Evaluation of Strain Measurement Devices for Inflatable Structures

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Inflatable Structures at NASA

- Inflatable habitats are fabric based pressure vessels
- Composed of multiple layers of materials for structure, pressure, micro-meteoroid and thermal considerations
- Fabric layers can be packed tightly for launch and expanded in orbit, providing significant volume savings
- Bigelow Expandable Activity Module (BEAM) was installed on the International Space Station (ISS) in April 2016 and is the first human rated inflatable habitat
- BEAM size module provides ~75% launch volume savings compared to similar sized metallic structure, when fully inflated
Inflatable Habitat Examples

- Inflatable structures can be used for a variety of applications and designs:
  - Lunar/Mars habitat
  - Airlock
  - Hyperbaric Chamber
  - Spacesuits

- Composed of two primary layers:
  - Pressure/bladder layer – holds the internal pressure
  - Restraint layer – structural layer, take loads from pressure layer and external forces

- Restraint layer is often made of broadcloth, cordage, straps or a combination of all three

- Habitat often has metallic or composite components to take launch loads or rigid interfaces (hatches, windows, etc) – not completely fabric or lightweight
Fabric Decelerator Examples

• Current work to use inflatable and expandable heat shield systems for Mars landing
  – Hypersonic Inflatable Aerodynamic Decelerator (HIAD)
  – Low-Density Supersonic Decelerator (LDSD)

• These systems have similar structure to inflatable habitats with an internal pressure vessel and restraint layer of cloth, straps and cords

• Still use metallic components for interfaces – not completely lightweight

• Fabrics are an emerging technology for space structures and have great potential for NASA’s future missions
Fabrics vs. Metals

- Inflatable habitats are made from high strength fabrics for their excellent strength-to-weight ratio.
- Broadcloth, straps, and cordage are made of fibers either twisted or woven together.
- Fabric materials are not isotropic and do not behave regularly like metals.
- Lack of manufacturing standards and knowledge of stress state creates a wide range of material properties for fabrics.
- Leads to a NASA required ultimate design factor of safety of **six for soft goods** and often an inefficient and over-conservative design.
- Need better strain monitoring techniques to evaluate performance of fabric structures.

Material Selection Plot
(Credit: University of Cambridge)
Fabric Structure Strain Measurements

• Important considerations for a strain measuring device:
  – Measure and stretch to high strains (10-50%)
  – Measure and withstand peak loads during dynamic loading
  – Measure stationary loads over extended periods of time without the loss of signal/creep
  – Ability to be ruggedly adhered to or integrated with a textile and staying fixed during the entire lifetime of the vehicle or test
  – Ability to be integrated with the textile such that it can be folded, packaged and limit snag hazards or interference with other components

• Traditional strain gauges and metallic devices do not work well on flexible materials

• New technologies need to be sourced and developed for accurate fabric strain monitoring
• Current strain monitoring techniques for inflatable structures utilize optical measurement systems on fabrics and traditional foil strain gauges on metallic components

• Photogrammetry/digital image correlation (DIC) uses a dual camera system and speckle pattern to measure the strain on the fabric restraint layer

• DIC system is very accurate and provides good results, but is limited to a small surface area

• DIC system only works for ground tests when the restraint layer is visible, it does not work in space environment with MMOD and thermal layers
HIAD Strain Measurements

- HIAD structure made of series of pressurized torus’ held together with system of straps
- Uses metallic load pins at strap to metal interface and strap tension gauges in-line with straps
- Foil strain gauges epoxied to pressurized torus broadcloth surface

(G. Swanson et al, 2014, International Planetary Probe Workshop)
Fabric Strain Measurement Devices

- Commercially available devices were sourced and six of the top performing devices were procured for structural evaluation.

- The most common type of strain gage is resistance based – it is made of a conductive material with an internal resistance that changes as the material is stretched.

- All of the devices tested are resistance based, except the StretchSense device which is capacitance based – its configuration creates a capacitor that changes capacitance as the material is stretched.

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Fabric Strain Gage Testing

• Structural testing of the gages included three primary tests:
  – **Low-rate tensile tests** to evaluate sensitivity to small changes in length
  – **Long-term creep tests** to record any loss of signal under a sustained load
  – **Short-term cyclic tests** to identify any hysteresis or timing issues of the resistivity changes over cyclic loading

• The sensors were tested using an electromechanical load frame and a Wheatstone bridge for data collection

• Beside these three main tests, additional testing will be completed in future phases of this investigation including:
  – Adhesion with the substrate material
  – Packaging
  – Electrical resources
  – Electro-magnetic interference (EMI)
  – Thermal effects
High Elongation Foil Strain Gage

- Gage: Linear pattern foil strain gage with 20% elongation rating

- Tested two adhesives to secure the gage to a Kevlar strap
  - RTV 142 – Silicone adhesive with 400% elongation
  - EA 9394 – Structural Epoxy with 2% elongation

- Tensile testing showed low strain measurements for the epoxy and high strain measurements for the silicone, both gauges dis-bonded at high strains

- Neither creep nor cyclic testing was completed for this device

- Neither RTV 142 nor EA 9394 produced good results

- HIAD project used composite epoxy resin to stiffen the Kevlar surface and then bond the strain gage in place

- Future work includes a test of the HIAD procedure on inflatable habitat straps
High Elongation Foil Strain Gage

Tensile Test of Foil Strain Gages on Kevlar Strap (6kbf)

- Applied Strain
- Strain Gage on Epoxy
- Strain Gage on RTV

Load Frame Displacement, in

- 0
- 0.5
- 1
- 1.5
- 2
- 2.5
- 3
- 3.5
- 4
- 4.5

Time, s

- 0
- 50
- 100
- 150
- 200
- 250
- 300
- 350
- 400
- 450
- 500

Measured Strain, microstrain

- 0
- 5000
- 10000
- 15000
- 20000

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Conductive Paint/RTV

• Gage: Conductive ‘Bare Conductive’ paint and conductive ‘Nickel Graphite’ infused RTV

• Can be directly applied to the surface of the fabric and allow for complete flexibility of the fabric

• Both materials were applied to the surface of a Kevlar strap to compare side by side

• Conductive paint produced the best results for all three tests
Conductive Paint/RTV

- Tensile testing showed good correlation for both materials

- RTV material exhibited cracking when stretched over 150% initial length, but no cracking was found in the paint material

- Creep testing of both materials showed significant drop in voltage over time

- Cyclic test for both materials showed hysteresis and drop in voltage over time
Conductive Thread Coverstitch

- **Gage**: Conductive threads sewn in a coverstitch pattern with changing resistance
- Developed by University of Minnesota to use for smart textiles and clothing
- Can be sewn directly into fabric structure and allow for maximum flexibility
- Initial evaluation was done with coverstitch sewn in Neoprene fabric, but a sewing test proved that stitching into Kevlar is possible
Conductive Thread Coverstitch

- Tensile testing results showed good correlation
- Creep testing showed a rising voltage drift over time
- Cyclic testing showed a drop in voltage over time
- All tests showed significant noise (cleaned up in post-processing) due to nature of thread and stitch
Conductive Polymer Cord

• Gage: Conductive silicone rubber in a cylindrical cord that changes resistance as it is stretched
• Used commercially for robotic stretch sensors
• Can be adhered or stitched to the strap at each end
• Tested as a single cord, but stitching tests showed that it can be integrated with a Kevlar strap
Conductive Polymer Cord

- Tensile test showed good correlation after initial voltage rise
- Creep test showed a drop in voltage over time
- Cyclic test showed a hysteresis drop in voltage over time
- Voltage drop potentially due to polymer chains aligning over time and through multiple cycles
NanoSonic Metal Rubber

- Gage: Highly elastic conductive polymer film that can be stretched to 200% of its initial length
- Can be adhered or stitched to the strap at each end
- Rubber samples were cut from a sheet of material and tested individually
- The conductive layer (top layer) was degraded during testing and the specimen was permanently deformed after one cycle
- Creep and cyclic testing were not completed for this material
Some correlation is shown in the linear region.

Maximum internal resistance was reached before 10% strain and the voltage signal dropped out, until the sample was relaxed below 10% strain.

Conductive film material was designed for EMI shielding and not intended for strain gages.
StretchSense Fabric Sensor

- **Gage**: Highly sensitive capacitance based stretch sensor commercially available with Bluetooth data acquisition system.

- Sensor portion of the sample is made of flexible Neoprene and can be sewn directly onto the surface of a strap or broadcloth.

- Testing was completed by installing the device into a load frame without a Kevlar substrate.

- Cyclic testing was not completed on this device due to testing equipment issues (planned to be tested in the near future).
StretchSense Fabric Sensor

- Excellent linear correlation with tensile testing
- Creep test showed good correlation over a short time
- Long term creep test produced minimal variation over 70 hours
Summary of Results

- StretchSense device is most promising gage for structural health monitoring of inflatables
- Future testing includes cold temperature tensile testing, EMI testing, and development of rosette designs
- Foil Strain Gage devices will also continue to be pursued using the HIAD installation procedure
Questions?

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