Evaluation of Strain Measurement Devices for Inflatable Structures

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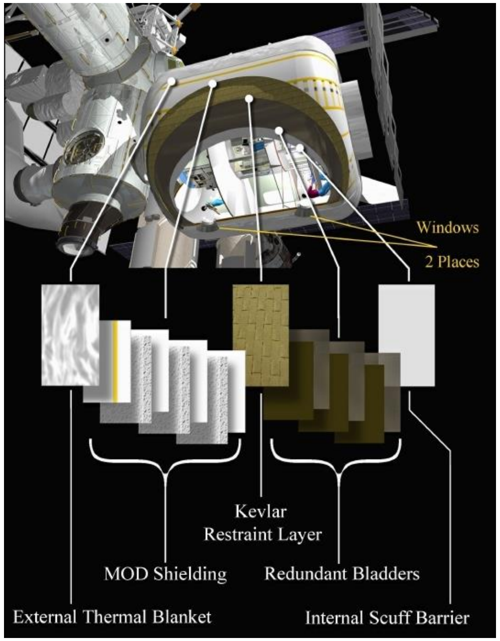
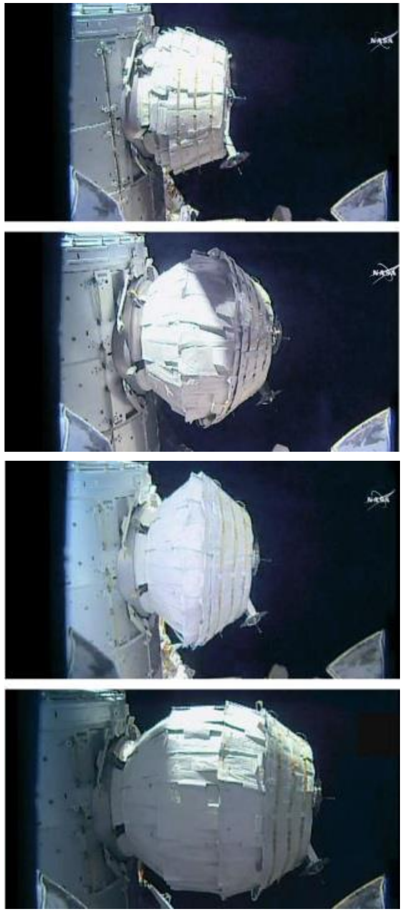
Inflatable Structures at NASA

- 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



Example Inflatable Module Layer Descriptions



BEAM Expansion on ISS

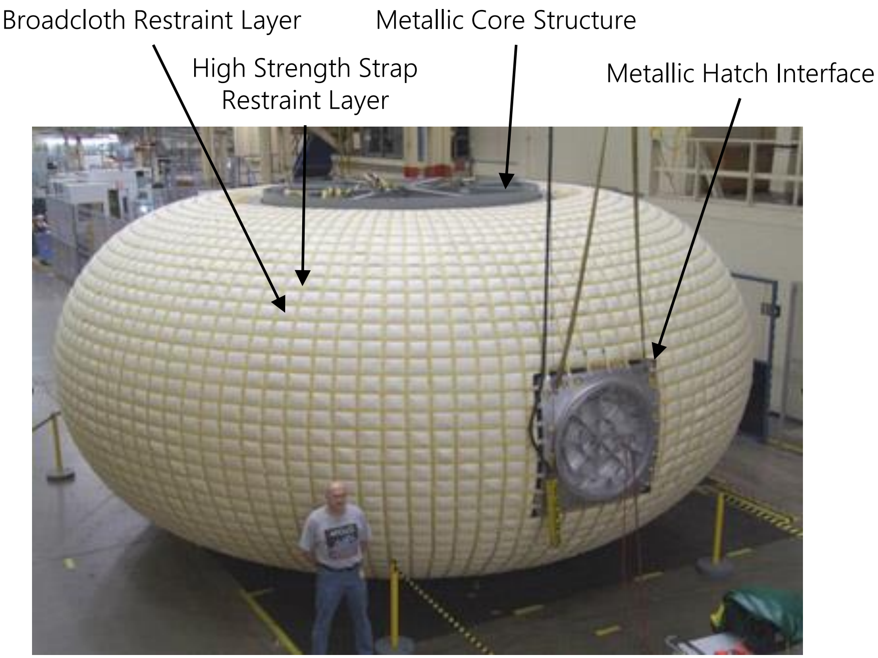
Inflatable Habitat Examples

- 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

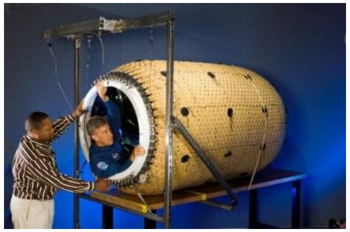
- Restraint layer is often made of broadcloth, cordage, straps or a combination of all three

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

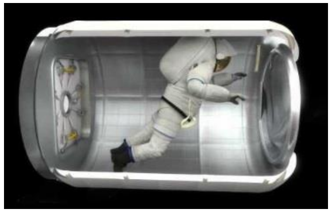


JSC Inflatable Lunar Habitat

NASA Z-2 Spacesuit



JSC Inflatable Hyperbaric Chamber



NASA Inflatable Airlock Concept

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**

LDSD Flight Test Article

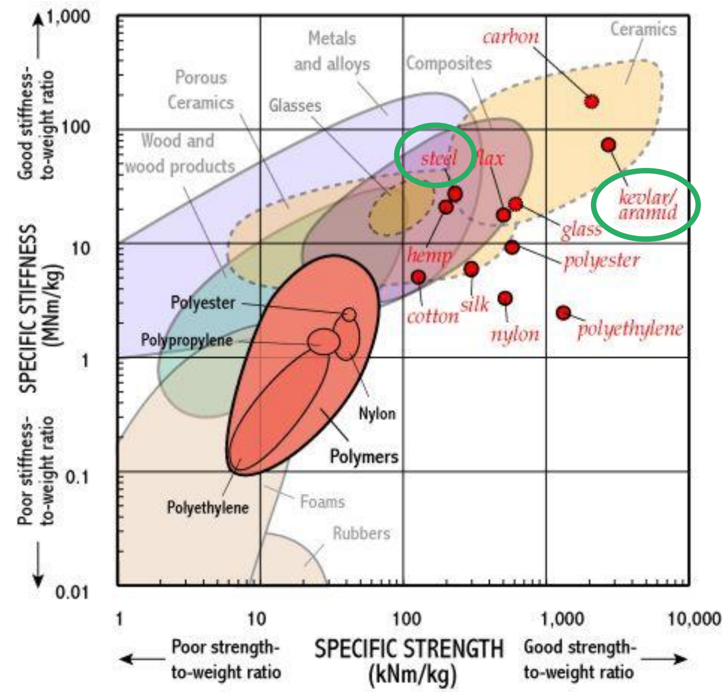
LDSD Flight Test Artist Rendering

HIAD Structural Layer

HIAD In-flight Artist Rendering

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

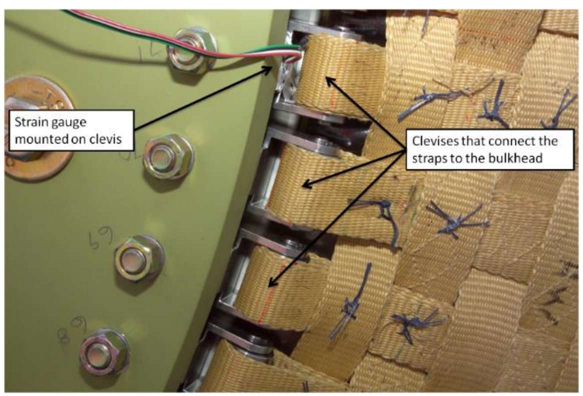
- Important considerations for a strain measuring device:
  - Measure and stretch to high strains (10-50%)
  - Measure and withstand peak loads during dynamic loading
  - Measure stationary loads over extended periods of time without the loss of signal/creep
  - Ability to be ruggedly adhered to or integrated 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

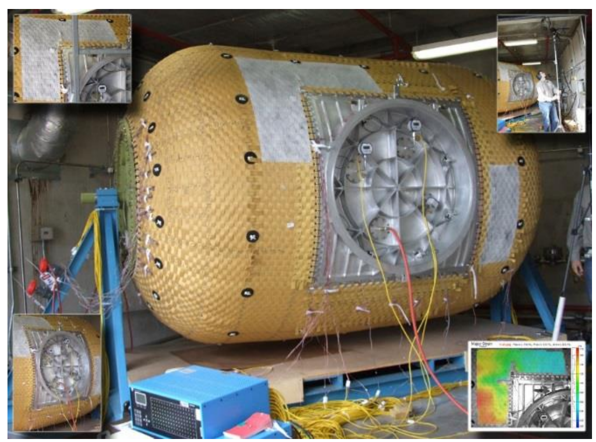
- **New technologies need to be sourced and developed for accurate fabric strain monitoring**

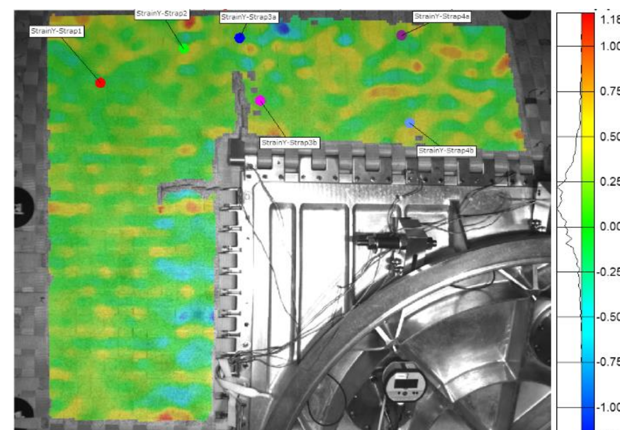
Inflatable Habitat Strain Measurements

- 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



Close-up View of Restraint Strap and Bulkhead Interface with Clevis Strain Gauge

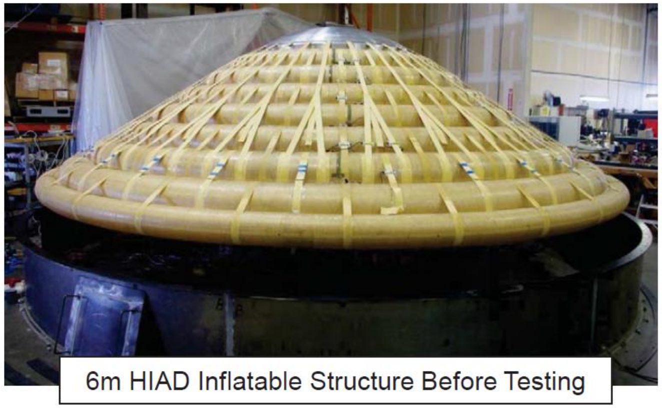




Photogrammetry Setup (Left) and Results (Right) from Pressurization Test Showing Strain in Straps (D. Litteken et al, 2012, AIAA Structures)

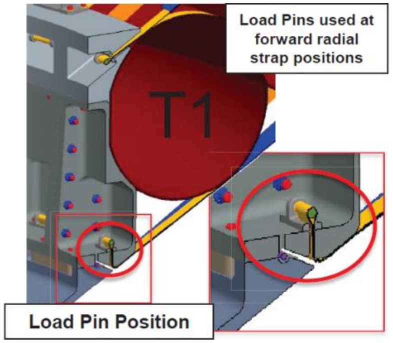
HIAD Strain Measurements

- 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

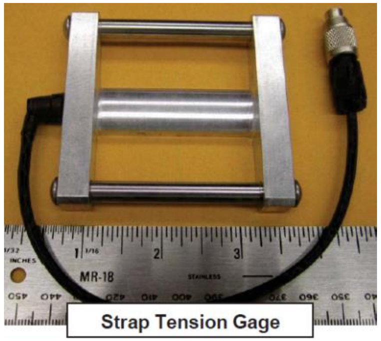


6m HIAD Inflatable Structure Before Testing

Strap Load Pin

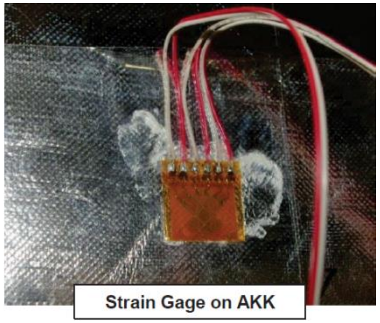


Load Pin Position

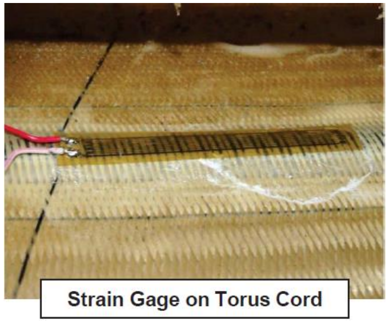


Strap Tension Gage

Strap Tension Gages on Crow's Feet Straps



Strain Gage on AKK

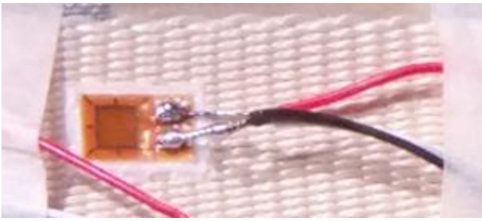
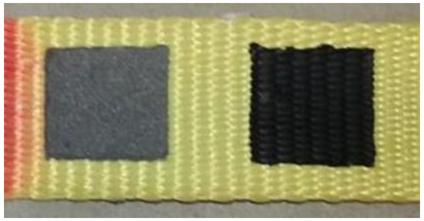
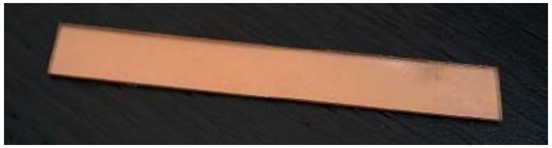


Strain Gage on Torus Cord

(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

High Elongation Foil Strain Gage	Conductive Paint/RTV	Conductive Thread Coverstitch
		
Conductive Polymer Cord	**NanoSonic Metal Rubber**	**StretchSense Fabric Sensor**
		

Fabric Strain Gage Testing

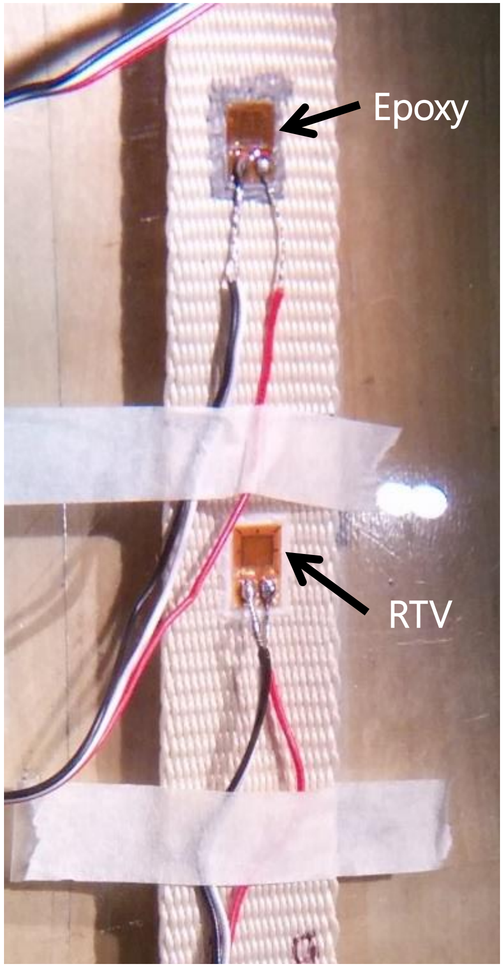
- Structural testing of the gages included three primary tests:
  - **Low-rate tensile tests** to evaluate sensitivity to small changes in length
  - **Long-term creep tests** to record any loss of signal under a sustained load
  - **Short-term cyclic tests** to identify any hysteresis or timing issues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

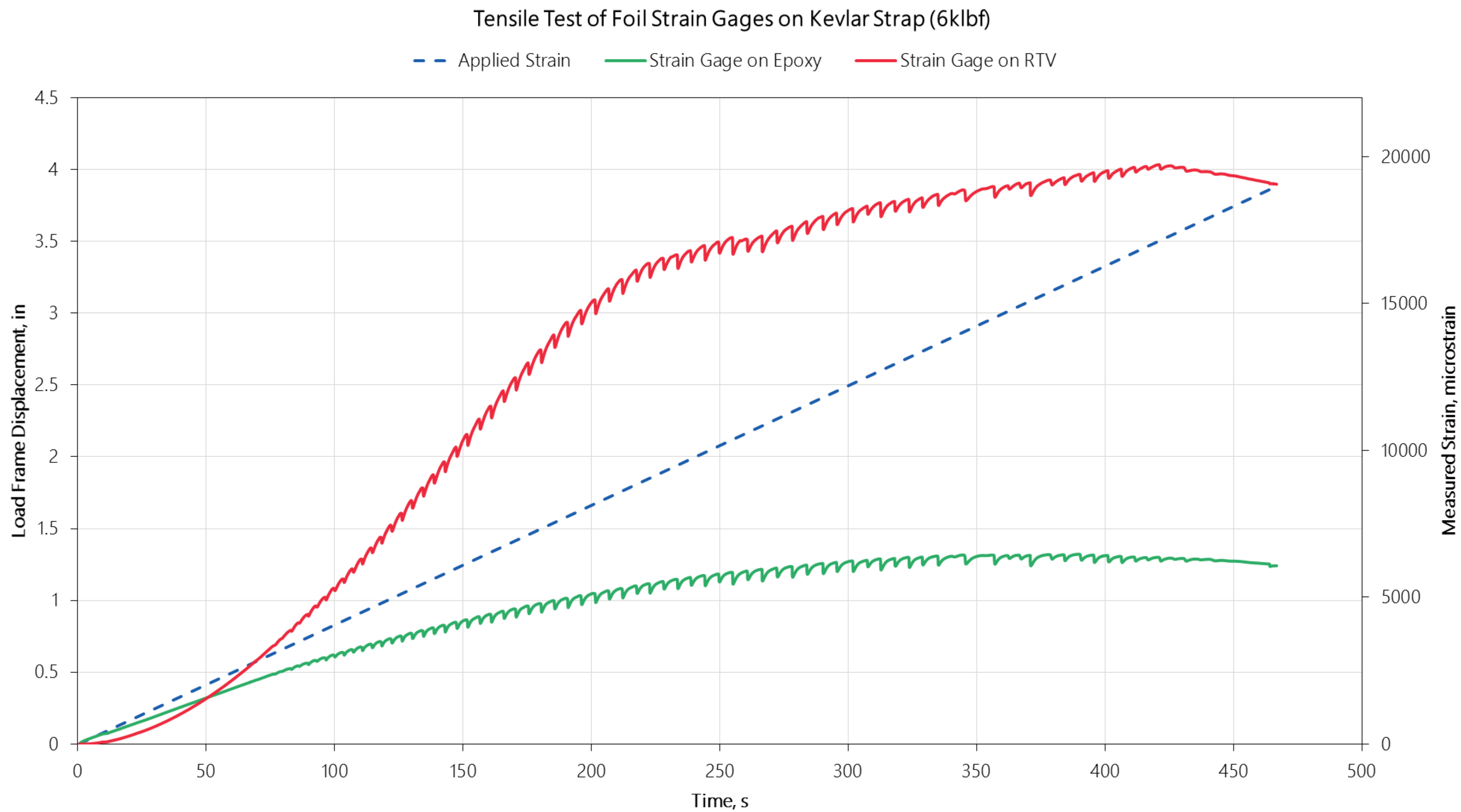
High Elongation Foil Strain Gage

- 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



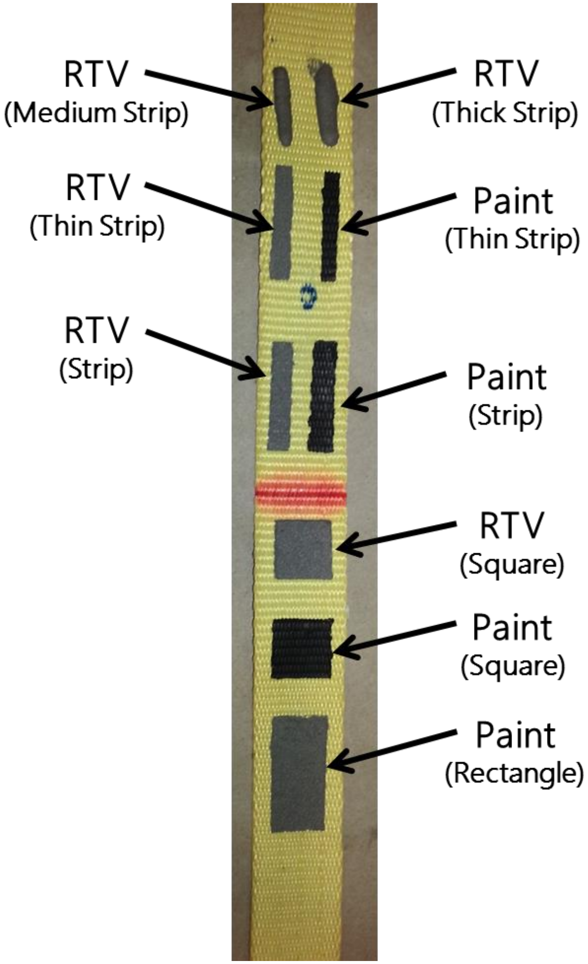
Kevlar Strap with Foil Gages Installed

High Elongation Foil Strain Gage

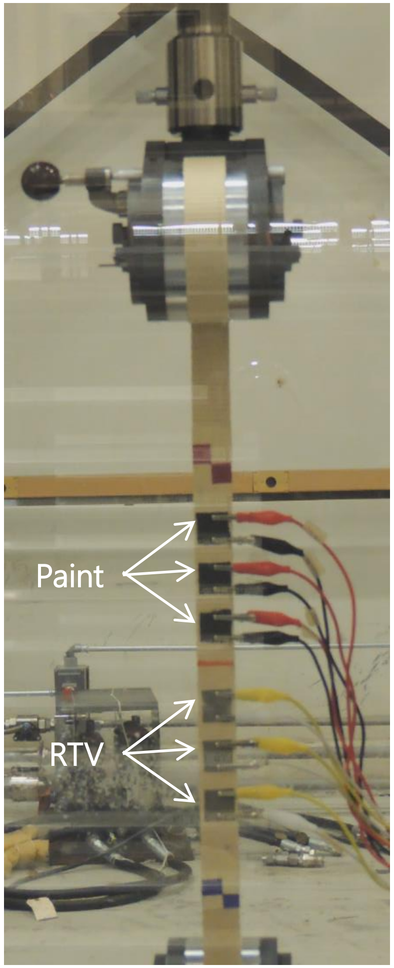


Conductive Paint/RTV

- 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

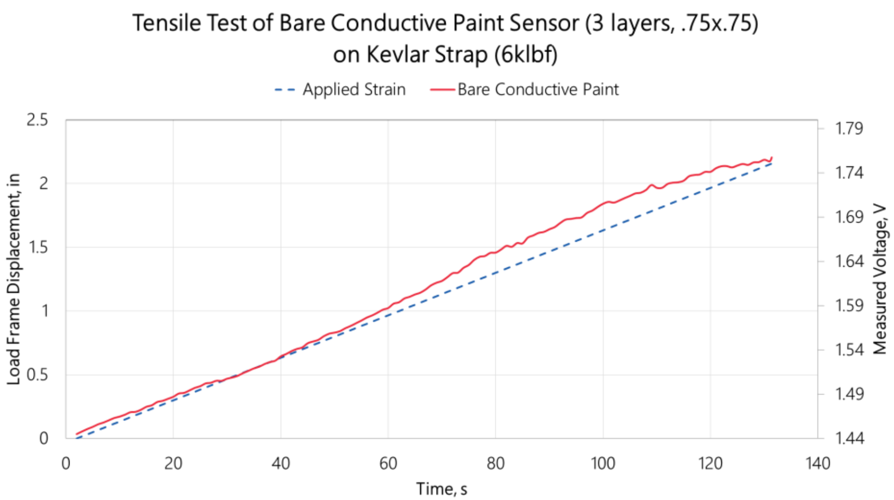


Kevlar Strap with Conductive Paint and RTV Samples

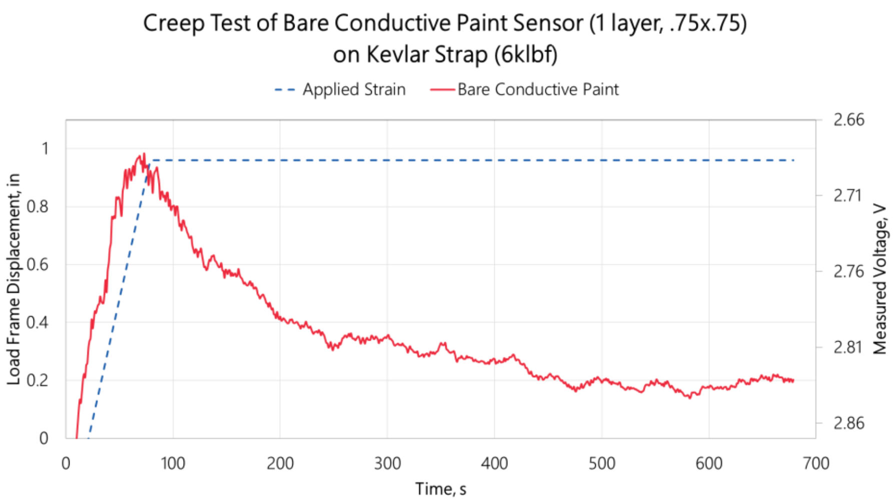


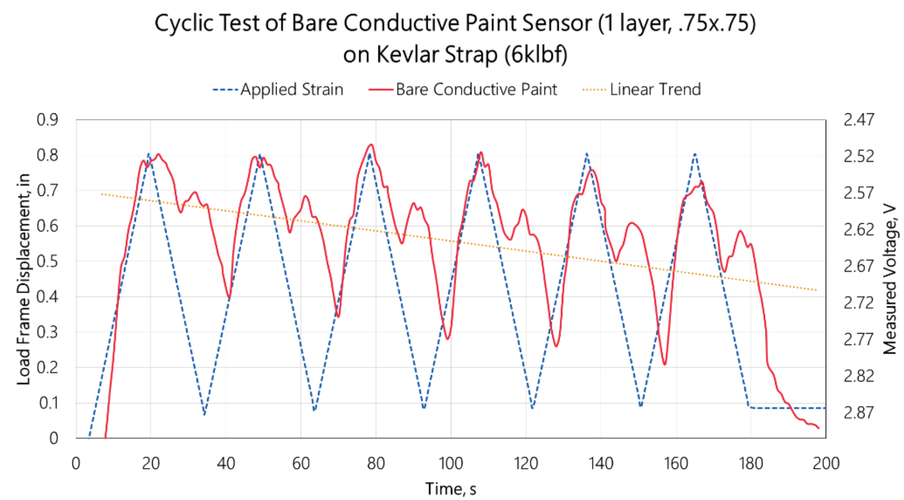
Kevlar Strap with Conductive Paint and RTV Samples

Conductive Paint/RTV



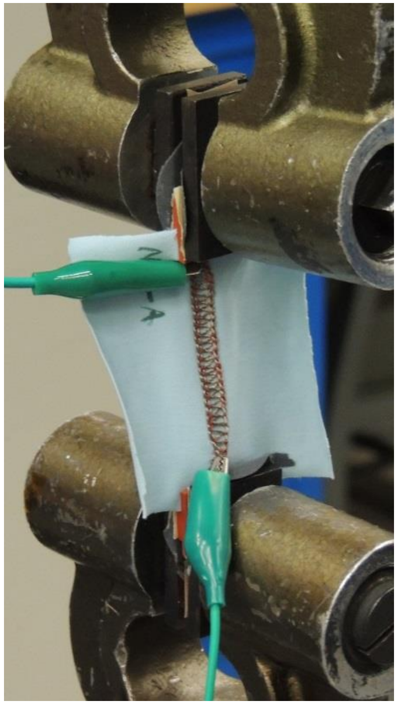
- Tensile testing showed good correlation for both materials
- RTV material exhibited cracking when stretched over 150% initial length, but no cracking was found in the paint material
- Creep testing of both materials showed significant drop in voltage over time
- Cyclic test for both materials showed hysteresis and drop in voltage over time



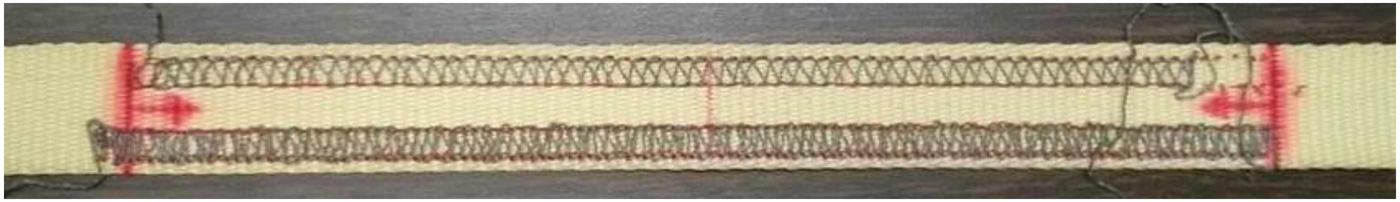


Conductive Thread Coverstitch

- 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

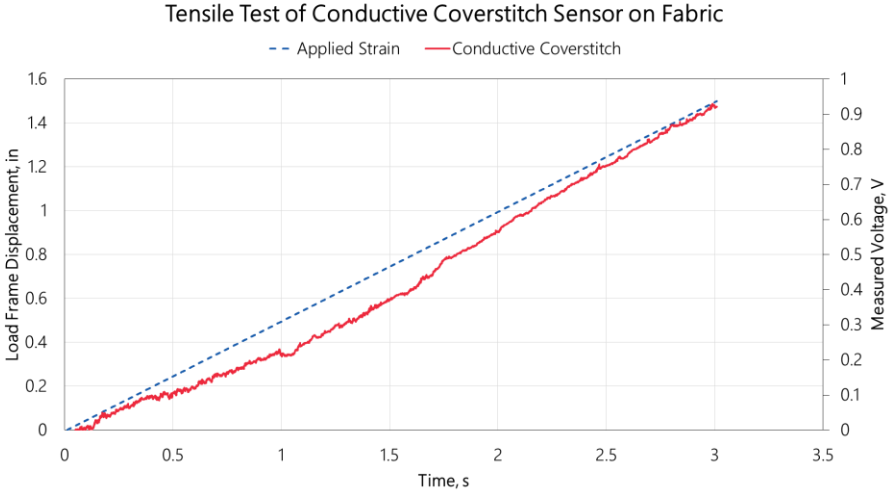


Coverstitch Sensor on Neoprene Fabric

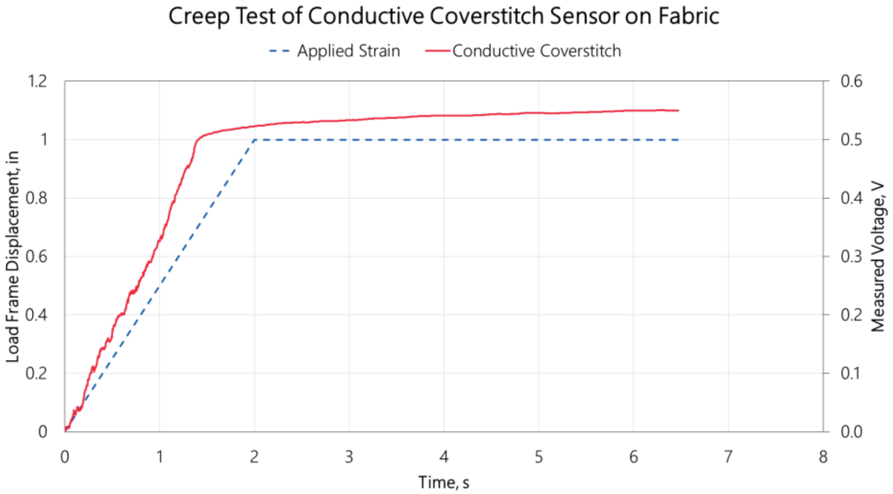


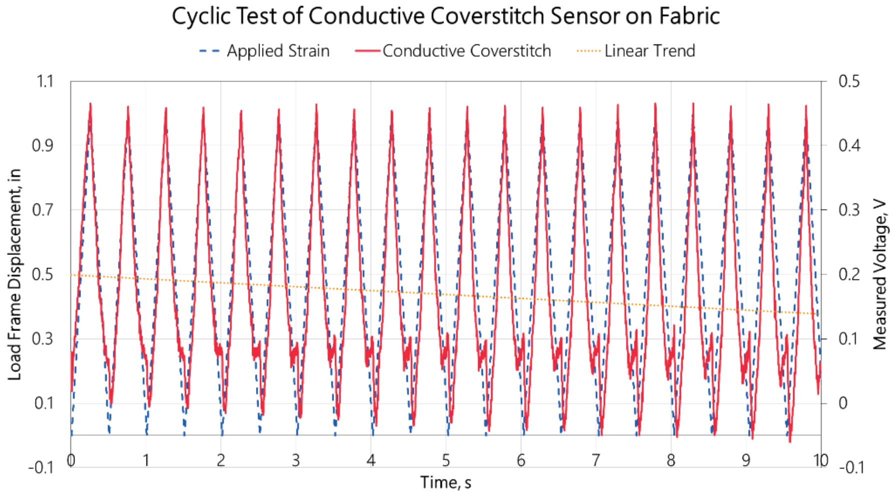
Coverstitch Sensor on Kevlar Strap

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

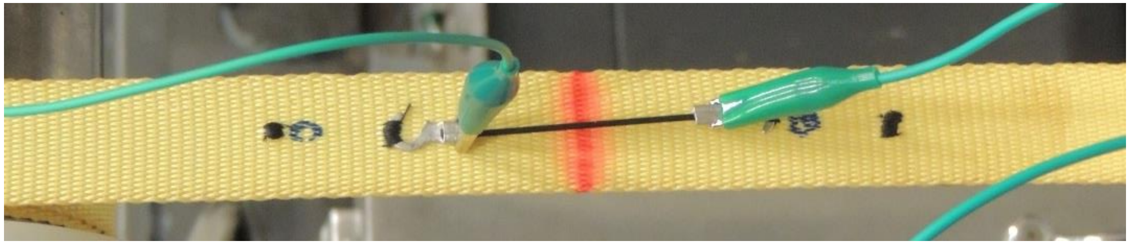




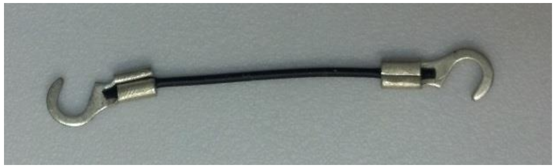
Conductive Polymer Cord

- 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 is can be integrated with a Kevlar strap

Conductive Polymer Cord in Tensile Testing

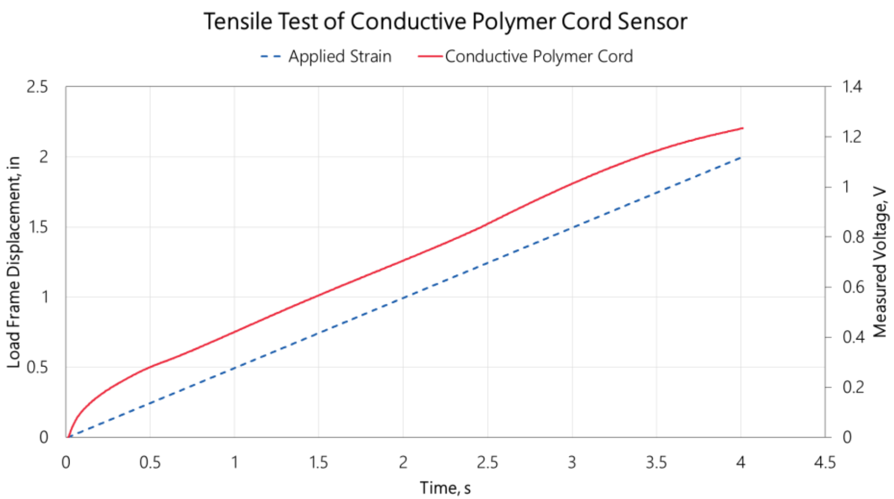


Conductive Polymer Cord Integrated with a Kevlar Strap

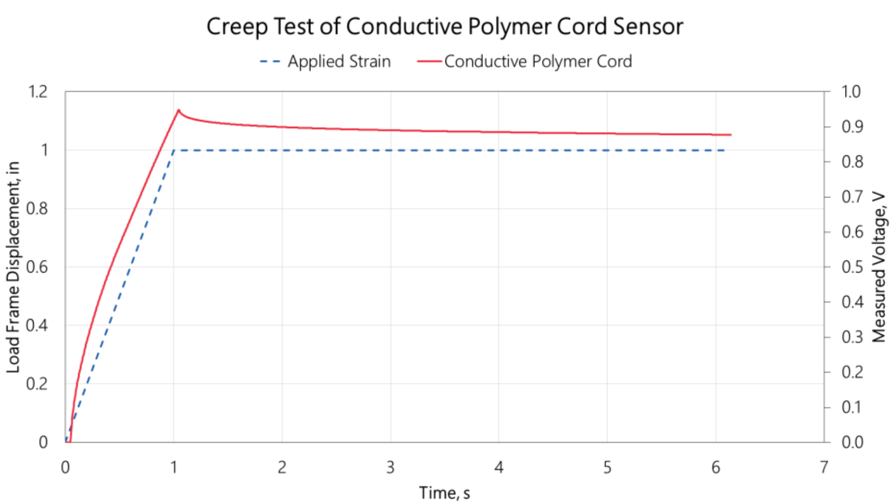


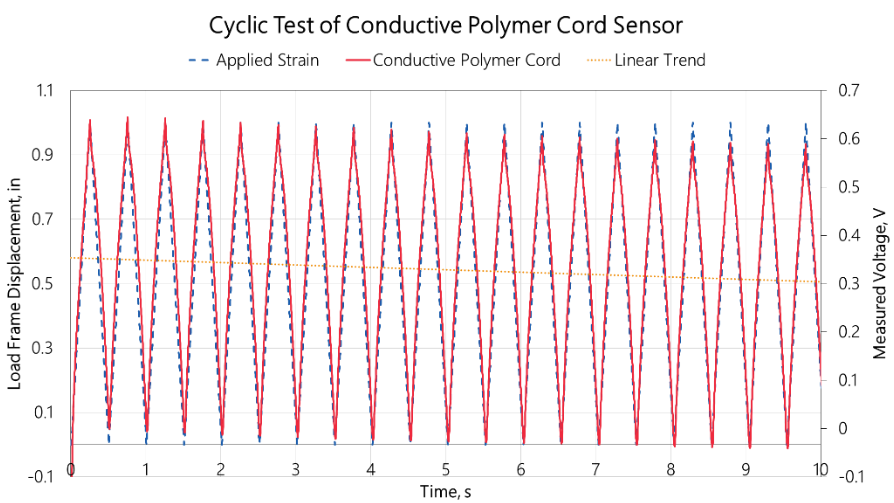
Conductive Polymer Cord Stretch Sensor

Conductive Polymer Cord



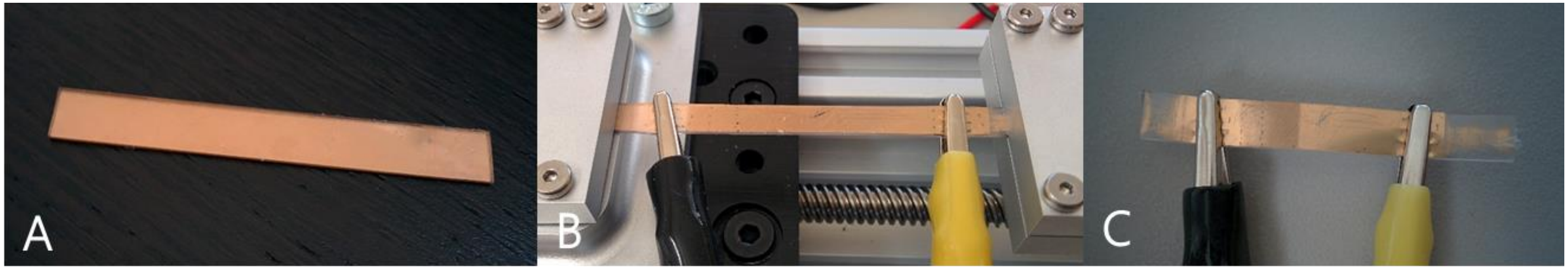
- Tensile test showed good correlation after initial voltage rise
- Creep test showed a drop in voltage over time
- Cyclic test showed a hysteresis drop in voltage over time
- Voltage drop potentially due to polymer chains aligning over time and through multiple cycles





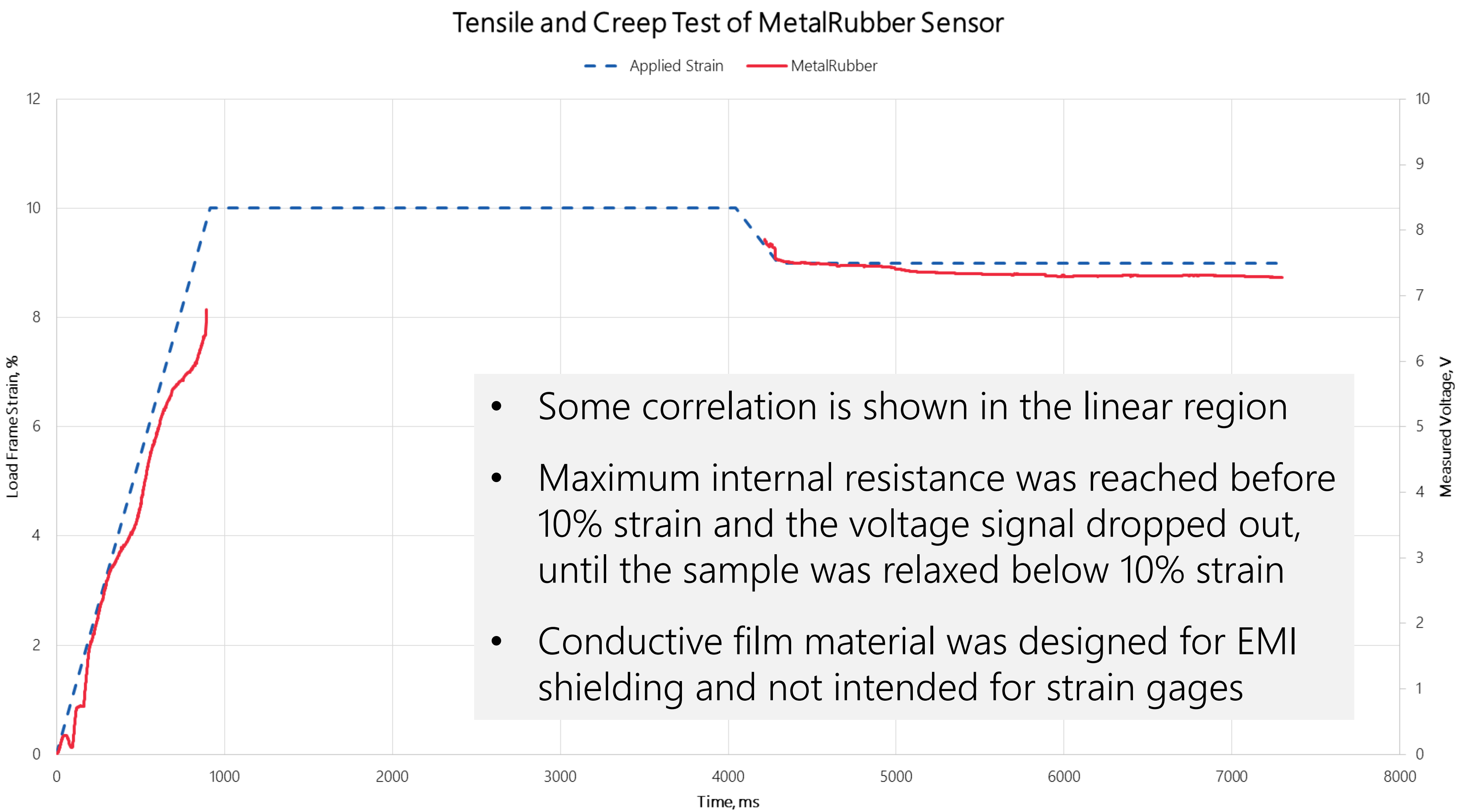
NanoSonic Metal Rubber

- 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



Metal Rubber Test Specimen Shown (A) Before, (B) During, and (C) After Testing Showing Permanent Deformation and Degradation of the Conductive Layer

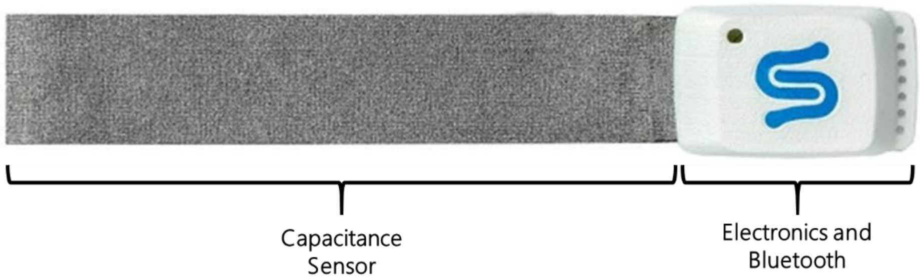
NanoSonic Metal Rubber



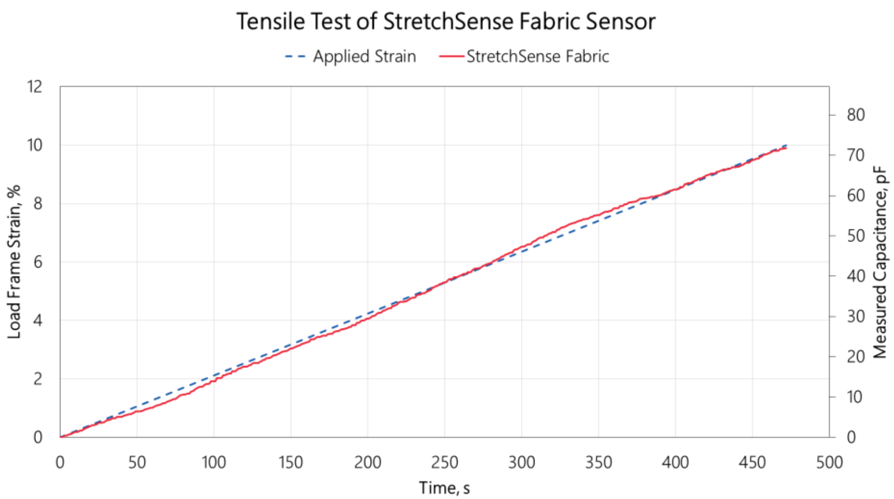
- Some correlation is shown in the linear region
- Maximum internal resistance was reached before 10% strain and the voltage signal dropped out, until the sample was relaxed below 10% strain
- Conductive film material was designed for EMI shielding and not intended for strain gages

StretchSense Fabric Sensor

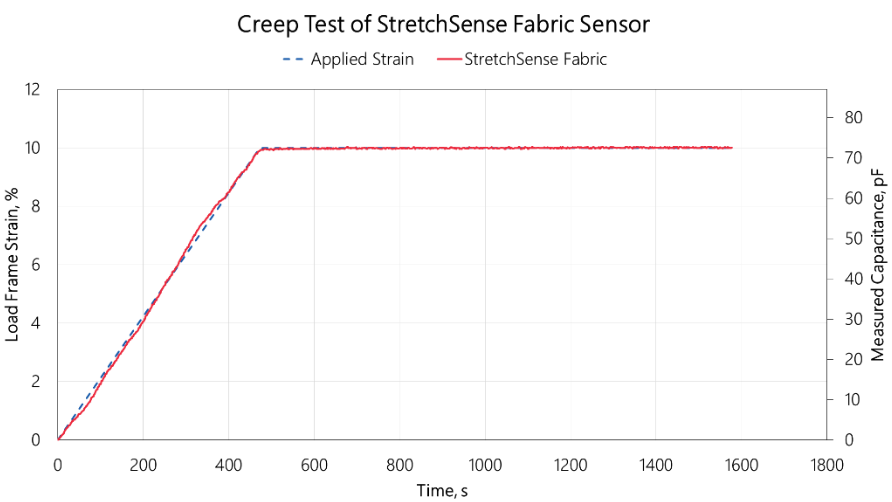
- Gage: Highly sensitive capacitance based stretch sensor commercially available with Bluetooth data acquisition system
- Sensor portion of the sample is made of flexible Neoprene and can be sewn directly onto the surface of a strap or broadcloth
- Testing was completed by installing the device into 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)

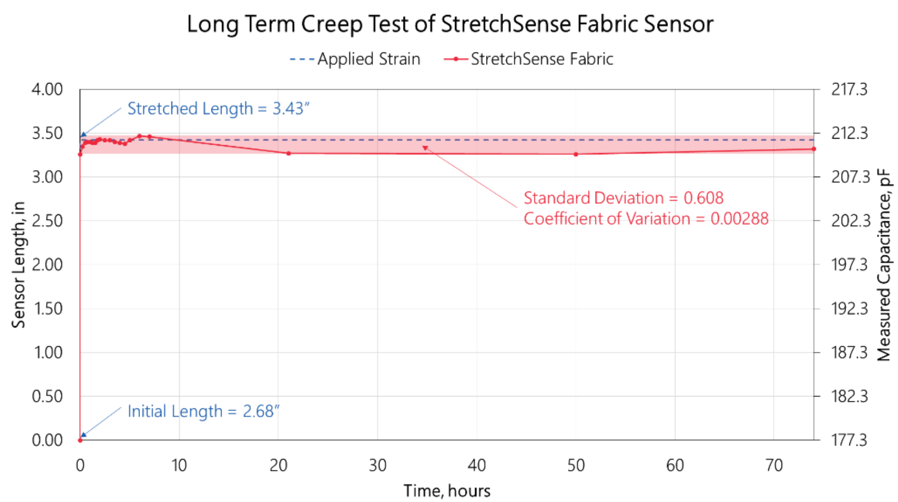


StretchSense Fabric Sensor



- 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

	High Elongation Foil Strain Gage	Conductive Paint/RTV	Conductive Thread Coverstitch	Conductive Polymer Cord	NanoSonic Metal Rubber	StretchSense Fabric Sensor
Electronics	Resistive	Resistive	Resistive	Resistive	Resistive	Capacitive
Installation Method	Adhere to surface using resin/adhesive	Paint directly onto surface	Stitch directly into substrate	Adhere to surface	Adhere to surface	Adhere to surface
Tensile Performance	Poor linear trend due to adhesive methods used	Good linear trend with some noise	Good linear trend with a lot of noise	Great linear trend with very little noise	Good linear trend up to material limit	Excellent linear trend with little noise
Creep Performance	N/A	Severe hysteresis	Slight hysteresis	Slight hysteresis	Slight hysteresis	No hysteresis
Cyclic Performance	N/A	Severe hysteresis	Slight hysteresis	Slight hysteresis	N/A	N/A
Continued Evaluation?	Yes	No	No	No	No	Yes

- 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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