Damage Tolerance Testing of a NASA TransHab Derivative Woven Inflatable Module

John Edgecombe[1], Horacio de la Fuente[2], and Gerard Valle[3]
NASA Johnson Space Center, Houston, TX, 77058

Current options for Lunar habitat architecture include inflatable habitats and airlocks. Inflatable structures can have mass and volume advantages over conventional structures. However, inflatable structures carry different inherent risks and are at a lower Technical Readiness Level (TRL) than more conventional metallic structures. One of the risks associated with inflatable structures is in understanding the tolerance to induced damage. The Damage Tolerance Test (DTT) is designed to study the structural integrity of an expandable structure.

TransHab (Figure 1) was an experimental inflatable module developed at the NASA/Johnson Space Center in the 1990's. The TransHab design was originally envisioned for use in Mars Transits but was also studied as a potential habitat for the International Space Station (ISS).

The design of the TransHab module was based on a woven design using an Aramid fabric. Testing of this design demonstrated a high level of predictability and repeatability with analytical predictions of stresses and deflections. Based on JSC's experience with the design and analysis of woven inflatable structures, the Damage Tolerance Test article was designed and fabricated using a woven design. The DTT article was inflated to 45 psig, representing 25% of the ultimate burst pressure, and one of the one-inch wide longitudinal structural members was severed by initiating a Linear Shaped Charge (LSC). Strain gage measurements, at the interface between the expandable elements (straps) and the non-expandable metallic elements for pre-selected longitudinal straps, were taken throughout pressurization of the module and strap separation. Strain gage measurements show no change in longitudinal strap loading at the bulkhead interface after strap separation indicating loads in the restraint layer were re-distributed local to the damaged area due to the effects of friction under high internal pressure loading. The test completed all primary objectives with better than expected results. This paper will discuss space inflatable structures, damage tolerance analysis, test results, and applicability to the Lunar architecture.

[1] JSC Expandable Structures Lead Analyst.
[2] TransHab Chief Engineer/ Expandable Structures Advisor.
[3] ETDP Expandable Structures Co-Lead, Project Manager, AIAA Member.

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Figure 1: NASA TransHab- Structural Restraint Layer with Internal Bladder

1. Introduction

a. Test objectives

The objectives of the DTT are to validate assumptions related to (1) the structural integrity of the assembled and pressurized structure when a section of the structural restraint layer is cut by a foreign object, and (2) the load distribution of the structural restraint layer during pressurization, as well as before and after the structural restraint layer is severed. For this test, a longitudinal structural restraint strap will be severed using a linear shape charge. The linear shape charge was designed specifically for this application to cut only a single longitudinal strap, while not damaging the bladder.

b. Pre-test Assumptions

(1) The JSC Expandable Structure team believed that when a structural member of the woven design, loaded to 25% of the burst pressure was severed, the load would redistribute to the adjacent structural members and the global structural integrity of the structure would be preserved. Demonstrating this fail-safe behavior was the primary purpose of this test.
(2) It was expected that in the short time following severing of the structural member, some dynamic load amplification would be evident in the adjacent straps as the load was redistributed. It was not clear to what extent the load would be temporarily amplified in the adjacent straps although it was believed that friction in the woven design would dampen the load amplification.
(3) Experience gained during testing of TransHab structural units demonstrated difficulty in achieving good correlation between analytical predictions and measurements of load at the interface between the restraint layer and polar bulkhead. Understanding this performance was a secondary objective of the Damage Tolerance Test.

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2. DTT Article Design Details

a. Overall Design

The Damage Tolerance Test Article consists of a load bearing restraint layer, a bladder or gas barrier, and a structural metallic core. The test article restraint layer is fabricated from one inch wide Kevlar webbing that is woven in a basket weave pattern. Underneath the structural restraint layer is the bladder or gas barrier. For this test the bladder was required to maintain pressure for testing only and was not representative of a flight design. The bladder and structural restraint layer attach to the structural core of the module at steel bulkheads at each end. The two bulkheads are separated by a 10 foot center tube which provides the structural support for the module when in a non-inflated state as well as resists a portion of the axial load when pressurized. The longitudinal members of the structural restraint layer are attached to the bulkheads using a series of clevises that are bolted to the bulkheads. Strain gages are placed on the clevises that can measure change in load when the structural restraint is inflated. The test module is 88 inches in diameter and 120 inches in height, and consists of a cylindrical section 78 inches in height, and two partial toroidal sections which transition the cylindrical region to the polar bulkheads.

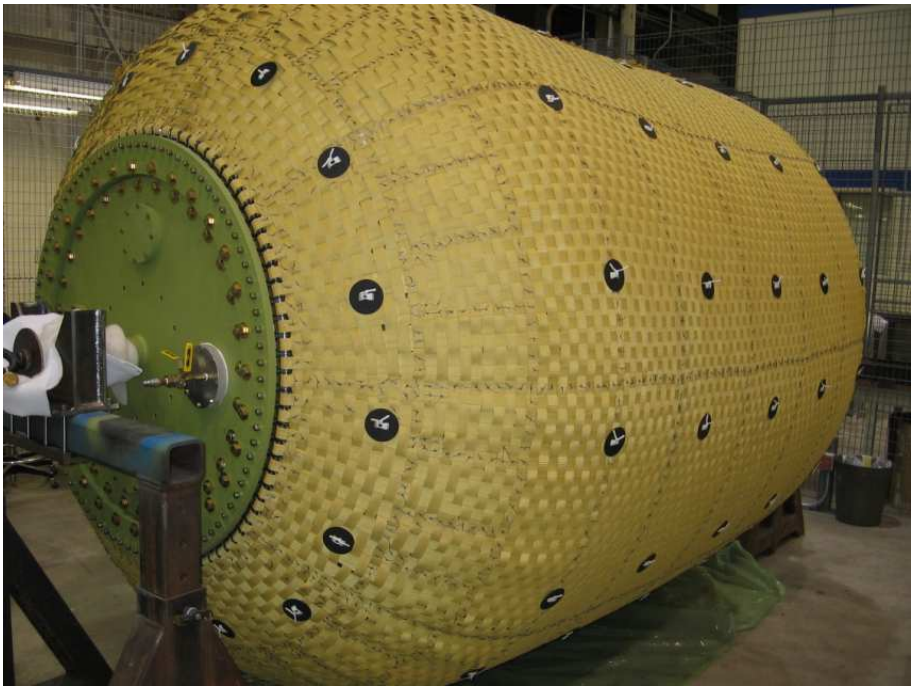

Figure 2: Damage Tolerance Test (DTT) Article

b. Weave

The 1" wide Kevlar straps are woven together in an over-under style basket weave pattern which provides locational restraint for the straps. Additional overall dimensional stability is achieved by the use of hand stitched indexes where the hoop and longitudinal straps are attached to help eliminate excess bunching of the straps during inflation. In the cylindrical section of the module, the longitudinal straps run parallel to one another with a gap of approximately 0.5" between straps. As shown in Figure 3 below, as the 120 longitudinal straps pass through the toroidal section, adjacent straps transition from being parallel to overlapping, and are joined at the 90 polar clevises.

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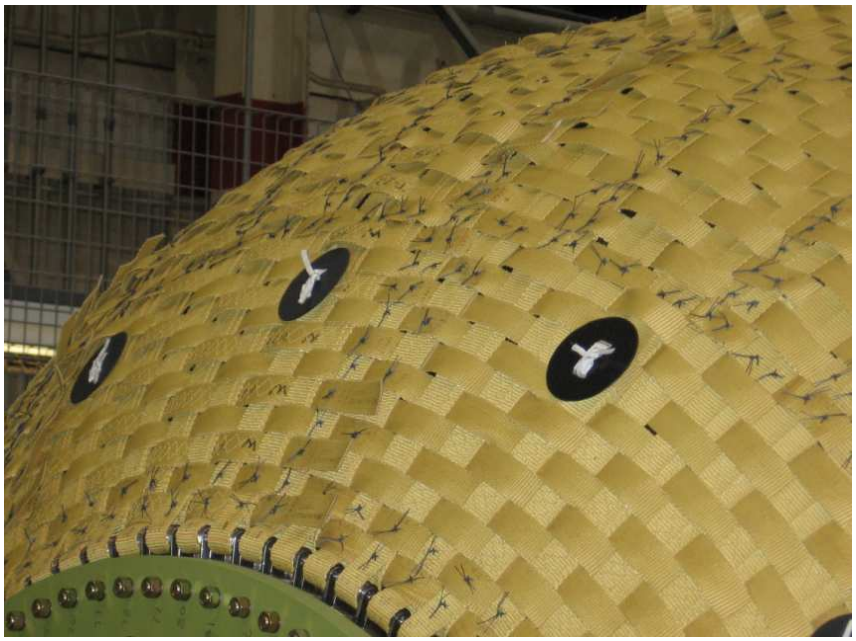

Figure 3: DTT Weave Detail

c. Linear Shape Charge

For the purposes of this test, three linear shape charge assemblies were developed to sever one longitudinal strap, and two hoop straps. The design of the shape charge was such that the bladder was shielded from damage, and the effects of the charge were limited to one strap only. The 20 grains per foot (gpf) Linear Shaped Charge was secured in a Lexan housing and placed on top of the Kevlar webbing to be cut. A metallic protective plate and Kevlar felt was placed between the bladder and Kevlar webbing to be cut. Cords and magnets were used to align the Lexan plate with the webbing and metallic plates. During testing, the LSC was detonated using a firing unit, blasting cap and flexible confined detonating cord (FCDC) line (Figure 4). During testing, only one LSC was initiated as described in the results section.

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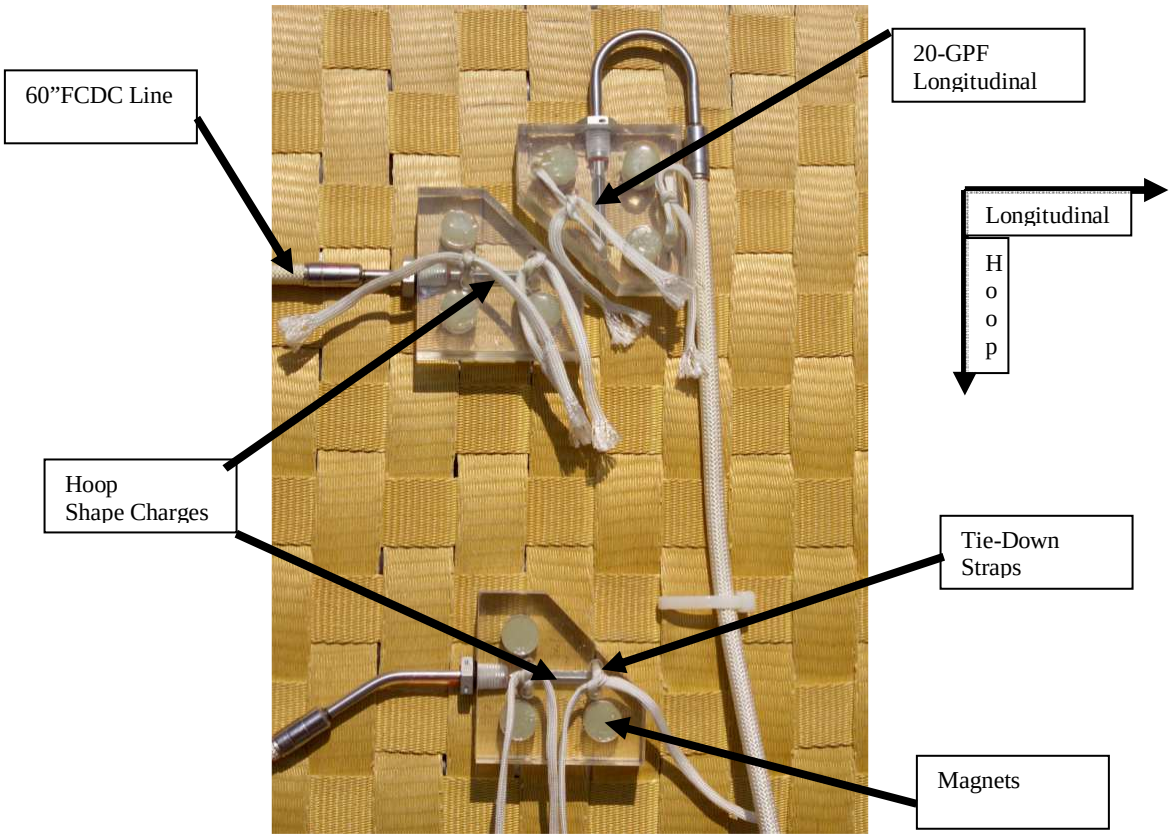

Figure 4: Linear Shape Charge Detail

d. Instrumentation

An array of strain gages are located at the bulkhead mounted clevises where the longitudinal restraint layer straps are attached. In order to capture data during the test, 32 strain gages are attached to the roller/clevis assemblies which attach the longitudinal strap restraints to the polar bulkheads. The gages are arranged as shown below in Figure 5 with 16 gages on each of the two bulkheads, with the majority of the gages arrayed about the site of the induced damage. The gages measure axial strain in the clevis produced by the tension in the longitudinal straps. After installation of each strain gage, calibration was performed to establish the relationship of microstrain to axial clevis load.

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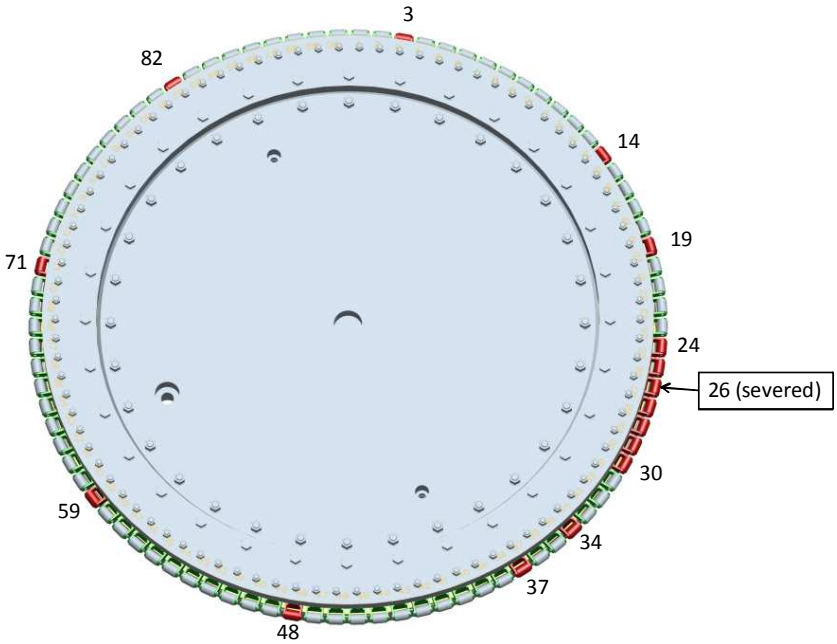

Figure 5: Polar Bulkhead with Clevis Numbering and Strain Gage Locations

e. Design Loads in Straps

Analysis of the test article was performed using a process developed and refined during the TransHab project. The calculation is based upon cylindrical and toroidal membrane theory, but also takes into account such factors as strap spacing or overlap, seam efficiency, and the non-uniform loading of hoop straps in the toroidal section.

The test pressure was defined as 45 psig (25% of the predicted burst pressure). Calculations predict each of the 240 longitudinal straps to be at a tension of 1122 lbs in the cylindrical region, and the hoop straps to be at a tension of 2063 lbs. At the polar bulkheads, the load at each clevis is predicted to be 1520 lbs.

2. Test Details

The damage tolerance test was performed at NASA's White Sands Test Facility (WSTF) due to the high stored energy of the test article. Test plans called for the module to be inflated to the test pressure of 45 psi, with several predefined intermediate hold periods at 10 and 22 psig. The intermediate holds were implemented to allow additional data recovery for comparison to calculated predictions of load, and also to allow inspection of the test article. Strain gage and pressure data was collected at 1Hz intervals throughout initial pressurization of the test article including holds at 10, 22 and 45 psig. Upon pressurization to 45 psig, data was collected at a rate of 1 kHz for a period of time starting 2.5 seconds before initiating the linear shape charge and ending 2.5 seconds after.

3. Test Results

a. Results after cutting strap

The figure below shows the strain gage output for the 5 second period surrounding the strap cutting event which occurs at 27.5 seconds. No measurable change in strap load was measured at any of the instrumented clevis locations. Figure 6 below shows the output for gages 1 thru 8, where gage number 4 is attached to the longitudinal strap number 26 which was cut. All 32 strain gages displayed similar data to that presented below.

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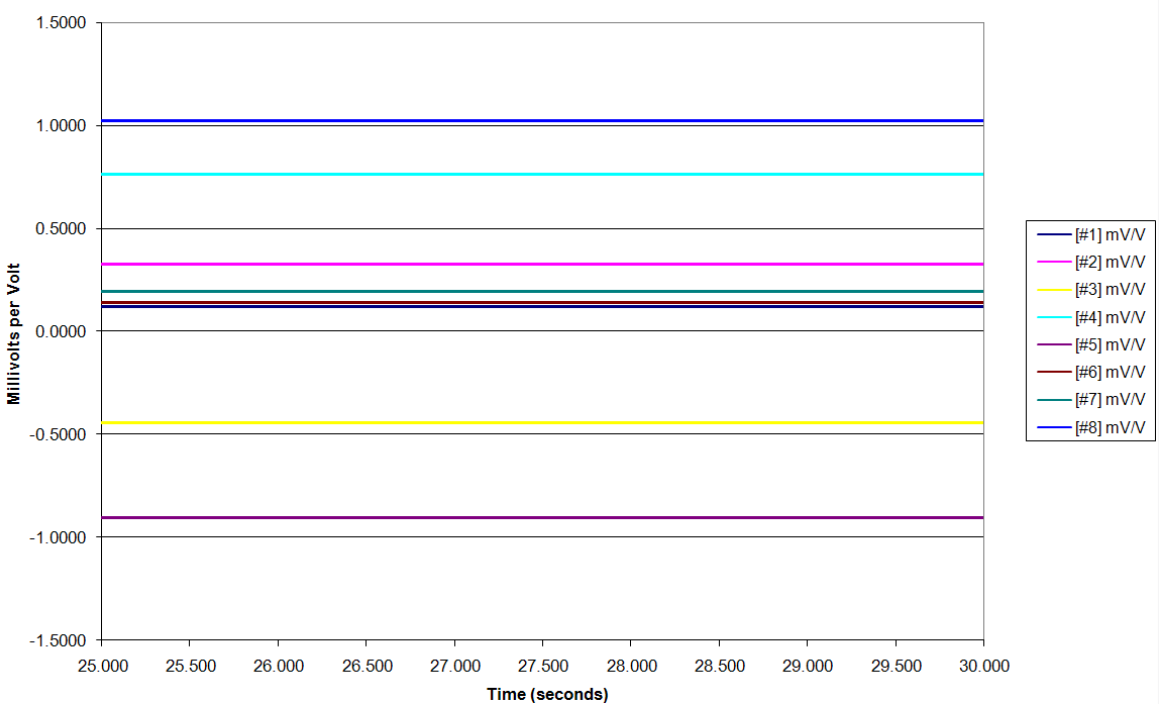

Figure 6: Strain Gage Output Enveloping Strap Cutting Event

The series of photographs shown in Figure 7a through 7c show the test article immediately before and after cutting of the longitudinal strap. Figure 7a shows the configuration of the test article just prior to the strap cutting event. The figure also identifies areas of interest for the subsequent post-cut configurations in figures 7b and 7c.

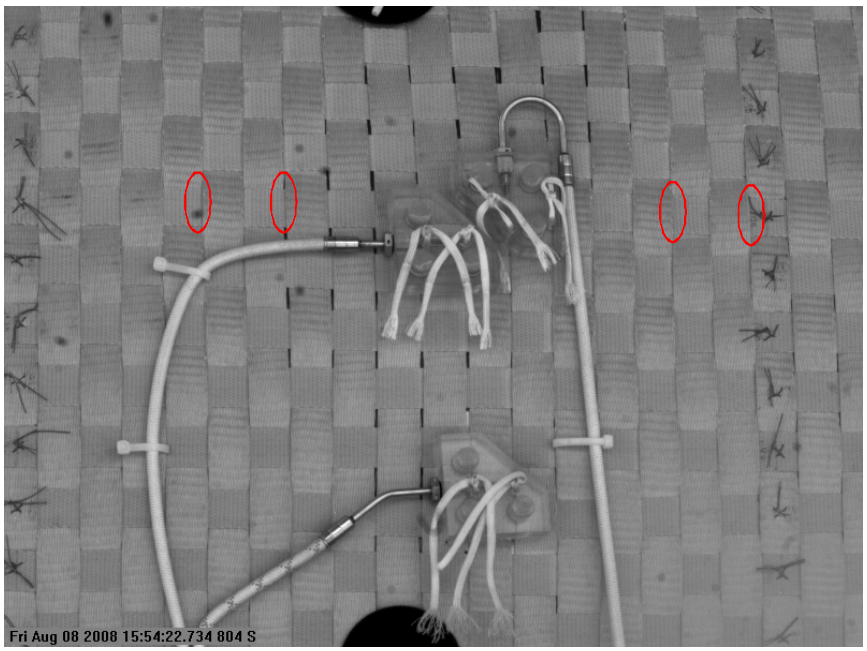

Figure7a: Test Article just prior to severance of an longitudinal strap (highlighted regions identify areas of interest in figures 7b and 7c)

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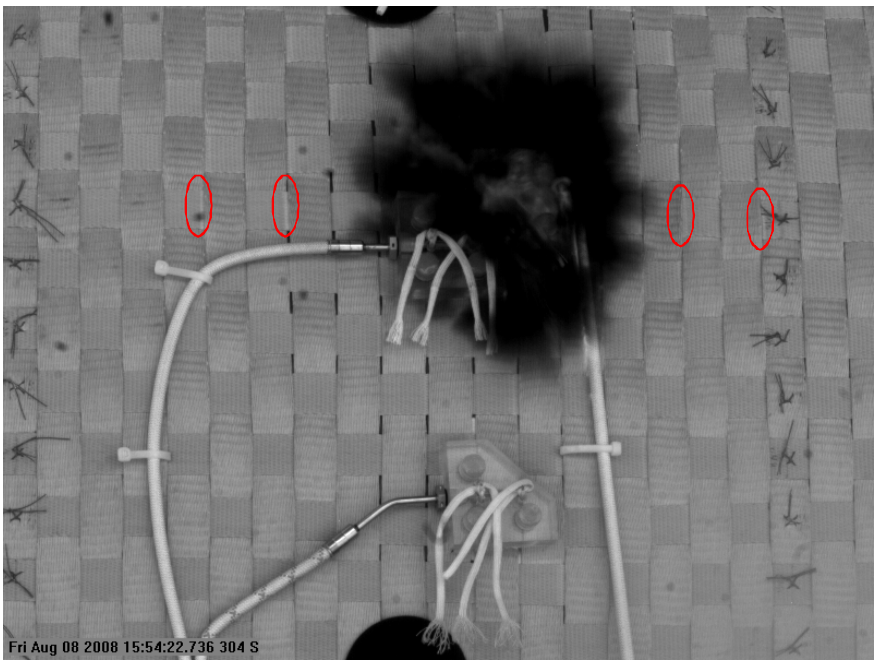

Figure 7b. Test Article Configuration immediately after the longitudinal strap is severed.

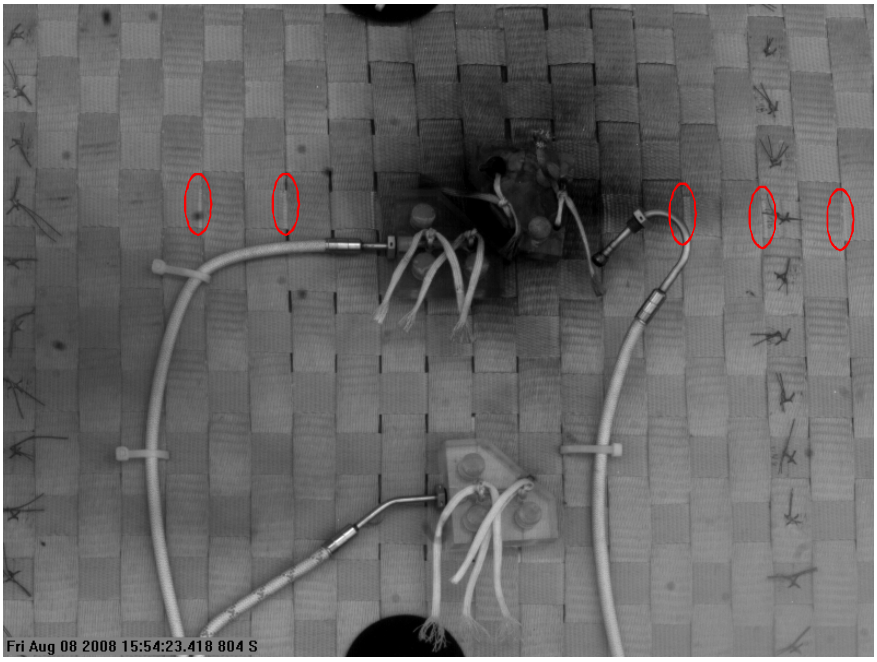

Figure 7c. Test Article Configuration after the longitudinal strap is severed.

Because the test was conducted outside in sunlight, the restraint layer straps were discolored due to UV exposure. However, due to the weave construction, the portion of the strap hidden by an overlapping strap was protected from sun exposure. This provided a natural indicator of the strap movement before and after the strap cutting event. As shown in Figures 7b and 7c, the cut strap has displaced away from the location of the cut (in the direction of the applied tension) and this displacement appears to be proportional to its proximity to the location of the cut.

It is worthwhile to note that there was no macroscopic observable behavior (deflection, vibration, etc) during the cutting of the longitudinal strap. In fact, a close inspection of the test article was required to confirm that the strap

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was indeed severed by the shape charge. In addition, it is important to note that strain gage measurements taken at each end of the cut strap did not show any measurable decrease in load after the strap was severed. After the strap was cut it was still carrying its full pre-cut load! This was an unexpected result. As the photos show, the frictional shear forces between the straps prevent the cut strap from immediately unloading. The integration of each overlapping shear load along the longitudinal strap is sufficient to carry the full tension load immediately after the strap is severed.

b. Rationale for detonating only one Linear Shaped Charge (LSC)

After the Linear Shaped Charge was initiated and no measurable change in any of longitudinal webbing loads was detected and from video inspection it appeared the longitudinal webbing was still intact, it was believe that either the LSC had misfired and not cut the longitudinal webbing or the LSC assembly had shifted during pressurization and the longitudinal strap was still at least partially intact and carrying the entire load. Since only selected longitudinal members had strain gauged clevises capable of measuring load and none of the hoop webbings were instrumented, cutting a longitudinal was the primary focus of the test. After much discussion back in the secure bunker of the White Sands Test Facility 700 area, a disappointed test team decided to call the test and reschedule for another day. After the DTT article pressure was reduced to a safe approachable pressure and the remaining live ordinance was discharged, a detailed inspection was performed and full longitudinal strap severance was observed indicating that due to inherent design of the woven structure load redistribution is a local effect. Thus, the woven design is even more robust than originally expected. This was a truly unexpected yet significant result! At that point cutting the hoop webbings would require complete deflation of the test article to reassemble the Linear Shaped Charge set-up, the test would be compromised after allowing the loads to relieve and redistribute, and since cutting the hoop webbing was a secondary objective, it was decided further testing was not required.

c. Comparison of measured strap loads with pre-test predictions.

Although not a primary objective, the test afforded an opportunity to compare strain gage measured strap load data to analytical predictions. The table below provides a comparison of the test data from the pressure holds at 22 and 45 psig to the analytical predictions.

Table 1: Clevis Loading at Pressure Holds

	Pressure Hold	
	45 psi	22 psi
Maximum Clevis Tension (Measured)	2759 lbf	1141 lbf
Minimum Clevis Tension (Measured)	485 lbf	189 lbf
Average	1724 lbf	662 lbf
Analytical Prediction	1519 lbf	743 lbf

Figure 8 shows the tensile load at the 32 instrumented clevis locations during the 45 psi pressure hold, prior to severing the longitudinal strap. As noted above, wide scatter in load was observed relative to the analytically predicted load.

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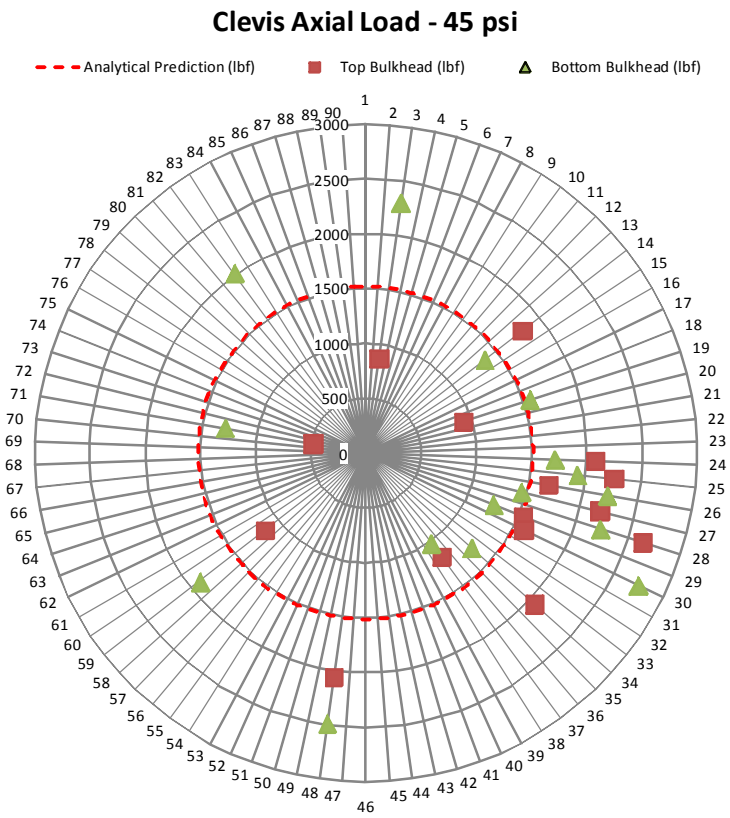

Figure 8: Polar Chart of Individual strap loads

The wide variation in strap loads (even at two ends of the same strap) suggests that the frictional shear load between straps is relatively large for this type of weave construction and on the order of magnitude of the strap tension load at this pressure level. However, the variability between the loads at the upper and lower bulkheads for the same strap indicates the high frictional shear forces that accumulate over the weave construction. Therefore, the same mechanism which made the woven test article damage tolerant, also makes localized predictions of load at the polar bulkheads difficult.

Previous burst testing of several woven inflatable structures of similar construction resulted in repeatable and predictable failures in the longitudinal straps in the cylindrical region of the module. This result indirectly demonstrates that at high pressures approaching the ultimate capability of the restraint, the high frictional forces in the cylindrical region are overcome resulting in a more uniform load distribution. As shown in Figure above, in the toroidal region of the restraint layer, nearest the clevises, the longitudinal straps are overlapped. This overlapping acts to reduce the tension in the straps as well as increase inter-weave friction. So, although a large amount of scatter in clevis tension was observed at the polar bulkheads, previous testing indicates that the same degree of scatter was not present in the cylindrical region at pressures approaching the ultimate capability of the restraint.

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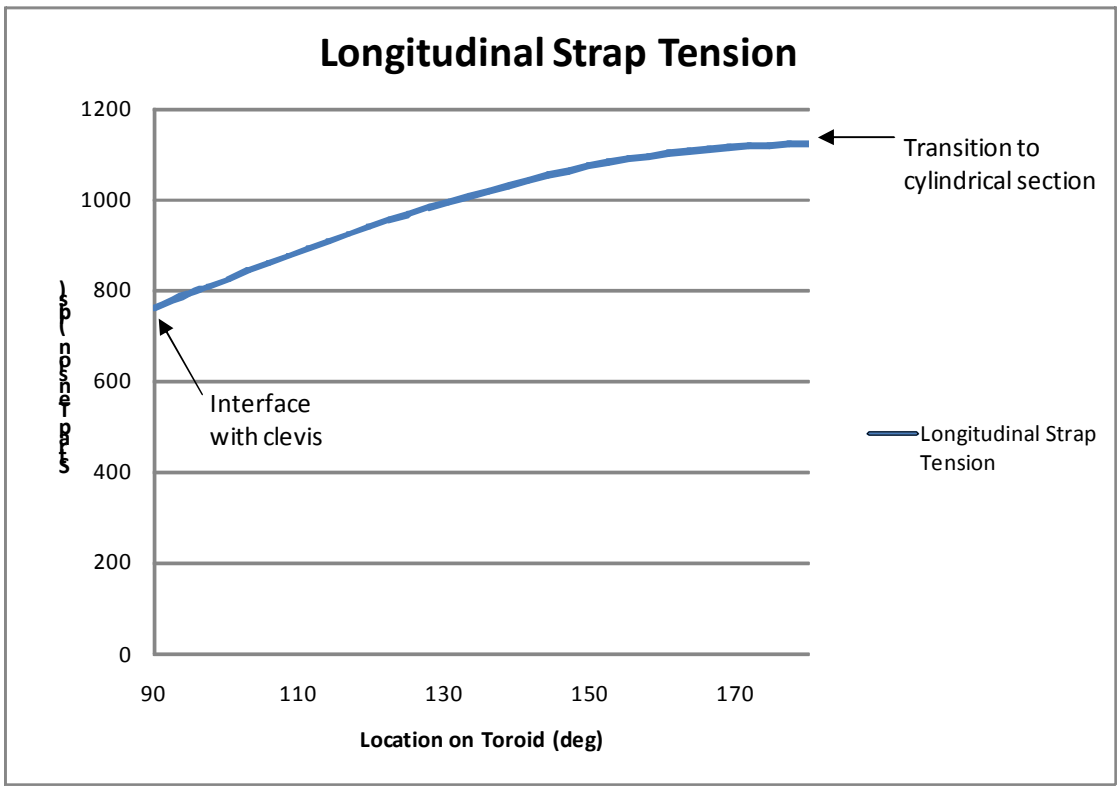

Figure 9: Longitudinal Strap Tension Along Toroidal Region

4. Conclusion / Future Work

The detailed behavior of an expandable pressure vessel under sudden structural integrity loss of one of its members has been tested and studied. The test revealed unexpected yet beneficial results. The results show that a tight weave construction helps eliminate a sudden and dynamic global re-distribution of strap loads. The high inter-weave friction allows loads to be carried by the failed structural member. It is expected that this load will relieve over time due to stick-slip mechanisms, and the load will then distribute to adjacent members. While beneficial for mitigating a highly dynamic structural response to a failed component, the high inter-weave friction also makes prediction of local stress distribution within and among straps difficult. It is possible that this variation in load could reduce and even out over time due to operational vibration but this should be the subject of future work. In the summer of 2009, the Damage Tolerance Test article integrated with a 40-inch hatch penetration will be pressure tested at WSTF and loads in the cylindrical region will be measured and compared with analytical predictions. Furthermore, also in 2009, a full-scale Constellation Trade Set (TS1a) Inflatable torus with integrated 40- hatch penetration will be pressure tested at WSTF with similar measurements and comparison.

References

De la Fuente, Raboin, Spexarth and Valle, "TransHab: NASA's large-Scale Inflatable Spacecraft", Structures, Structural Dynamics, and Materials Conference Paper No. AIAA 2000-1822, 3-6 April 2000, Atlanta, GA

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