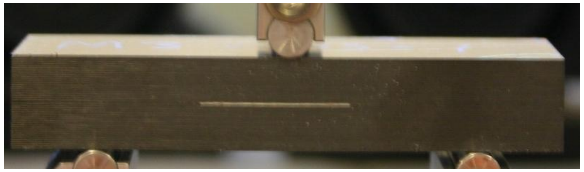
# Background



- Idea:
  - Use piezoelectric sensors and actuators as part of active vibration control of composite fan blades
  - Embed the piezoelectric elements into the composite material
- Question:
  - How does the inclusion of packaged piezoelectric elements into composites affect the strength?
- Previous Research:
  - Generally full inclusion of piezo into composite:
    - Warkentin and Crawley (1991) – embedded silicon chips
    - Bronowicki et al. (1996) – tension, compression, temperature, fatigue
    - Mall et al. (1998, 2000) – tension, electromechanical fatigue
    - Paget and Levin (1999) – tension and compression
    - Lin and Chang (2002) – fabrication techniques; tension, compression, shear, quasi-static impact
    - Konka et al. (2012) – foam sandwich structures, flexible piezoelectric elements; tension, bending, short beam shear
- Our goal – Determine localized strength of the composite with embedded piezoelectric elements

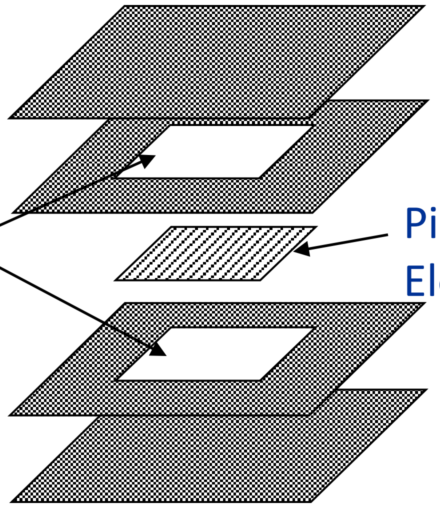
# Approach

- ✓ Embed off-the-shelf piezoelectric sensors into carbon fiber composite material
- ✓ Mechanical Testing
  - – 4-Point Bending
  - – Short Beam Shear
  - – Flatwise Tension
- ✓ Vibration Sensor Testing
  - – Effect of curing temperature and pressure on sensor
- Application to composite fan blades
  - – Active vibration control:
    - ✓ Spin testing with surface-mounted piezoelectric elements in small subscale fan blades
    - Vibration testing with embedded piezoelectric elements in larger subscale fan blades

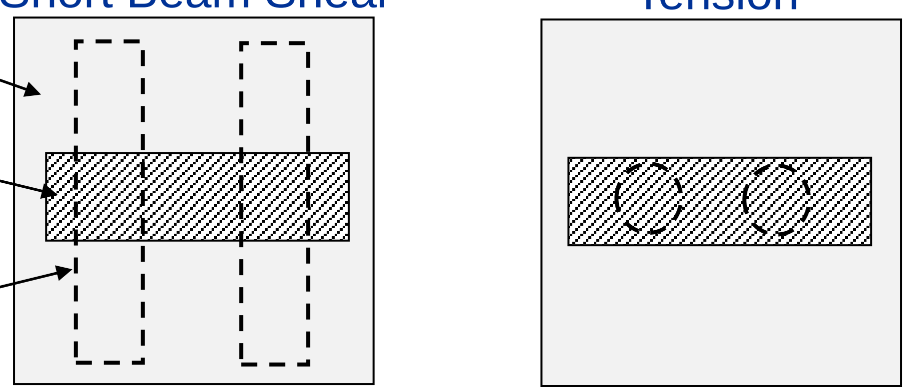
# Materials

| Composite Material | Type | Description |
|---|---|---|
| Polymer matrix fiber composite | HexPly 8551-7 with IM 7 carbon fibers | Epoxy resin with unidirectional carbon fibers, ply stack-up |
| **Piezoelectric Elements** | **Type** | **Description** |
| Monolithic | Non-flexible, PZT-5A, solid material | 250μm (0.010”) thick PZT |
| Flexible-1 | Flexible, PZT-5A, rectangular fibers | 175μm (0.007”) thick PZT fibers |
| Flexible-2 | Flexible, PZT-5A, circular fibers | 250μm (0.010”) thick PZT fibers |

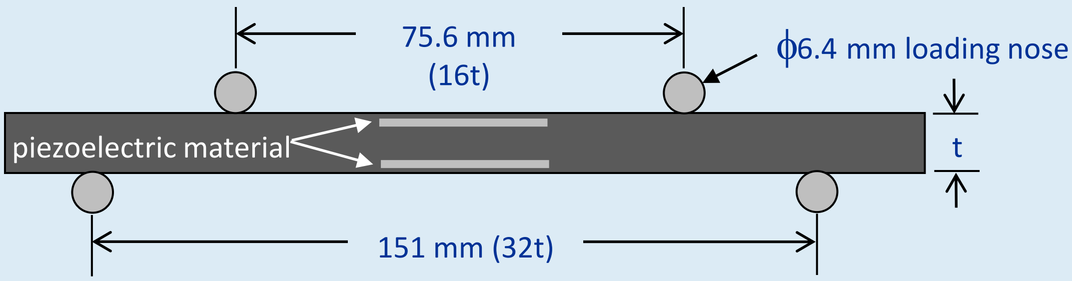
# Mechanical Test Specimen Preparation



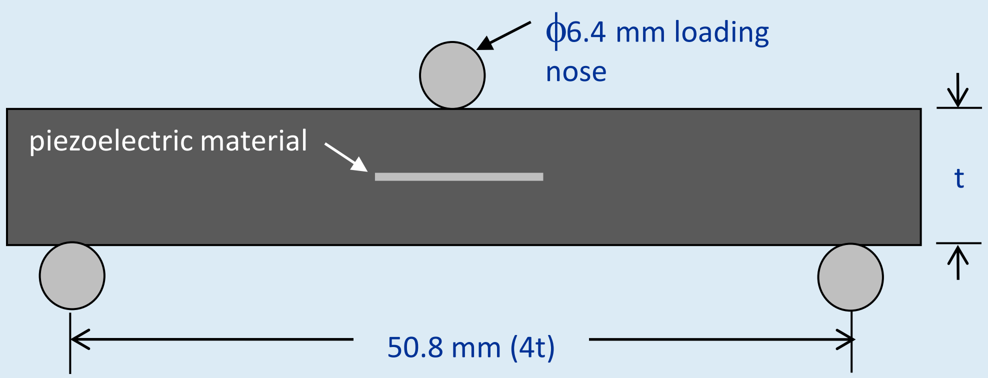

Cured at 175°C (350°F) and 690 kPa (100psi) for two hours



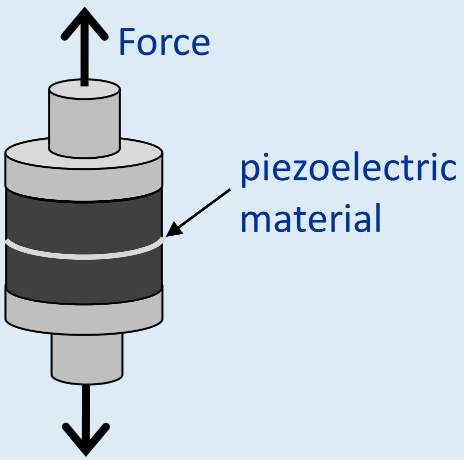
# Mechanical Testing




4-Point Bending




Short Beam Shear



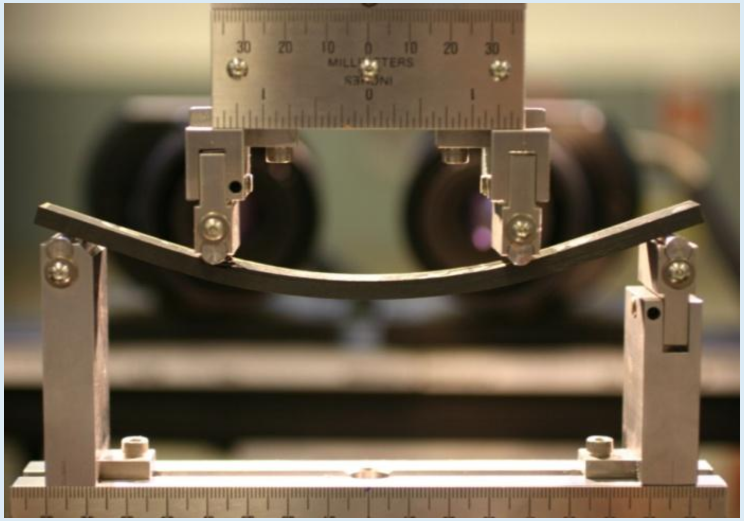

Flatwise
Tension

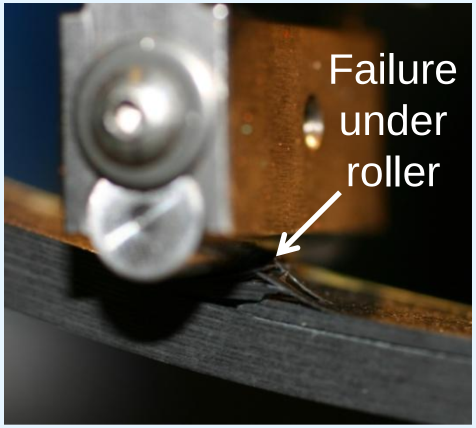
# Mechanical Testing

| Test Type | Standard | Specimen Dimensions | Piezoelectric Location |
|---|---|---|---|
| 4-Point Bending | ASTM D7264 | 165 mm x 12.7 mm x 4.72 mm (6.5” x 0.5” x 0.186”) | Two patches, piezo surface 0.3 mm (0.012”) below PMFC surface |
| Short Beam Shear | ASTM D2344 | 76 mm x 25 mm x 12.7mm (3.0” x 1.0” x 0.5”) | One patch located at midplane |
| Flatwise Tension | ASTM D7291 | 22 mm diameter x 20 mm thick (0.88” dia. x 0.78” thick) | One patch located at midplane |

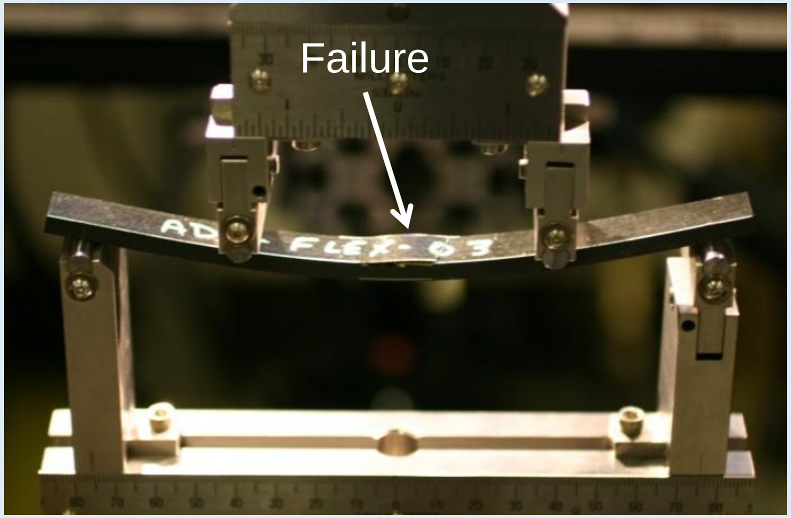
# 4-Point Bending

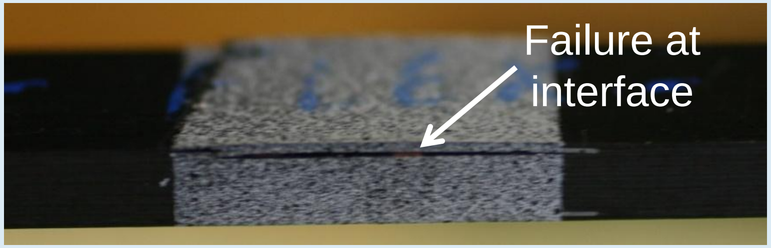
## Baseline






## Embedded



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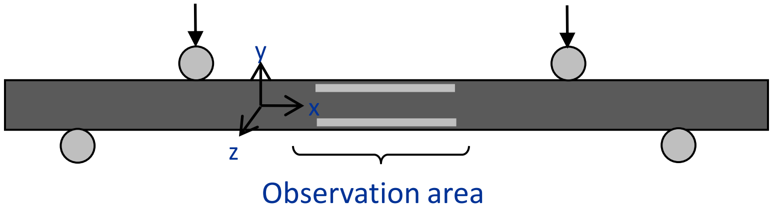
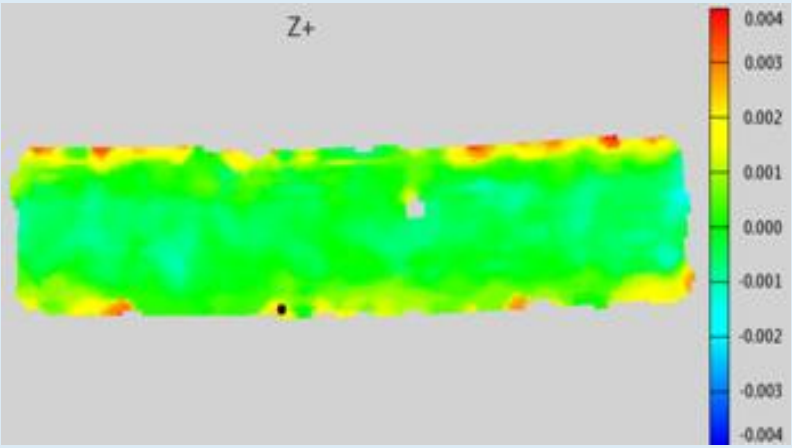
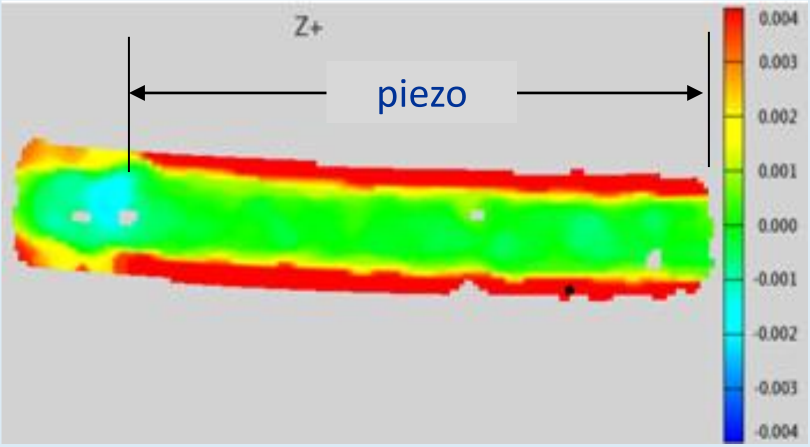


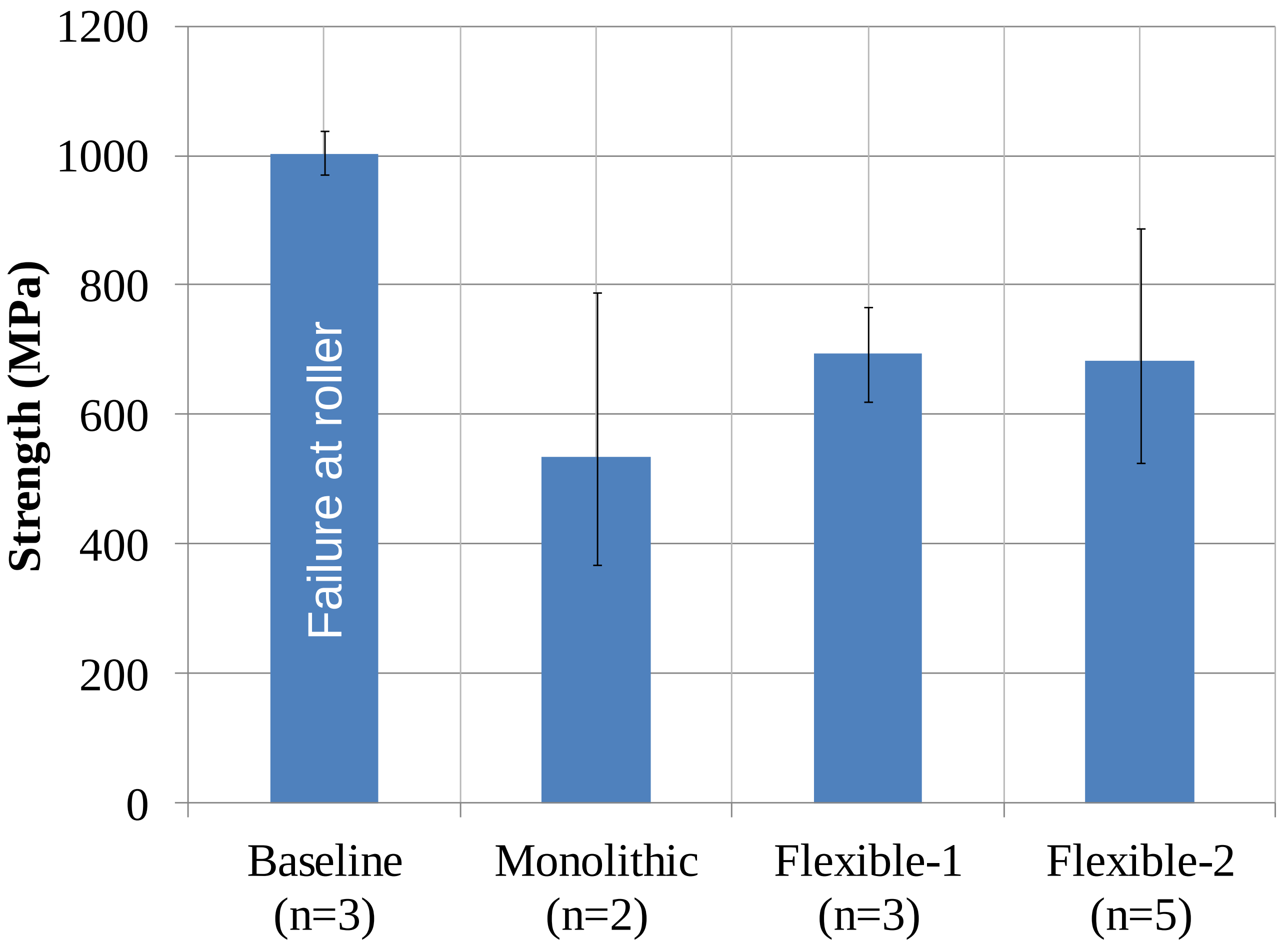

## Baseline Shear Strain



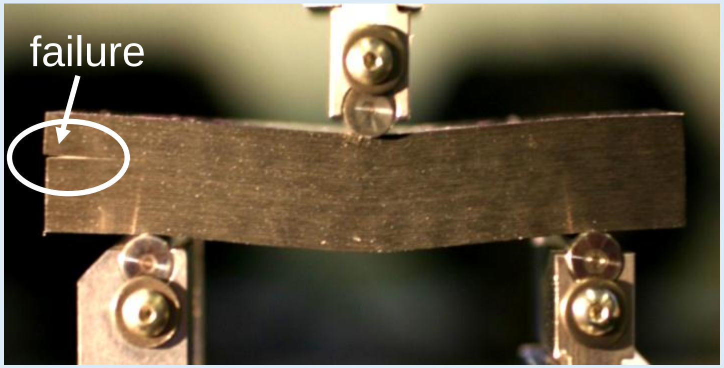

## Embedded Shear Strain

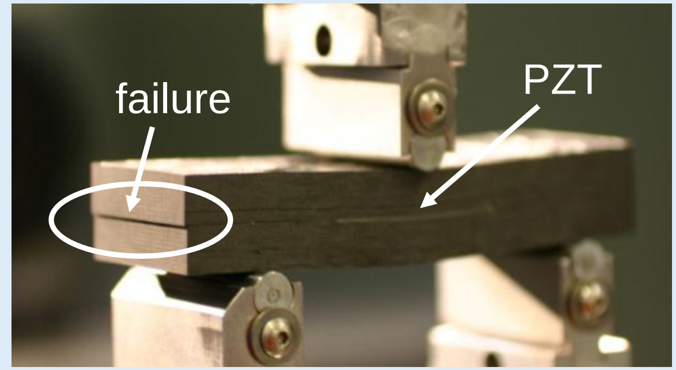


# 4-Point Bending

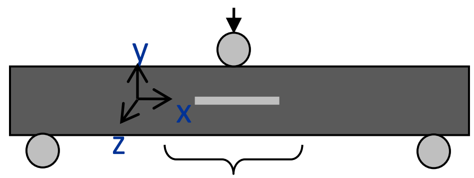


# Short Beam Shear

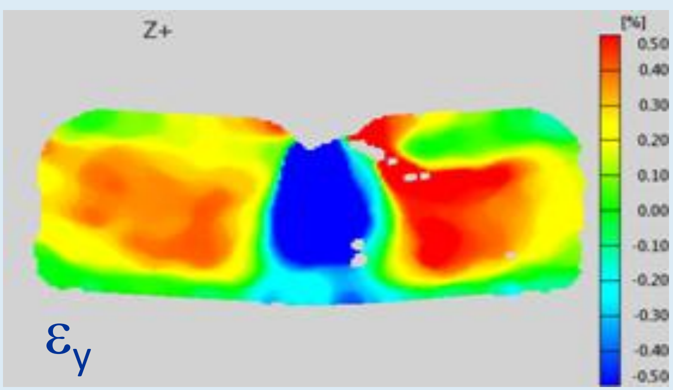


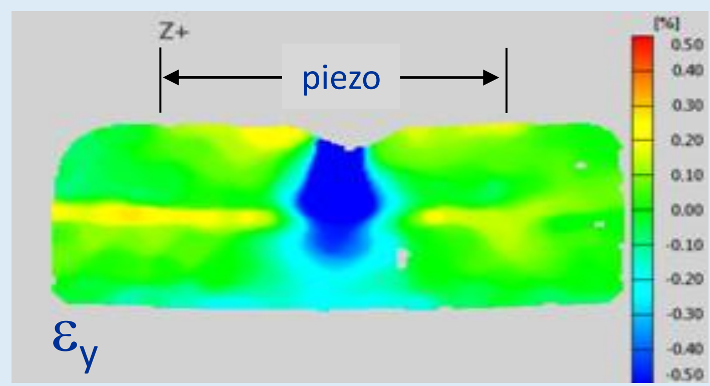




Baseline




Embedded



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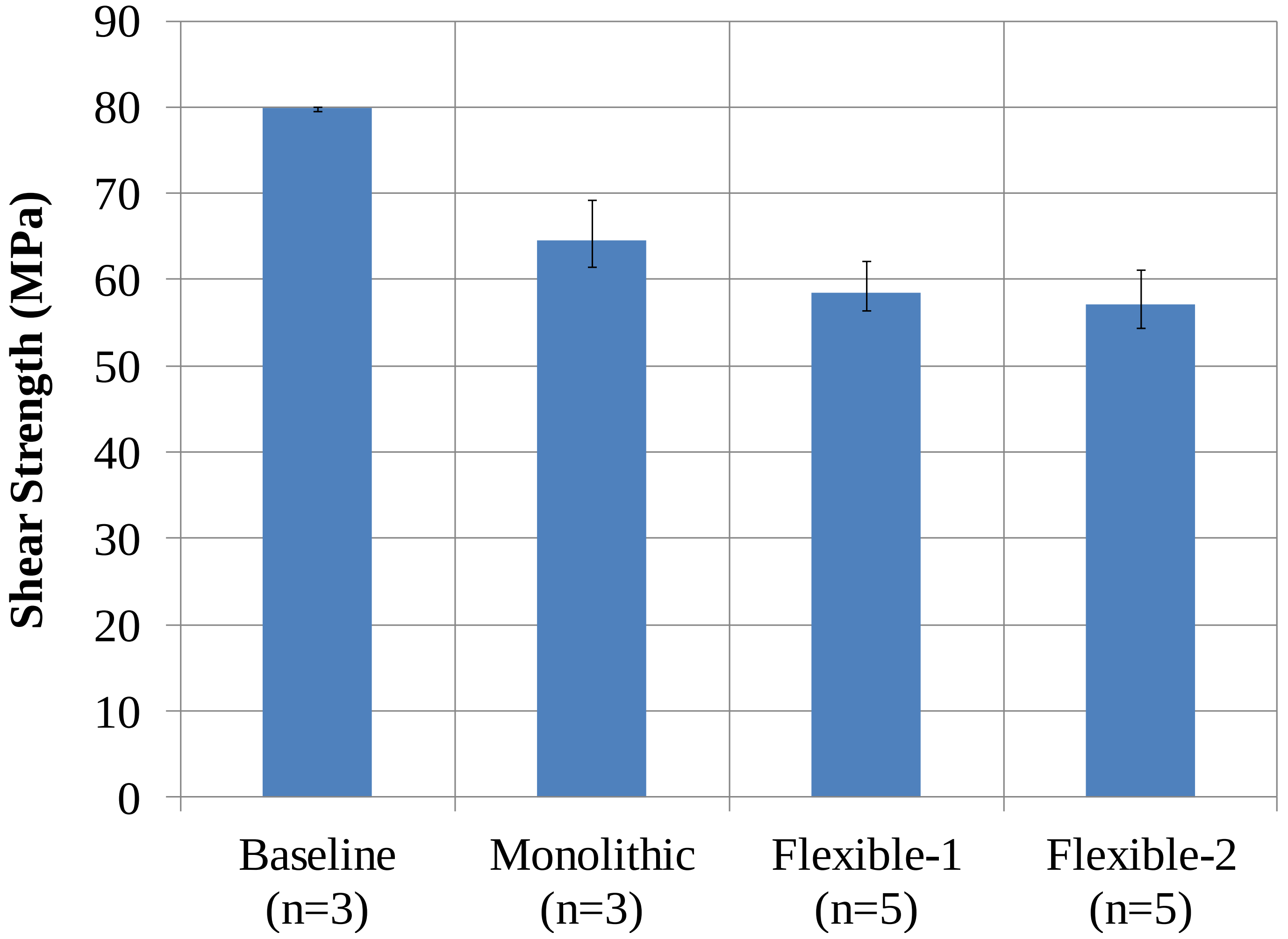
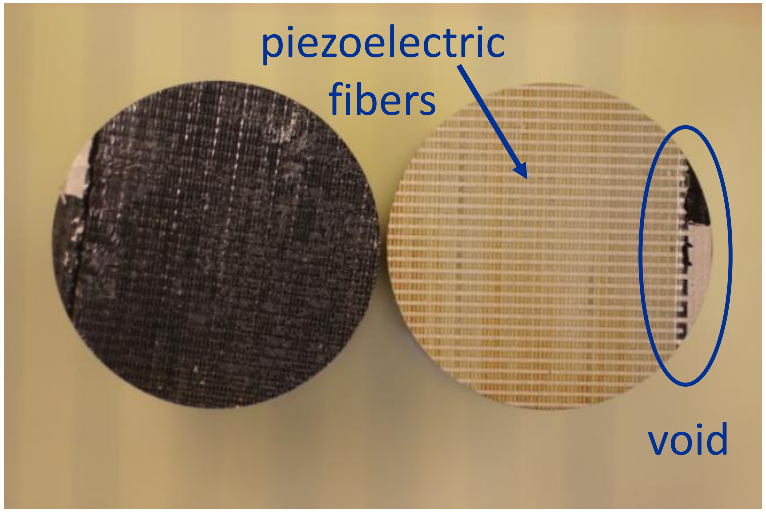
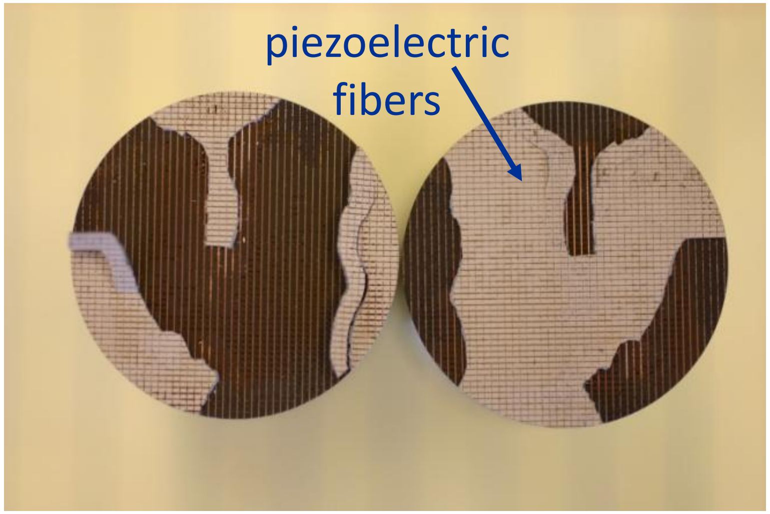


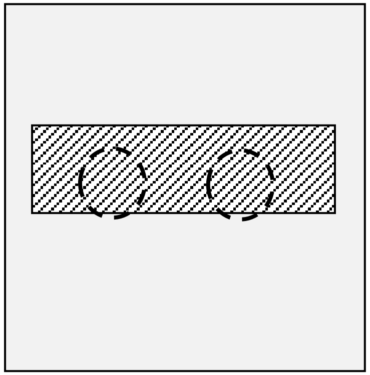
# Flatwise Tension

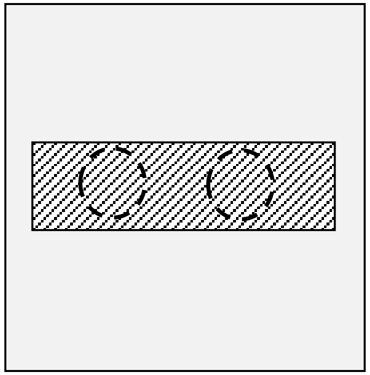



Failure within patch
at interface




Failure within patch
at piezoelectric





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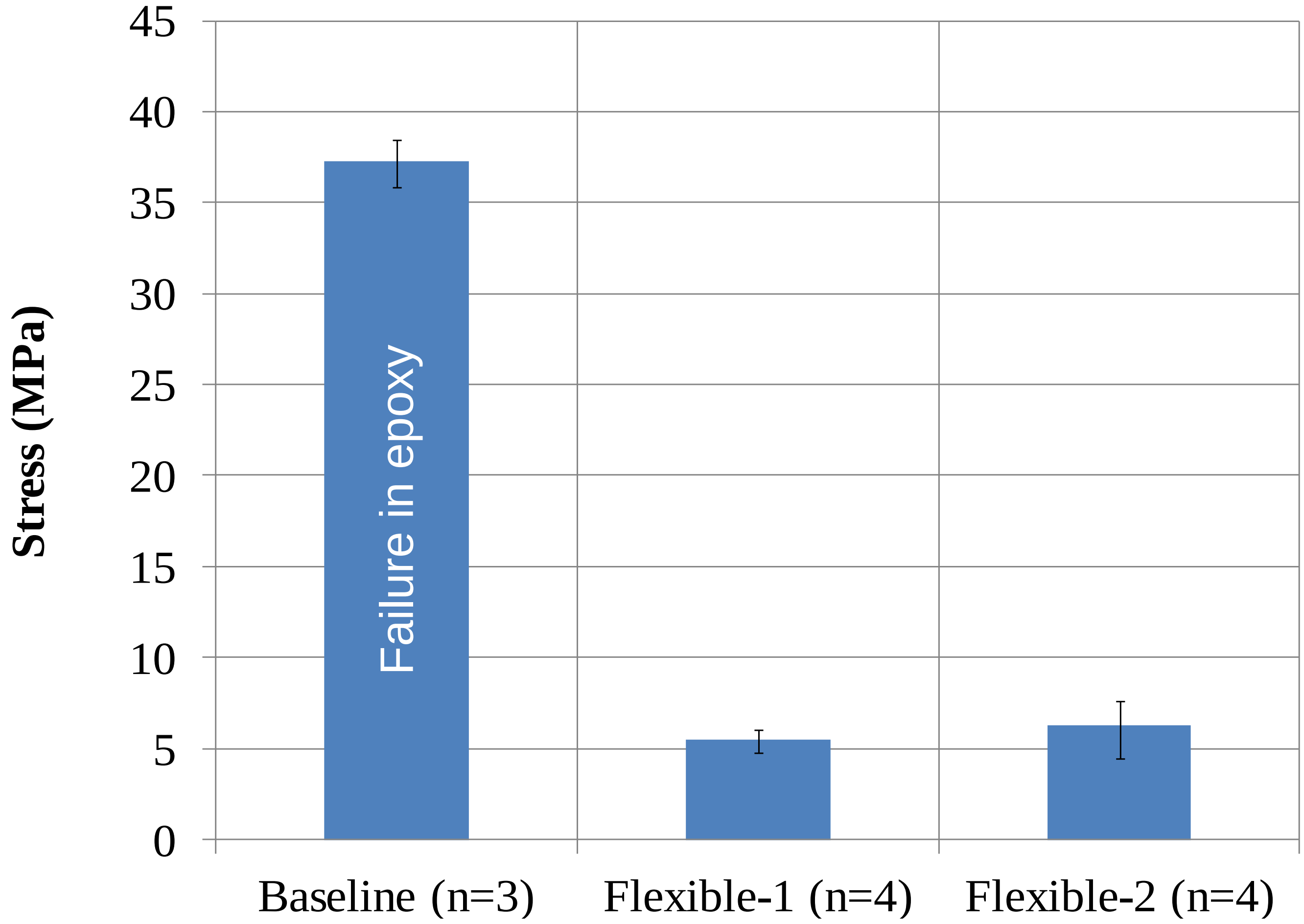
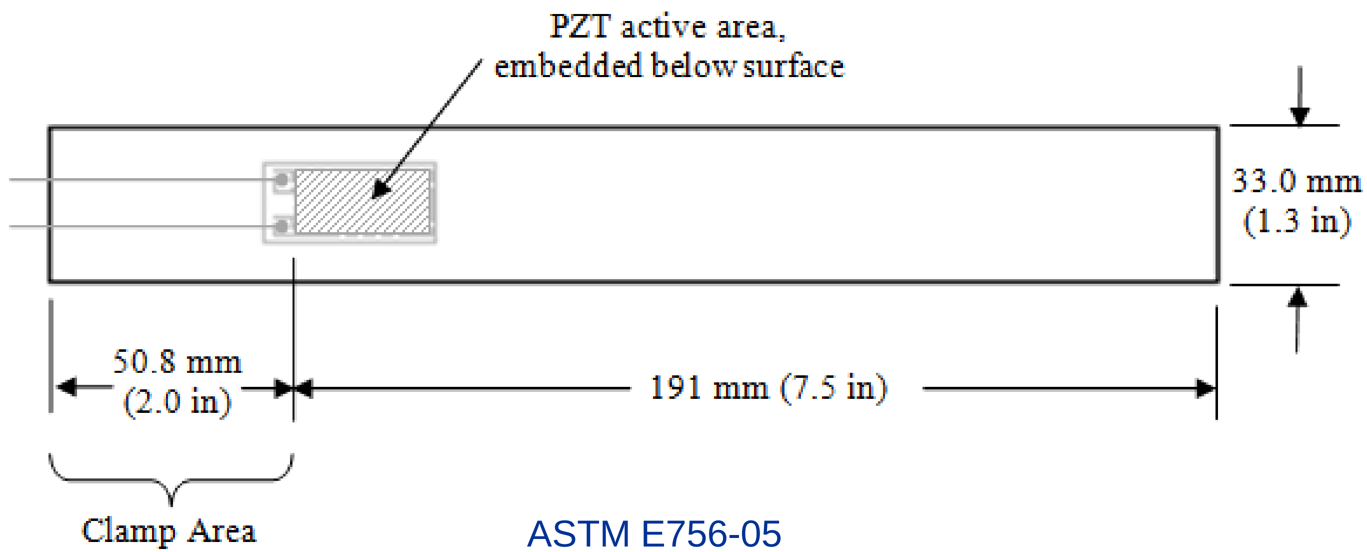


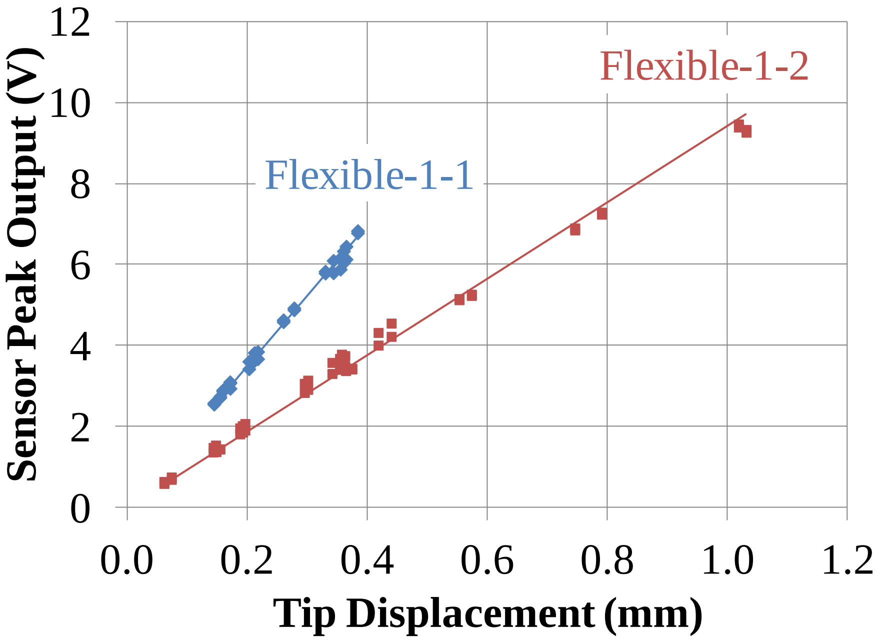
# Vibration Testing

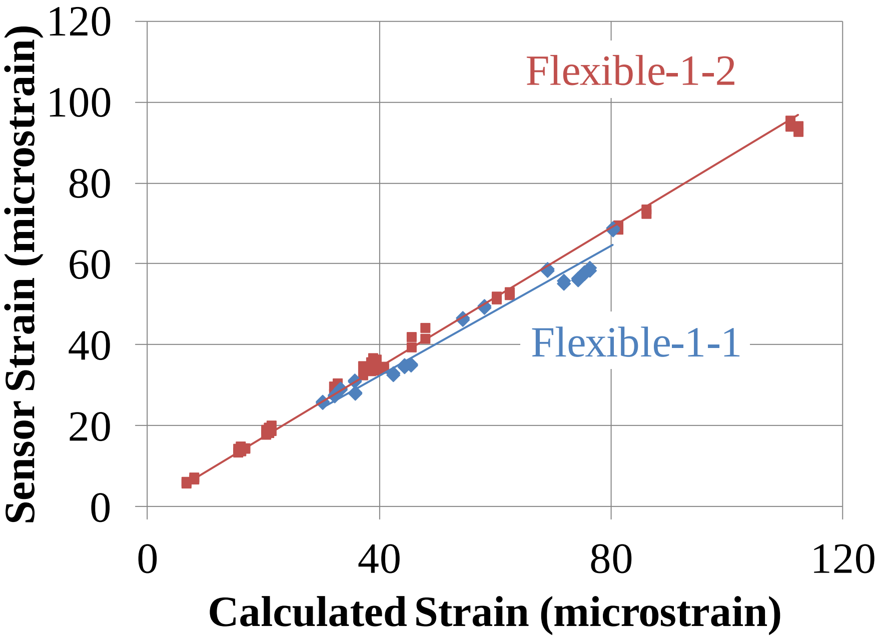



ASTM E756-05

| Beam Dimensions (Beyond Clamp) | Patch Dimensions | Patch Properties | Patch Sensitivity | Configuration ID | Embedding Depth |
|---|---|---|---|---|---|
| 191 mm (7.5") long<br>33.0 mm (1.3") wide<br>5.66 mm (0.223") thick | 28.0 mm x 14.0 mm<br>(1.10" x 0.55") | C = 25 nF<br>E = 30.3 GPa<br>$d_{31}$ = -210 pC/N | $10 \times 10^{-6}$ m/m/V | Flexible-1-1 | 0.3 mm<br>(0.012")<br>deep |
| | | | | Flexible-1-2 | 1.5 mm<br>(0.060")<br>deep |

# Vibration Testing



# Conclusions

- Mechanical Testing
  - 4-Point Bending – 31-47% reduction in strength
  - Short Beam Shear – 19-29% reduction in strength
  - Flatwise Tension – 83-85% reduction in strength
- Vibration Testing
  - Curing process did not adversely affect sensing ability
- Improving Strength
  - Active vibration control will reduce resonant stresses in the structure; however, it may not be adequate to account for the reduced composite strength
  - Perform analysis to better understand stresses in and between composite and piezoelectric elements
  - Investigate embedding techniques to reduce stresses in piezoelectric elements (e.g. interlacing)
  - Develop packaging techniques to increase the strength in piezoelectric elements
- Plans
  - Embed piezoelectric elements into subscale composite fan blade, perform active vibration control of resonant modes