National Aeronautics and Space Administration

Exploration of Thermal Isolation Potential in 3D Printed Tensegrity Structures

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Objective

Produce a tested flight-like thermal isolation solution by: 1) Print and assemble our design and determine analytical structural and thermal response. 2) Quantify the thermal isolation and vibe responses to calibrate theoretical analysis to practical applications.

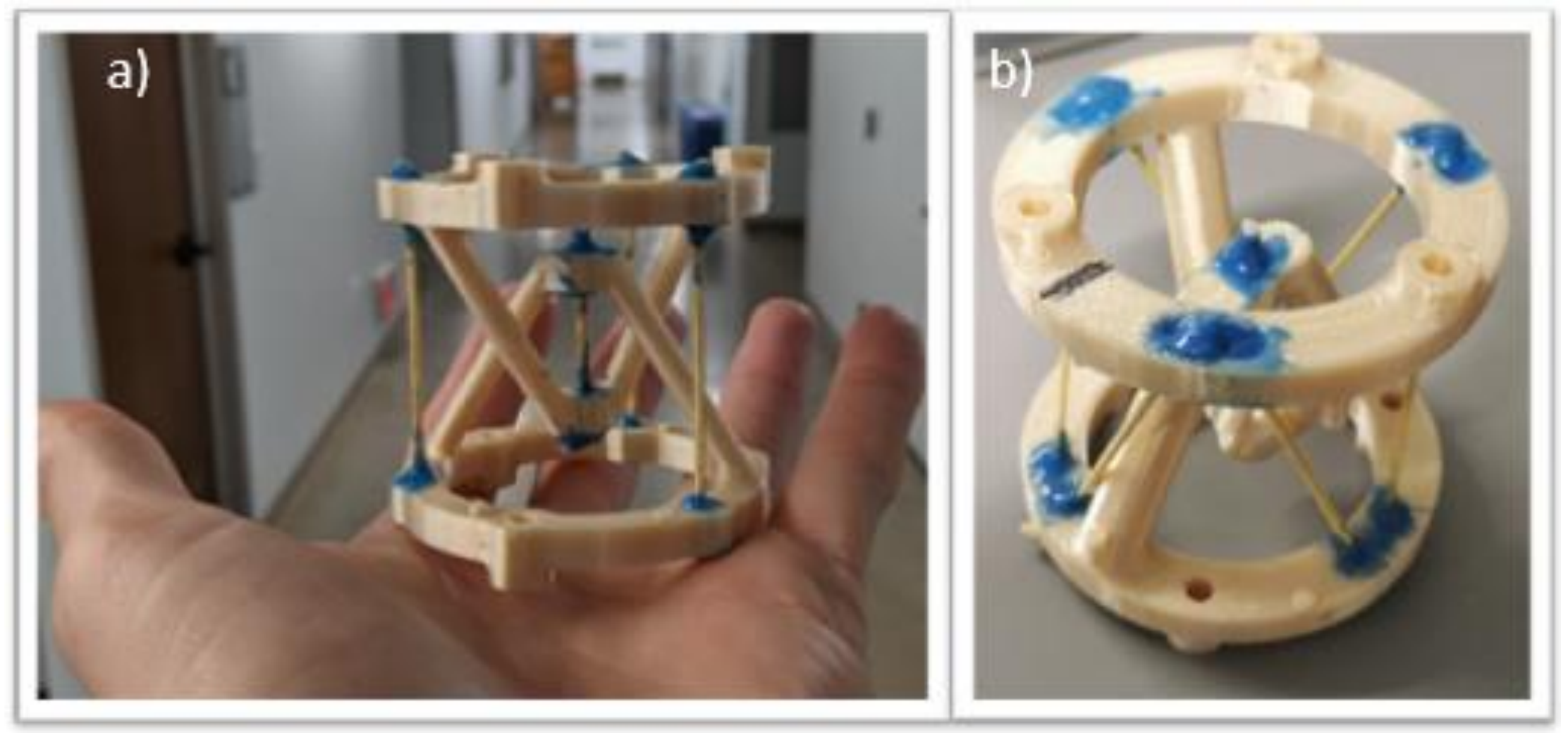

Figure 1. Finished Ultem Thermal Tensegrity structure: a three vertical outside Kevlar lines prototype, b) second iteration, diagonal Kevlar outside, thicker supports to hold more tension.

Background

Thermal isolation within flight systems often have tight tolerances and are expensive, massive, and complicated. **A promising path to reduce mass and complexity is the application of tensegrity principles to thermal isolation systems.** Tensegrity designs rely on discontinuous sets of lightweight tensile elements, achieving minimal conductance paths. Recent work by co-PI Daraio has shown that tensegrity systems have excellent structural properties [1-3] and can be 3D printed using readily available commercial printers with a sub-millimeter resolution [4-5]. 3-D printing capabilities enable complex integrated structures that can be inexpensive, and made using Flight approved materials such as Ultem. Combining these capabilities allows for tensegrity inspired thermal isolation structures printed with Ultem and tensioned with Kevlar threads at 20x decrease in component density. These solutions also have terrestrial applications where thermal stability and isolation is of the utmost importance, e.g., isolation in cryogenic systems. It is an open question whether these novel structures can meet both stiffness requirements to pass a flight vibe test while also meeting thermal isolation requirements.

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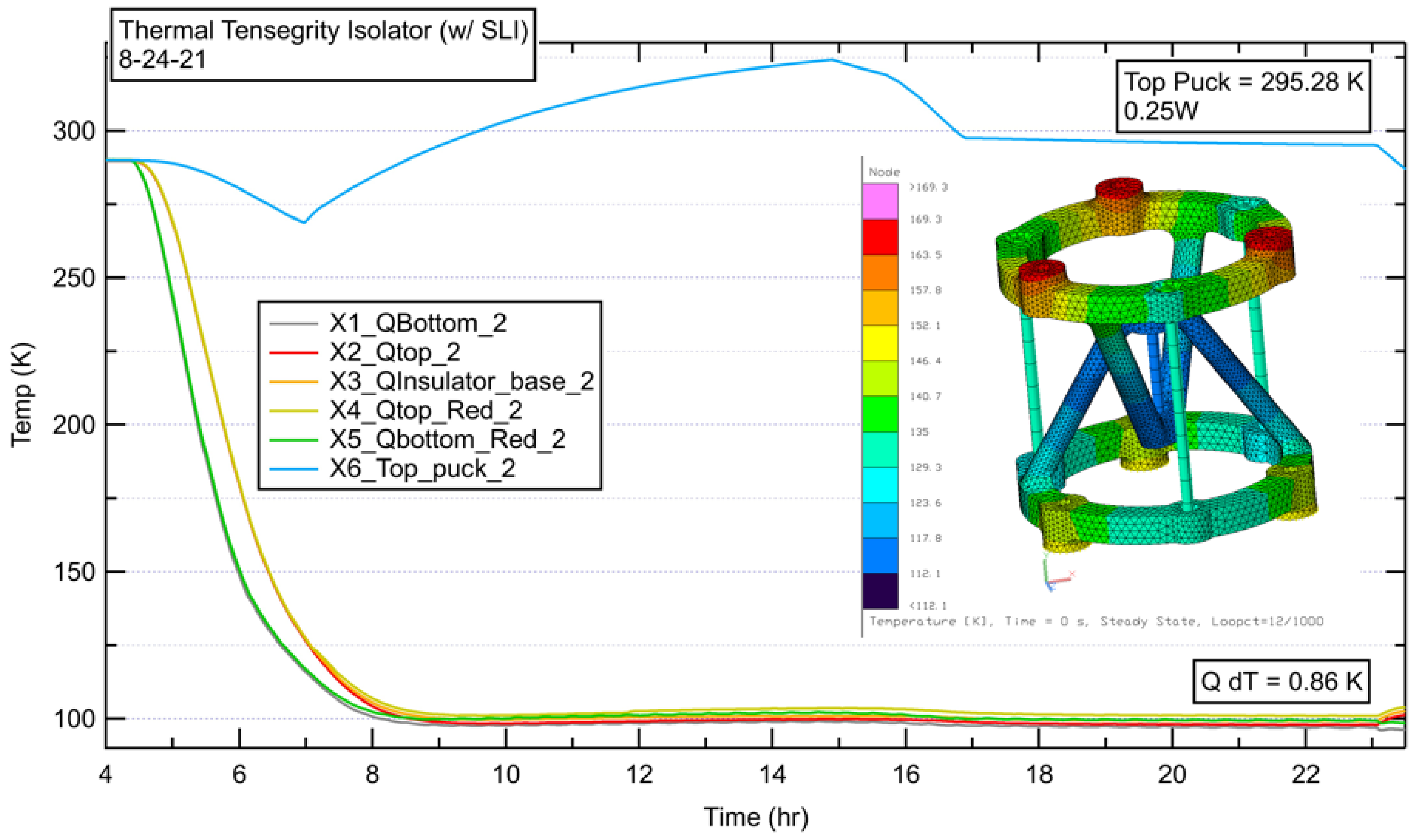

Figure 2. Thermal Results from a thermal vacuum test with a delta temperature of ~200 K with 0.25W of heating.

Approach and Result

For 1) we initially printed six of the first design through the JPL print shop and tensioned two to 10kg each, one of which was used for our thermal testing (Figure 1a). To fabricate it, we knot and string Kevlar through the outer holes and hang an equal mass on each, then apply epoxy EA 9360 where the Kevlar meets the 3d printed Ultem. The 3d printed supports and the identical hanging masses keep a uniform separation between the top and bottom pieces. Once the epoxy cures, we knot and string Kevlar through the center portion while removing the 3d printed supports. Then we apply a known mass that will tension the entire isolator and apply epoxy to the center connection points. To identify the maximum force that this isolator design could handle, we took one print and crushed each side separately in an Instron (Figure 3). This gave us an upper limit of around 60kg (~125lbf), which we used to tension the rest of the isolators to 15kg, 20kg, 30kg, 40kg for comparative structural laser vibrometer resonance tests. Using the crush test results, we redesigned the isolator to strengthen certain components. Additionally, for the redesign we created an offset feature of the outer Kevlar lines that decreased any lateral or rotational motion and stiffened the structure substantially. This also simplified the fabrication process by removing the requirement for pre-tensioning those lines. We have additional design iterations that will be printed by the JPL print shop and fabricated at Caltech (Figure 4). PI-Daraio's group at Caltech is working on an analytical model of the design for these structures and Co-I Anderson performed thermal analysis on the existing design. For 2), PI Stone lead a series of thermal conductivity tests at JPL, using a pre-existing thermal chamber setup (Figure 2). The final test incorporated a single layer insulation around the separate sides of the isolator. When we ran the test to calculate the thermal conductivity we discovered that this design exceeded our expectations and pushed the limits of what the test setup could measure. We were able to maintain a temperature differential across the isolator of **~200 K with only 0.25W** of power on the hot side (Figure 2). The resultant G value from our tests resulted in **0.0052 W/K** which matches qualitatively with the thermal model from Co-I Anderson of 0.00114 W/K, when including test effects. An idealized theoretical value of 0.00058 W/K could potentially be achieved by adding aluminized Kapton tape around the Ultem parts to decrease emissivity. The Caltech team performed elastic vibration tests using a laser vibrometer to characterize the modal response of the system for the various tension samples, which they are still analyzing. All these results justify starting the process of writing a research paper that will be submitted to Proceedings of National Academy of Science or International Journal of Solid and Structures.

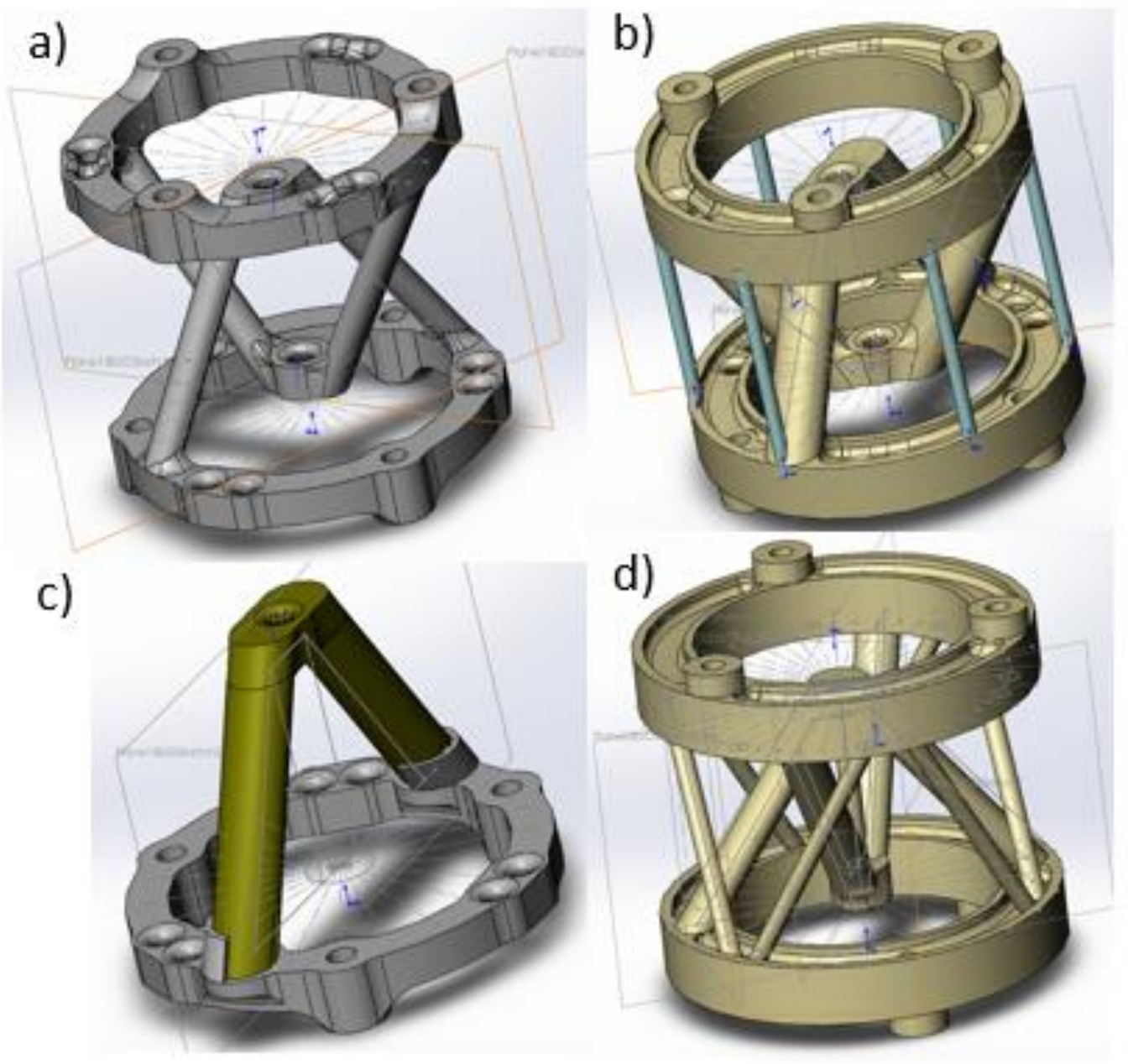

Figure 4. Upcoming models: a) Titanium/Aluminum design, b) Reinforced Ultem design, c) Hybrid Titanium/Ultem d) Full Ultem design with no Kevlar.

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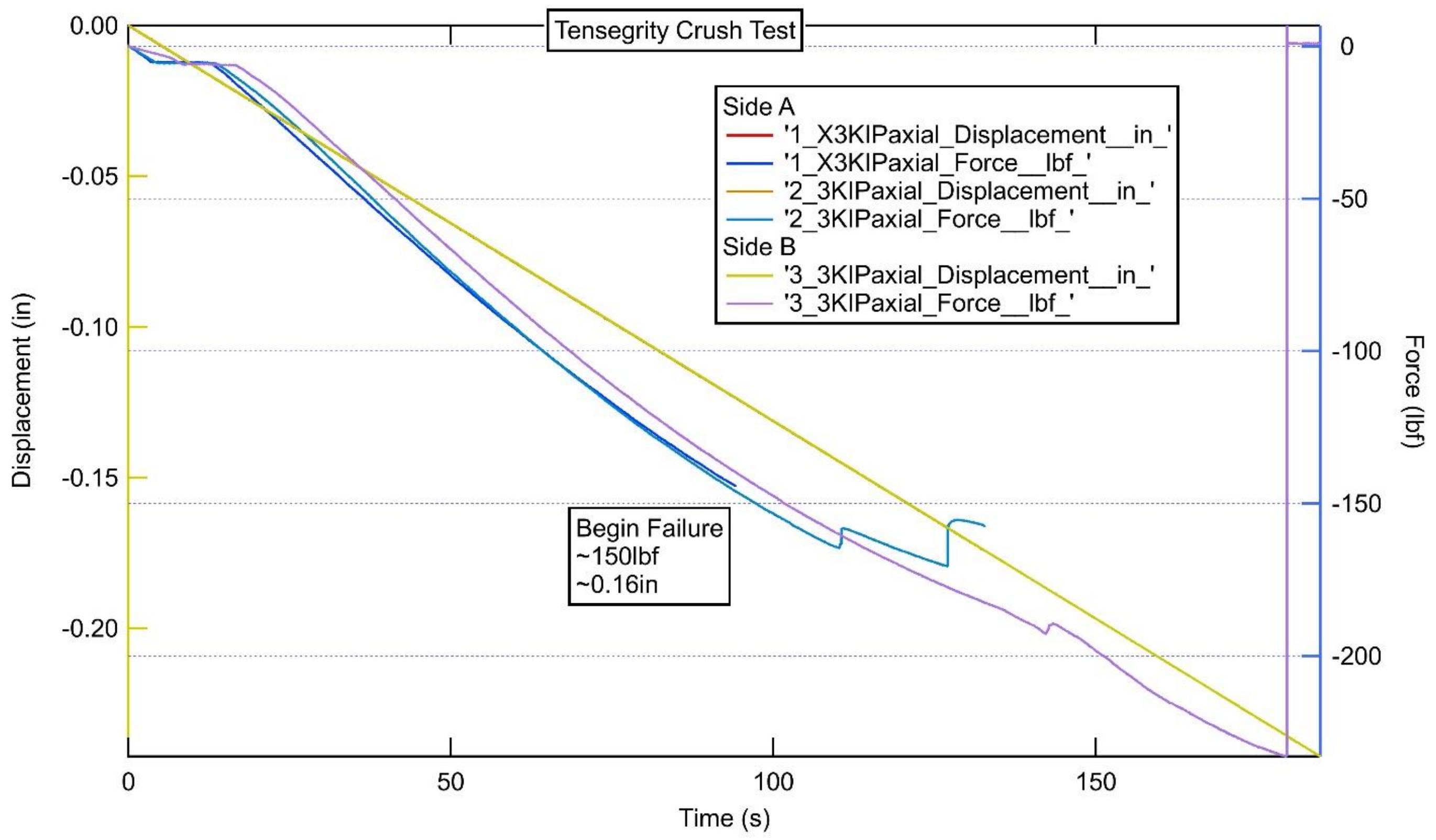

Figure 3. Graph of crush results – Max Load before deformation of one side of the triangle supports, ~125-150lbf at ~-0.16in), used to identify max load of first prototype.

Significance/Benefits to JPL and NASA

We reached our stated objectives of developing an inexpensive 3d printed tensegrity-inspired thermal isolation structure that is a viable contender for lunar lander thermal isolation applications, including potentially as a replacement for the thermal isolators slated for PALETTE. A lunar lander requires the utmost isolation to maintain internal temperatures during lunar night, and these new isolators are competitive with traditional alternatives at a fraction of the cost. With access to a vibe table we would be able to identify if this design could pass the launch vibe test with an applicable mass. Since the design is modular and its dimensions can be adjusted easily, it is also appropriate for a variety of NASA missions including terrestrial cryogenic systems that require high thermal isolation in their structural supports. We will use the data gathered to apply for a full RTD at the next opportunity to continue our collaboration between JPL and Caltech, further developing these highly effective, reproducible, and cost-effective thermal isolation structures.

Figure 5. Final step in Tensioning one of the initial Thermal Tensegrity designs with 30kg while applying epoxy.

References

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