Time-Dependent Behavior of High-Strength Kevlar and Vectran Webbing

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High-strength Kevlar and Vectran webbings are currently being used by both NASA and industry as the primary load-bearing structure in inflatable space habitation modules. The time-dependent behavior of high-strength webbing architectures is a vital area of research that is providing critical material data to guide a more robust design process for this class of structures. This paper details the results of a series of time-dependent tests on 1-inch wide webbing including an initial set of comparative tests between specimens that underwent real-time and accelerated creep at 65 and 70% of their ultimate tensile strength. Variability in the ultimate tensile strength of the webbings is investigated and compared with variability in the creep life response. Additional testing studied the effects of load and displacement rate, specimen length and the time-dependent effects of preconditioning the webbings. The creep test facilities, instrumentation and test procedures are also detailed. The accelerated creep tests display consistently longer times to failure than their real-time counterparts; however, several factors were identified that may contribute to the observed disparity. Test setup and instrumentation, grip type, loading scheme, thermal environment and accelerated test post-processing along with material variability are among these factors. Their effects are discussed and future work is detailed for the exploration and elimination of some of these factors in order to achieve a higher fidelity comparison.

I. Introduction

THE two major constraints on any payload launched into space are the mass and volume capability of the launch vehicle. Inflatable space structures, and specifically those used for pressurized habitats, are an enabling technology for human exploration due to their high packaging efficiency and large deployed volume. They also hold the promise of reduced mass and improved robustness over traditional rigid shell structures[1]. Inflatable habitats consist of multiple, flexible layers (Fig.1a) that protect the astronauts from radiation, micrometeoroid and orbital debris (MMOD) and the extreme thermal environment of space using multi-layer insulation (MLI). An outer Atomic Oxygen (AO) protection layer is also added to prevent oxidation and erosion. Beneath these external layers, redundant bladders retain the atmosphere while a weave of high-strength webbings (Fig.1b) carries the loads induced by the internal pressure. These webbings are made of liquid crystal polymer (LCP) materials, such as Kevlar and Vectran, which have extremely high uniaxial strength, and low density. A great deal of characterization of the short-term properties of the primary layers was performed during NASA's TransHab program[2-3] in the late 1990's (Fig. 1c). However, there has been little research on the long-term characteristics of these materials. Characterization of the long-term creep behavior of the loaded restraint layer materials was recently determined by a multi-center expandable structures group at NASA to be the single most vital research needed for risk mitigation in the design and use of inflatable modules. With mission durations of between 10 and 15 years being investigated, this testing is a critical component in the development and certification of inflatable structures as a viable alternative to rigid shell pressure vessels.

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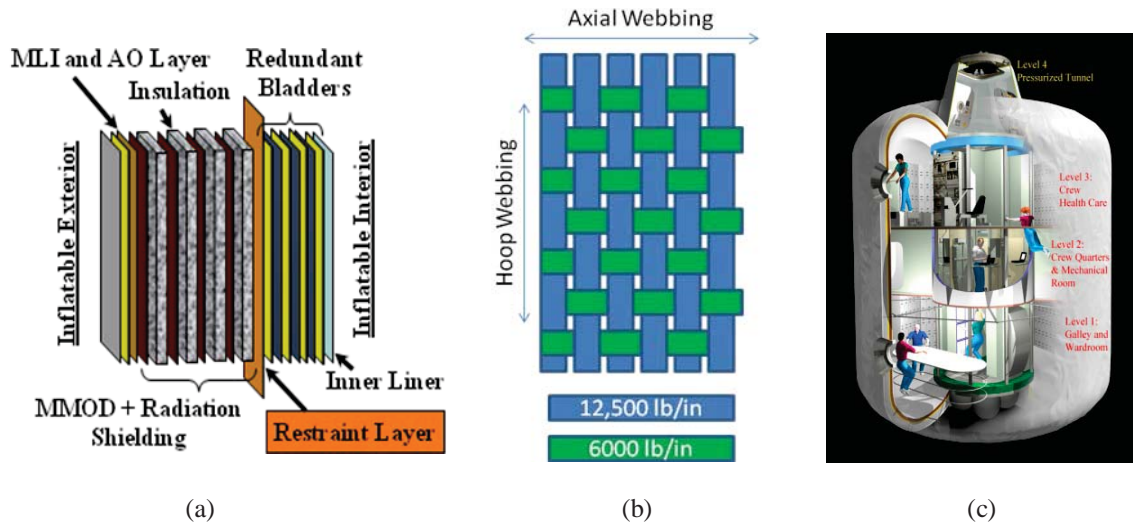
Figure 1. a) Multi-layer inflatable structure, b) typical restraint layer weave, and c) TransHab.

The objective of this test program is to study the time-dependent behavior of high-strength Kevlar and Vectran webbings and explore the feasibility of creep life determination through accelerated testing. Kevlar and Vectran webbings are currently used by NASA and industry as the primary load-bearing structure in inflatable space habitats. Vectran is of particular interest due to its manufacturer's claim of significantly improved creep life performance over high-strength aramid fibers such as Kevlar. Real-time creep tests on these webbings require a significant investment in both time and facilities. It is therefore desirable to accelerate the creep behavior, if possible, to reduce the cost and time of testing and provide mission critical data early on in the design process. Currently, inflatable habitats are designed to a safety factor of 4 on burst pressure, principally due to the uncertainty in the change in mechanical properties after several years of continuous service. Due to the constant loading in the restraint layer, creep is believed to be one, if not the, primary mechanism of material degradation over time.

This paper details the development tests and comparison of an accelerated creep test methodology and data to real-time creep tests performed in parallel. Each accelerated and real-time test, for a given initial temperature and load, produces a master creep curve (Fig. 2) that gives the time to failure and creep strain rate over the lifetime of the webbing. The temperature of the loaded restraint layer webbings in an inflatable module should remain close to room temperature as they are in contact with the interior surfaces and are protected from the space environment by layers of insulation. This assumption was made for all webbings tested under this program. The applied load is measured as a percentage of the ultimate tensile strength (UTS). UTS tests are performed on every roll of material, and creep test specimens are marked with the roll number and tested at a percentage of the average UTS of that roll.

Typical creep behavior characteristically falls into three phases. Primary creep is a transient stage during which the material deforms at a decreasing strain rate. The deformation is primarily elastic, but the total creep strain is only partially recoverable, therefore some plastic deformation is also present. This occurs at a molecular level in aligning the polymer backbones within the crystal structure, through slip and chain-direction shear[4]. At the architectural level (i.e. the weave of the yarns), decrimping and fiber locking is also only partially recoverable, with the amount of recoverability at both levels being dependent on the applied test load. Given the highly oriented polymeric structure initially present in these materials (hence their high tensile strength), the majority of chain alignment has already been accomplished during processing, and thus the primary creep stage may be quite short. During secondary creep, the creep rate remains essentially constant in logarithmic time. This equates to a gradual reduction in the strain rate in linear time which suggests a strain hardening of the material up to the point of failure. This is typical of linear viscoelastic materials and this phenomenon is assumed in the accelerated creep test data reduction process. In the classic tertiary stage of creep, material necking reduces the cross-sectional area of the specimen leading to higher local stresses and a rapidly increasing strain rate until failure. For high-strength webbings, the Poisson's effect is very small due to a very low percentage of fill yarns versus the axial warp yarns; therefore a tertiary stage is not typically observed. However, due to imperfect loading of the yarns from small length differences set during manufacturing, it is probable that some of the yarns will be under higher stresses than others during the creep test. These yarns will naturally have a shorter creep life and may lead to either a propagating failure of the webbing or to
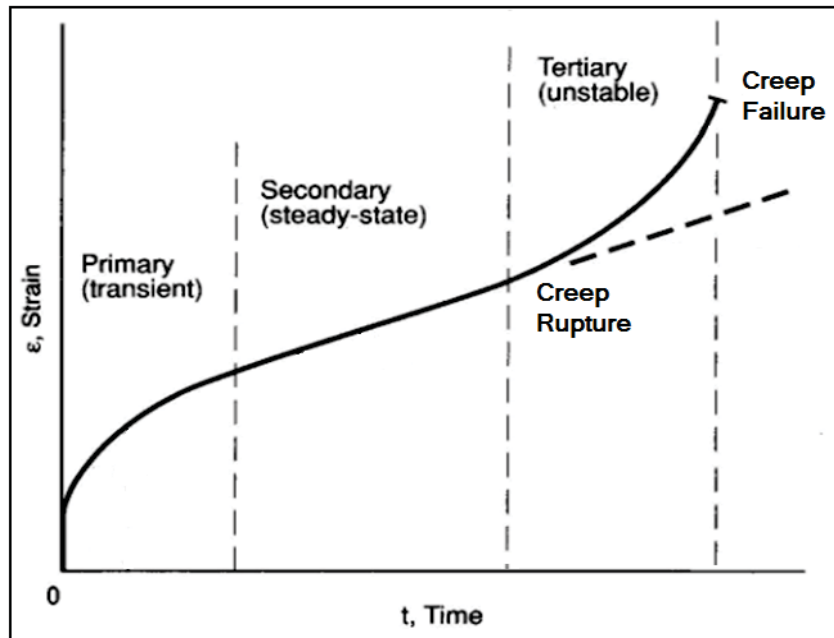
Figure 2. Typical master creep curve. Creep strain versus Time.

a branching of the master creep curve, whereby the creep strain rate jumps to a higher constant value as the remaining fibers absorb the additional load from any fibers that have failed.

Additional micro- and macro-level effects influence the creep behavior of high-strength webbings. There are variations in the strength of individual fibers due to a normal distribution of flaws in the constituent filaments. Twist in the yarns reduces this strength variance by allowing better load sharing among filaments through friction. At the macro-level of the webbing architecture however, the yarns themselves behave more like a series of loosely bundled tensile elements, with weaker interactions from friction due to the small percentage of cross fibers, and low crimp angle. This is especially evident in Vectran with a coefficient of friction half that of Kevlar and could be a reason for higher UTS variability observed in Vectran webbings (as discussed in the 'Ultimate Tensile Testing and Variance' section). Given the increasing number of yarns in higher strength webbings it is reasonable to predict that the variability in the creep behavior will increase due to an increased probability of local fiber failures and subsequent unpredicatable increases in the strain rate, dependent on the severity of the failures.

The materials tested in this study are the same webbing architectures and strengths used in NASA's Transhab module and subsequent NASA inflatable designs. These consist of 4 primary types, all of which are 1-inch wide and manufactured to Mil-T-87130 specifications. The two nominal load ratings for the Kevlar and Vectran webbings are 6,000 lbs and 12,500 lbs (henceforth referred to as 6K and 12K respectively) all with a custom light "R" resin treatment per MIL-W-27265E (Table 1)**.** The test methodologies, setup and instrumentation detailed herein are meant to be widely applicable to other high-strength webbings, and these materials are simply used as a convenient baseline architecture for these studies. Kevlar was used in Transhab primarily due to its heritage, but Vectran has shown promise as a comparable material with better creep properties. This work is part of the effort to better characterize and compare the two materials while using the same webbing architecture. Table 2 lists the Mil-T-87130 specifications for the 6K and 12K webbings tested. This former USAF military specification for para-aramid webbings and tapes and has now been reissued as a Parachute Industry Association specification, PIA-T-87130B. Kevlar is an *ar*omatic poly*amid*e, or *aramid*, which is a lyotropic liquid crystal polymer (LCP), where the liquid crystalline phase exists upon dissolution of the polymer in a solvent. The lyotropic LPC is then spun into fibers, with the liquid crystalline order resulting in the highly-oriented fiber structure. Vectran is not an aramid, but rather an aromatic polyester, which is a thermotropic LCP. The liquid crystalline phase is exhibited over a particular temperature range (melts at 330°C). Vectran fibers are then created through melt-spinning and extrusion through a die. Mil-T-87130 was created for para-aramids, which are long chain aramids that include Kevlar, Technora and Twaron. It is evident from UTS data that Vectran, although structurally and morphologically similar to these materials may not perform optimally in the same webbing architecture.

Table 1. Material specifications for 6K and 12K Kevlar and Vectran webbing used in this test program.

	KEVLAR 6,000 lb RATED WEBBING	KEVLAR 12,500 lb RATED WEBBING
TYPE	1991-1" Natural "R" Kevlar Tape	2736-1" Natural Kevlar "R" Treated Webbing
SPEC	Mil-T-87130 Type VI Class 9 Mod to R	Mil-T-87130 Type VI Class 11 Mod
PUT-UP	60 Yd Rolls, 15 Yd MUTTS (+1/-0)	25 Yd Rolls (+1/-0)
VENDOR	Bally Ribbon	Bally Ribbon

	VECTRAN 6,000 lb RATED WEBBING	VECTRAN 12,500 lb RATED WEBBING
TYPE	6996-1" Natural "R" Vectran Webbing	1" Natural Vectran Webbing (100% Vectran)
SPEC	Mil-T-87130 Type VI Class 9 Mod to R	Mil-T-87130 Type VI Class 11 Mod to R
PUT-UP	25 Yd Rolls (-0/+1)	50 Yd Rolls
VENDOR	Bally Ribbon	Offray Specialty Narrow Fabrics

FINISH ON ALL WEBBING: Mil-W-27265E "R" - Polyvinyl Butyral Resin

Table 2. Mil-T-87130 manufacturing specification for 6K and 12K high-strength webbing.

Mil-T-87130 Specification				Lineal Density			WARP (Axial Threads) Properties				
Minimum UTS (lbs)	Width (inches)	Type	Class	Max Wt (oz/yd)	Max M/L (lbs/in)	Total M/L	Denier	Ply	Total Ends Minimum	Fiber M/L (lbs/in)	Warp M/L (lbs/in)	% Warp by Mass
6000	1	VI	9	1	0.001736	0.001325	1500	3	44	9.3329E-06	0.001232	92.96%
12500	1	VI	11	1.65	0.002865	0.002576	1500	3	89	9.3329E-06	0.002492	96.74%

Mil-T-87130 Specification						FILL or WEFT (Cross Threads) Properties				
Minimum UTS (lbs)	Width (inches)	Type	Class	Weave Type		Denier	Ply	Picks (per inch)	Fiber M/L (lbs/in)	Weft M/L (lbs/in)	% Fill by mass
6000	1	VI	9	Plain		1500	1	10	9.3329E-06	9.3329E-05	7.04%
12500	1	VI	11	Plain		1500	1	9	9.3329E-06	8.3996E-05	3.26%

II.   Test Facilities, Instrumentation and Test Methodology

The real-time creep test facility (Fig. 3) is setup in an air-conditioned high-bay using cantilevered I-beams attached to a steel back-stop. Five to fifteen specimens can currently be hung in the facility at any one time,
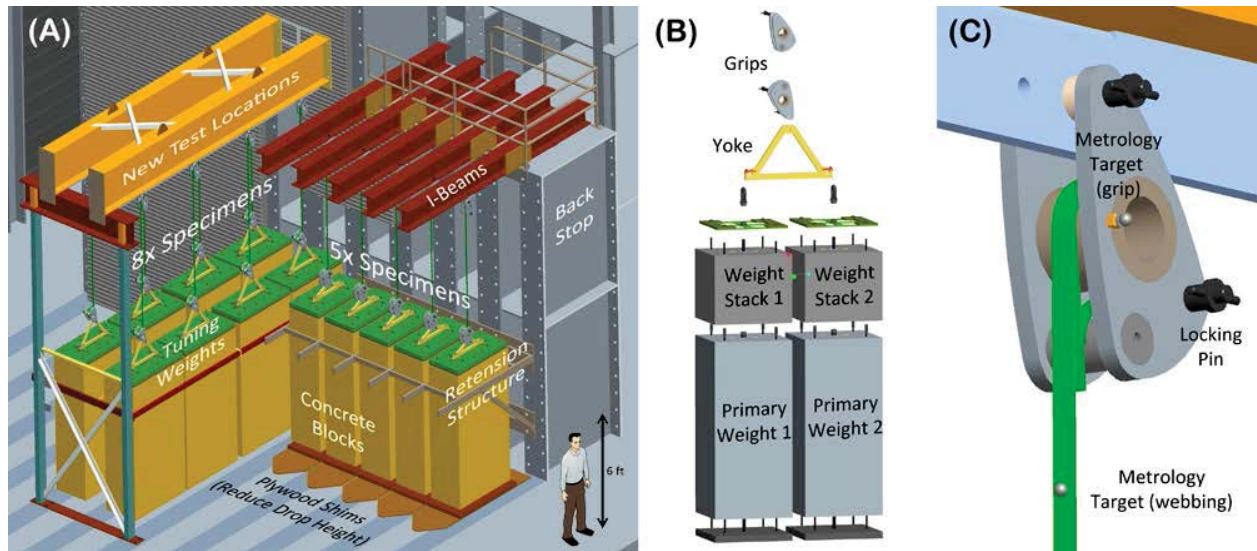

Figure 3. a) 12K creep specimens with concrete blocks and tuning weights attached, b) side view with weight stacks shown, c) custom Mil-T-87130 webbing grips and metrology target spheres.

depending on the size of weight required for the test webbings. An additional apparatus for concurrent testing of eight to sixteen more specimens is currently nearing completion. For the real-time tests discussed in this paper, specimens with a 12,500 lb ultimate tensile strength (UTS) were used; therefore only five specimens were tested simultaneously. Two concrete blocks were used per specimen, with the capability to attach custom steel plates for tuning the total weight. The specimens were attached to the I-beams and weights via custom Mil-T-87130-based webbing grips. These grips were modified to include a locking pin that engaged a sewn loop at the end of each specimen to prevent slippage over time. Given the number of concurrent specimens being tested and limited funds, the grips were designed to be easily and cheaply manufactured by welding steel plates and cylindrical bars. A scanning laser radar metrology system was setup across from the test webbings and measured the displacements of steel metrology balls attached to the specimens and to the grips every 20 to 30 seconds. The metrology balls attached to the webbings were bonded to small metal snaps that were carefully sewn on to the top and bottom of the specimen's test section via a small loop. The metrology system measures the position of the targets to within 1/1000 inch, and the displacement data is used to derive the creep strain.

The real-time creep test methodology consists of specimen preparation and target application, load-up and test, and data reduction and comparison. The test specimens are cut to length and a loop is sewn at each end. Snaps are then sewn on to hold the metrology targets. Each specimen is first wrapped and pinned around the top grip, followed by the bottom grip in one of the test stations. The weight, having been pre-tuned to the correct creep test load (for example, 70% of UTS), is held via an overhead crane while the specimen is wrapped. The weight is then lowered until the webbing has fully taken up the load. The metrology balls are snapped into place immediately after load up and the webbings are checked to make sure they are seated correctly in the grips. Laser metrology begins as soon as the targets are in place. After the test specimen fails, the data files are collated via a MATLAB script and the creep strain is calculated.

The accelerated creep test facilities and instrumentation are detailed in Jones *et al*[1] but are summarized here with some modifications. The core components are a high capacity tensile load frame with webbing grips, a precision environmental chamber and a photogrammetry system (Fig. 4) for strain measurement. Two test stands are currently used for testing. The first is a 55-kip MTS load frame with an Applied Test Systems (ATS) oven, capable of ±2 °C hold, while the second setup uses a taller 110-kip MTS load frame with a tall ATS oven also with ±2°C capability. The height of the second setup allows testing of longer specimens to account for the possibility of local defects affecting creep life and more closely approximates the length of specimens used in the real-time creep tests and actual inflatable modules. The small setup permits a 10-inch test section versus a 74-inch test section in the tall load frame and oven. Comparisons of results between the two setups are described later in this paper. ASTM-D6775, split-capstan, sedam webbing grips are used in both, and are the preferential grips for webbing tests if available due to their high gripping force without shearing the webbings. They are 5 to 6 times more expensive than the custom
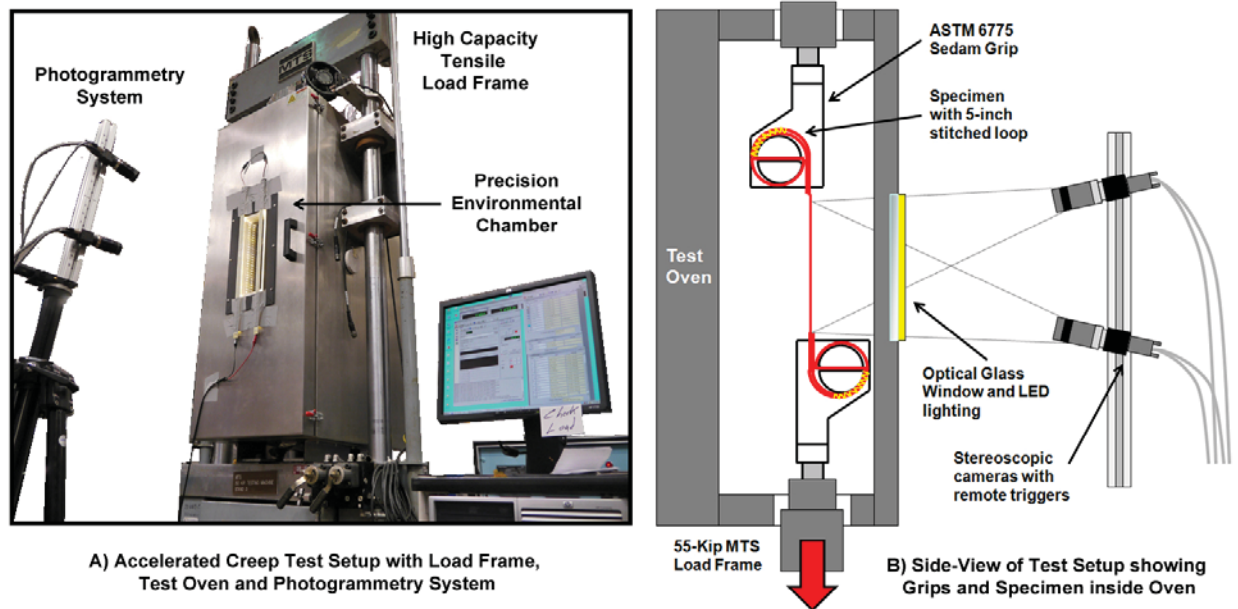

Figure 4. A) Accelerated creep test equipment, B) Side-view of test setup and cameras.

real-time wrap grips, but are cost effective when only testing one sample at a time, as was the case for the accelerated tests. The accelerated test specimens are looped through the grips and have a stitched loop to avoid slippage. This was found to be necessary with Kevlar and Vectran given their low coefficients of friction and the elevated temperatures required by the accelerated creep procedure. The stereo photogrammetry system consists of two high resolution digital cameras with precision lenses capturing images of the test specimen through an optical grade glass window in the oven. The cameras are triggered by pulses from the MTS load frame controller that runs the accelerated creep test load and temperature profiles. The specimen is prepared by sewing a loop at each end and speckling the test section with a fine, random black and white dot pattern. This pattern is then tracked by the photogrammetry system and displacements and strains are calculated and output to a data file for each test.

The accelerated creep test methodology used in these tests is the Stepped Isothermal Method (SIM). This method is based on the principle that the viscoelastic strain behavior of Kevlar and Vectran are strongly time-temperature dependent and their creep life can be exponentially shortened via application of increasing temperature steps. Through post-processing the collected strain data through a series of shifts on to a log-time plot, a master creep curve can be produced that emulates a test performed in real-time at the same initial temperature[5]. A MATLAB script was coded that can compute these master creep curves by guiding a user through the SIM shifting procedure using the output from one of the accelerated test runs. The accelerated test procedure is programmed into the MTS controller, which controls the load ramp up, hold load, temperature steps, and trigger pulses that control the photogrammetry cameras. The test begins at room temperature (25°C) and zero load. The load is ramped up to and held at a set percentage of the average UTS (that was predetermined for the current test roll) for the duration of the test. During the ramp-up, 1 image per second is captured until the hold load is reached, to accurately capture the large displacements occurring in the specimen. The temperature is then held at 25°C for 4 hours, and image capture is reduced to 1 image per minute. After each four hour hold period the temperature is ramped up by 10°C at 5°C / minute. During this temperature ramp-up, images are triggered at 1 image every 4 seconds, to increase the resolution of this transition region which must be accounted for and removed in the post-processing. This continues until the specimen fails, at which point the load is zeroed and the temperature is returned to 25°C. The load, stroke and temperature readings from the MTS controller are sent to the photogrammetry system via an analog input board every time the cameras are triggered, providing a coherent time-synced data set for each test.

III.   Material Characteristics and Test Effects

During the testing and formulation of the experimental approach for both real-time and accelerated creep, several material characteristics were observed that motivated further investigation. Strength variance and stiffness behavior were studied directly from the data collected for each UTS test series. Load and displacement rate effects, specimen length, and the effects of preconditioning (or load cycling) were explored as separate tests and will be detailed in the following sections.

A. Ultimate Tensile Strength (UTS) Testing and Variance

The Kevlar and Vectran webbing is manufactured in runs of several thousand yards from which rolls of 25 to 60 yards of material are cut. The rolls arrive in random order, so to quantify the variance in the run, each roll is tested to provide an accurate average UTS for each set of creep test specimens. The UTS testing follows the ASTM-D6775-02 standard test method for breaking strength and elongation of textile webbing, tape and braided material. The major specifications of the standard are listed in Table 3. To date, 87 total rolls of material have been tested for UTS across the four types of webbing included in this study. The average, minimum and maximum UTS for each roll are plotted in Figs. 5 and 6 along with the rated load (the minimum load required to meet the Mil-T-87130 specifications). The specific percentage variance about the mean is then plotted for all rolls in Figs. 7 and 8.

Table 3. ASTM-D6775-02 standard test method for breaking strength of textile webbing

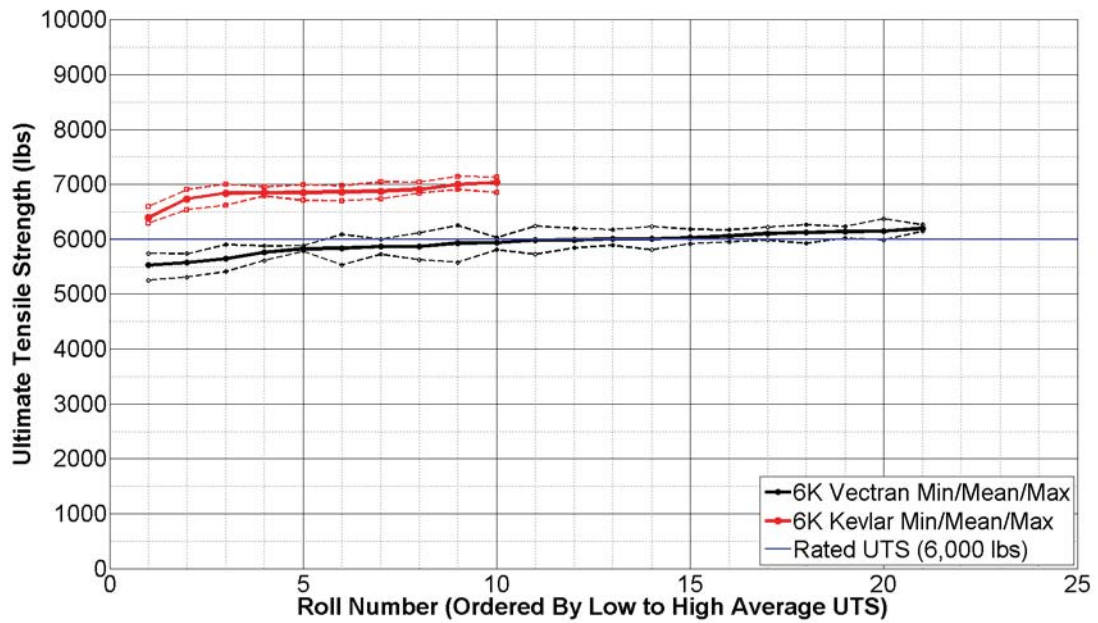| Grip Type	Diameter Drum (in)	# of Test Samples	MIN Sample Length (in)	Test Section (in)	Max UTS (lbs)	Displacement Rate (in/min)
Split-Drum	4 ± 0.05	5	54	10 ± 0.5	20,000	3 ± 1

Figure 5. 6K Kevlar and Vectran minimum, mean and maximum ultimate tensile strengths for every roll of material tested. Solid line is the mean, dashed lines are minimum / maximum values per roll.
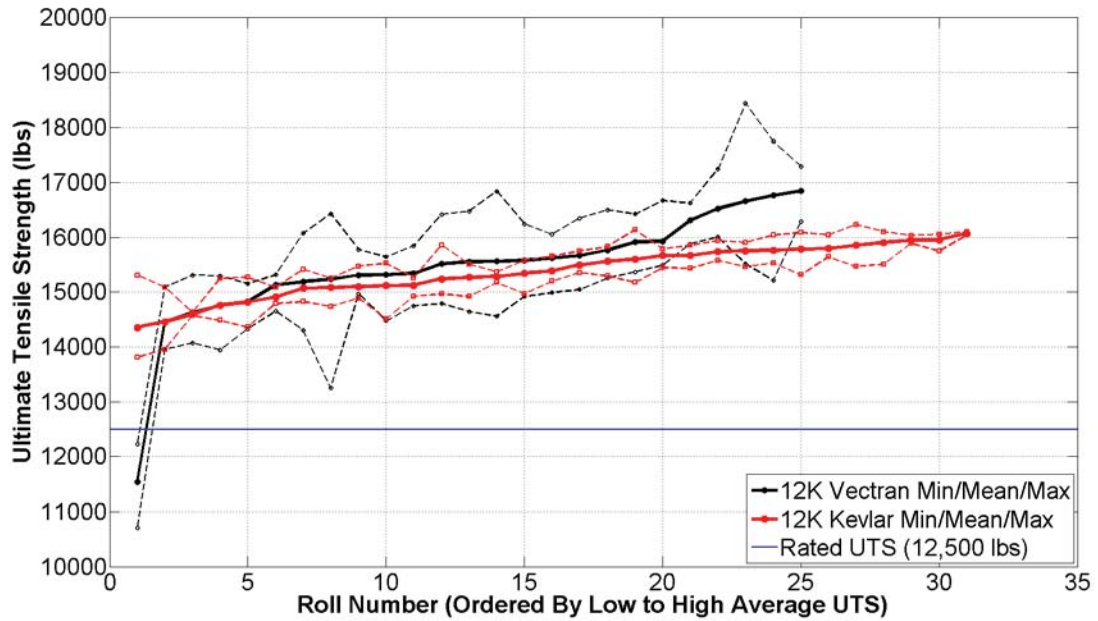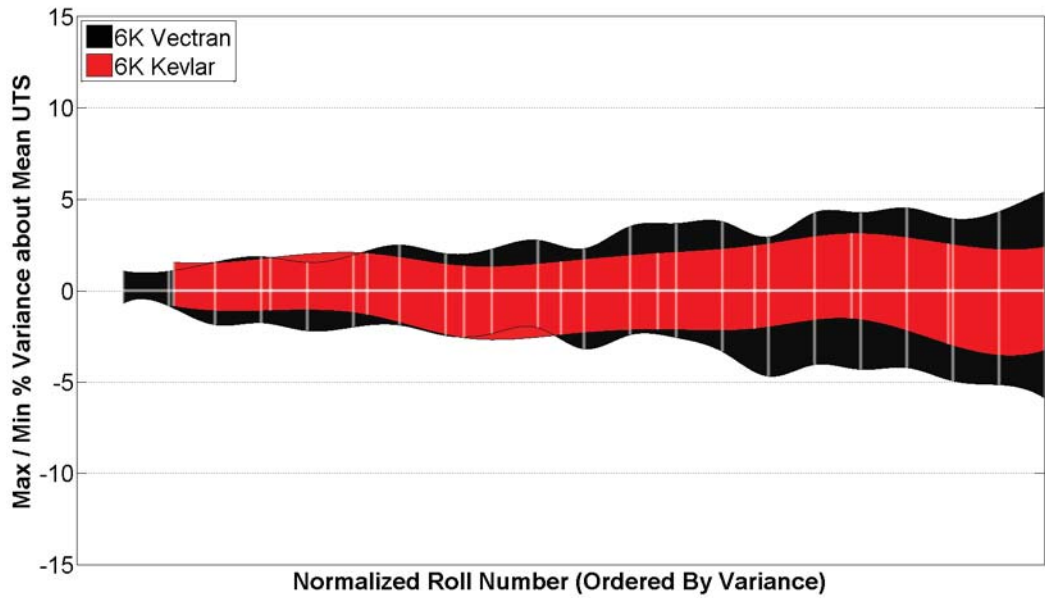

Figure 6. 12K Kevlar and Vectran minimum, mean and maximum ultimate tensile strengths for every roll of material tested. Solid line is the mean, dashed lines are minimum / maximum values per roll.

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Figure 7. 6K Kevlar and Vectran % variance about the mean UTS for each roll tested. This plot is normalized by roll number to more easily compare variance between material types.
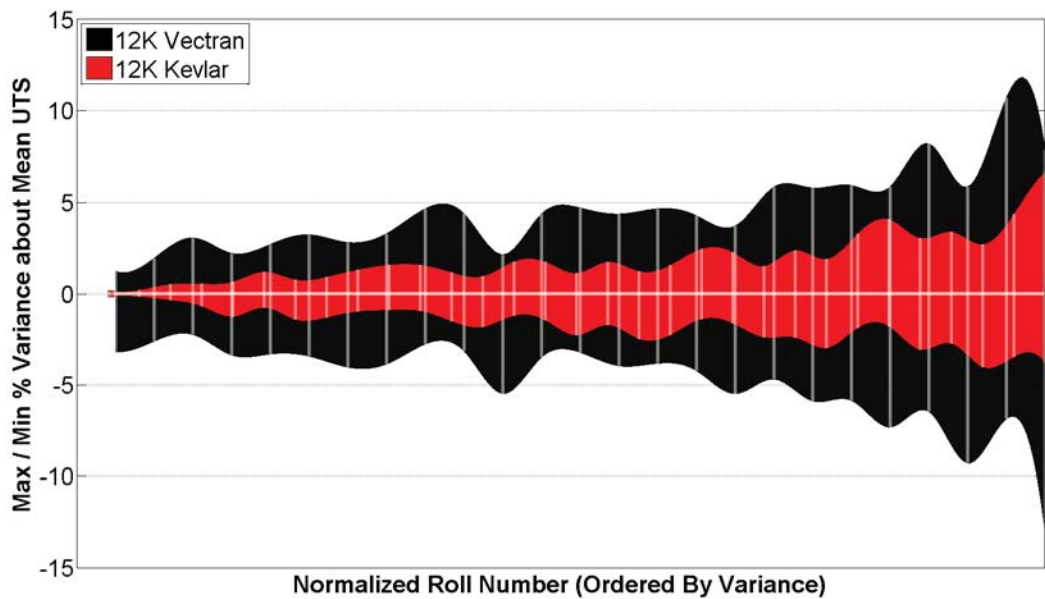
Figure 8. 12K Kevlar and Vectran % variance about the mean UTS for each roll tested. This plot is normalized by roll number to more easily compare variance between material types.

It is immediately clear from these figures that Vectran has higher variance than Kevlar, in both 6K and 12K architectures, and markedly so in the 12K webbings, that exhibit an average variance of 9.4% versus only 3.7% in Kevlar. Indeed two of the 12K Vectran rolls displayed variances just below and right at 20%. This can have a significant effect on the creep test results, as creep life increases exponentially with a linear decrease in the percentage of UTS load. As creep tests are performed at a percentage of the average, a 20% variance in the measured UTS may result in an order of magnitude difference in the creep life obtained for samples off that roll as some of the specimens will be significantly stronger or weaker than the average.

The second point of interest is the difference in the fidelity with which the two materials meet the Mil-T-87130 minimum breaking load of 6,000 and 12,500 lbs. Only 9-of-21, 6K Vectran rolls met the specification when manufactured using the same architecture as the 6K Kevlar. NASA JSC requested that additional fibers be added to the original architecture on subsequent manufacturing runs to meet the minimum specification. The 12K webbings show the opposite trend, with breaking loads up to 48% higher than the minimum (18439 lb) in the case of 12K Vectran, with an average UTS for both 12K Kevlar and Vectran, approximately 23% higher than required. Evidently these architectures are not well optimized, even for the para-aramids for which they were intended, but Vectran exhibits a particularly wide variance not just within a roll, but also across a manufacturing run. One 12K Vectran roll was significantly different from the rest with an average UTS of 11,548 lbs; the only 12K roll to test below the minimum. Even if that is ignored as an aberration, 12K Vectran still exhibits a range of average UTS values more than twice as wide as 12K Kevlar. This data suggests that more research is needed on the manufacturing process of these webbings to better optimize their architectures to hold closer to an intended load rating, with lower variance.

B. Load versus Stroke Data from UTS Testing

Stress-Strain plots are typically used to characterize the stiffness behavior of a material; however, for woven materials it is more useful and practicable to consider load-strain data, given the difficulty in calculating stress from what may be considered to be an imprecise cross section. Strain data can be attained via a photogrammetry system (discussed in the Test Facilities, Instrumentation and Test Methodology section), but typically the UTS tests are run without this, due to the additional specimen and equipment preparation time. Load-stroke data is an alternative when strain is not available and provides insight into the consistency of the stiffness behavior from strap to strap in a given roll of webbing and between rolls. This method is subject to additional variability however, due to slippage and non-uniformity in the initial stages of loading when using wrap grips. These effects can be removed by zeroing the stroke values at a chosen normalization load for each specimen in a test roll. A value of 0.5% of the UTS average for the 5 specimens was found to be a reliable normalization load. Every load frame has some inherent noise in the load cell. For the load frames capable of failing these high-strength webbings, the noise level is approximately ±10 to 20 lbs. 0.5% of the average UTS is on the order of 30 to 80 lbs for 6K and 12K webbings respectively, which places the initial reading just above the nominal noise level. This load level is also low enough so as not to impact the characteristic behavior illustrated by the load-stroke plot.

The results plotted in Figs. 9 through 12 show the average load-stroke curves for a number of rolls in each material type. These plots give an impression of the variance in the characteristic slopes observed for rolls of the same material type. Each curve is the interpolated average of five UTS specimens that have been normalized to 0.5% of their average UTS. A lower slope on the load-stroke curve is equivalent to higher compliance in the webbing. Assuming the webbings all have the same number of axial fibers, this suggests that fewer fibers are actually being loaded in these cases. It is logical then to predict that the rolls with lower compliance would also have lower breaking strength in general due to higher stresses in the loaded fibers at the same load. This is well illustrated by the presented curves, where the data is organized by lowest to highest average UTS. The solid curves (lowest UTS) have the lowest stiffness and the dashed and dotted lines (higher UTS) display higher stiffness. The reasoning for this difference could be attributed to a number of effects including: friction, stick-slip between fibers, misalignment on the grips and micro-level differences in the number of flaws. This behavior is present in all four types of webbing tested. Indeed, examining the individual webbings from rolls with the lowest variance in strength shows minimal differences in the load-stroke curve, in contrast to the more significant differences for those rolls with a high level of variance in webbing strength. If a better understanding of the mechanisms behind the variance in stiffness behavior can be found, it could elucidate the cause of the high variance in the strength of these webbings.
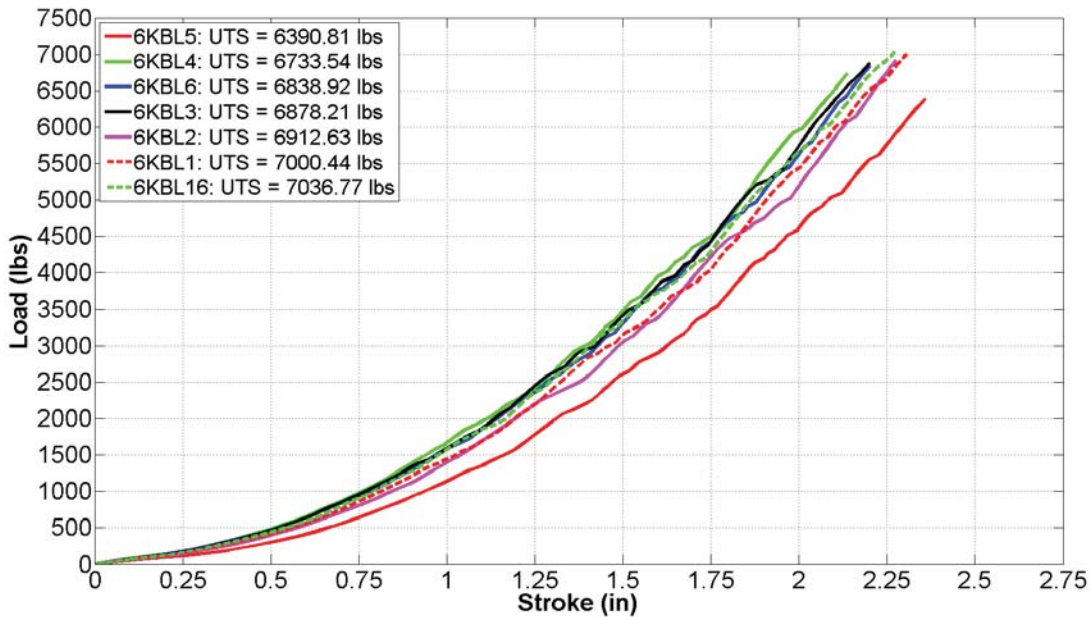
Figure 9. 6K Kevlar average load-stroke plot for 7 rolls. Average UTS also shown in legend. Each curve is a 5-specimen average, normalized to 0.5% of the UTS average.
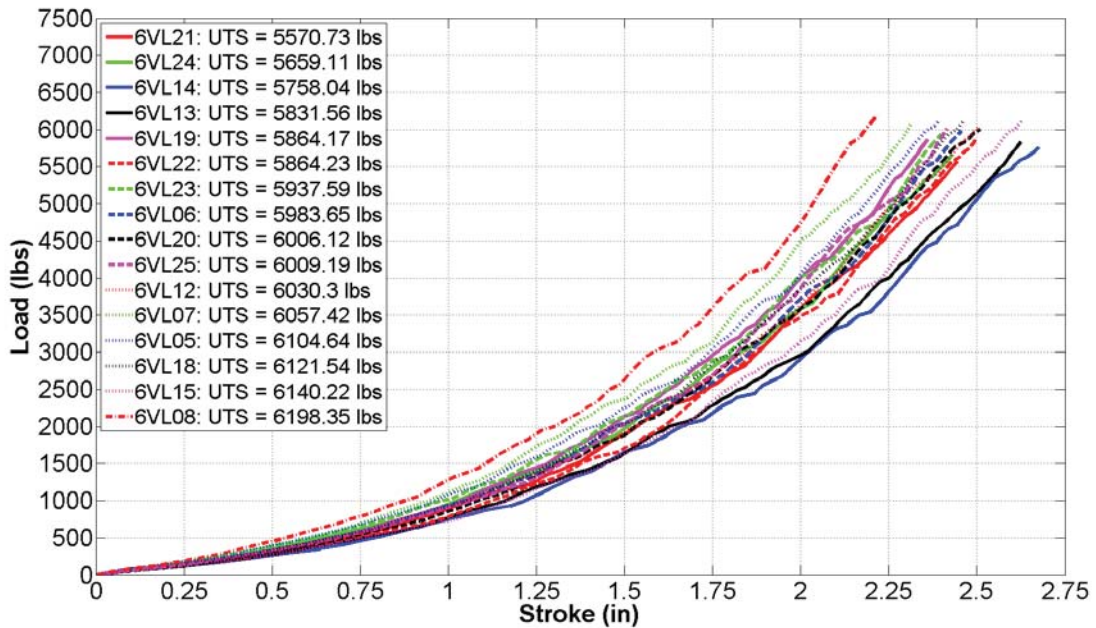

Figure 10. 6K Vectran average load-stroke plot for 16 rolls. Average UTS also shown in legend. Each curve is a 5-specimen average, normalized to 0.5% of the UTS average.
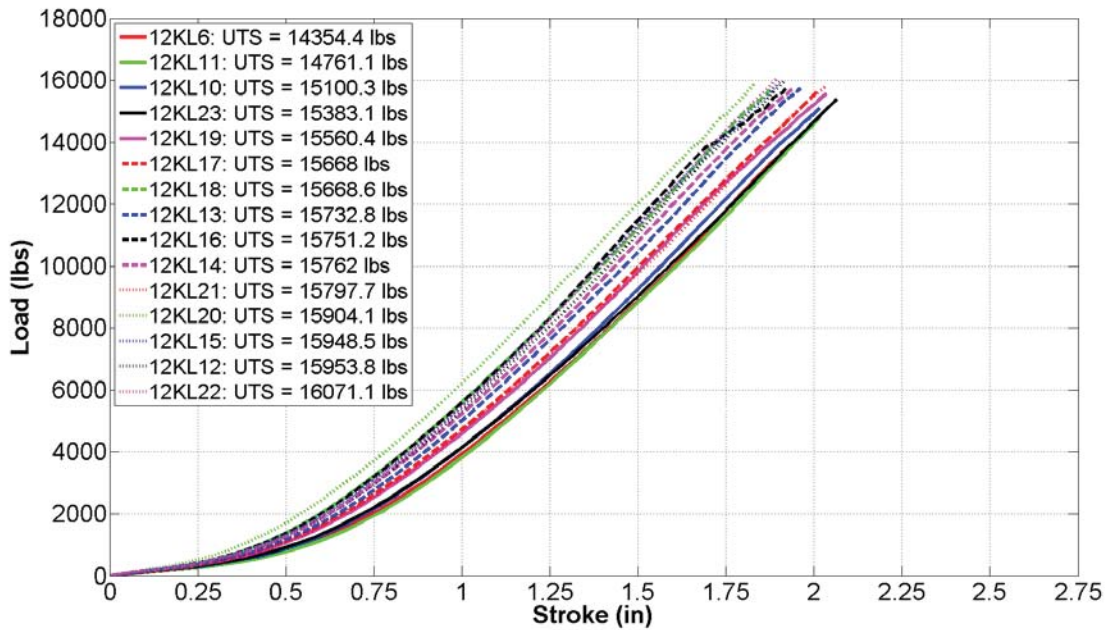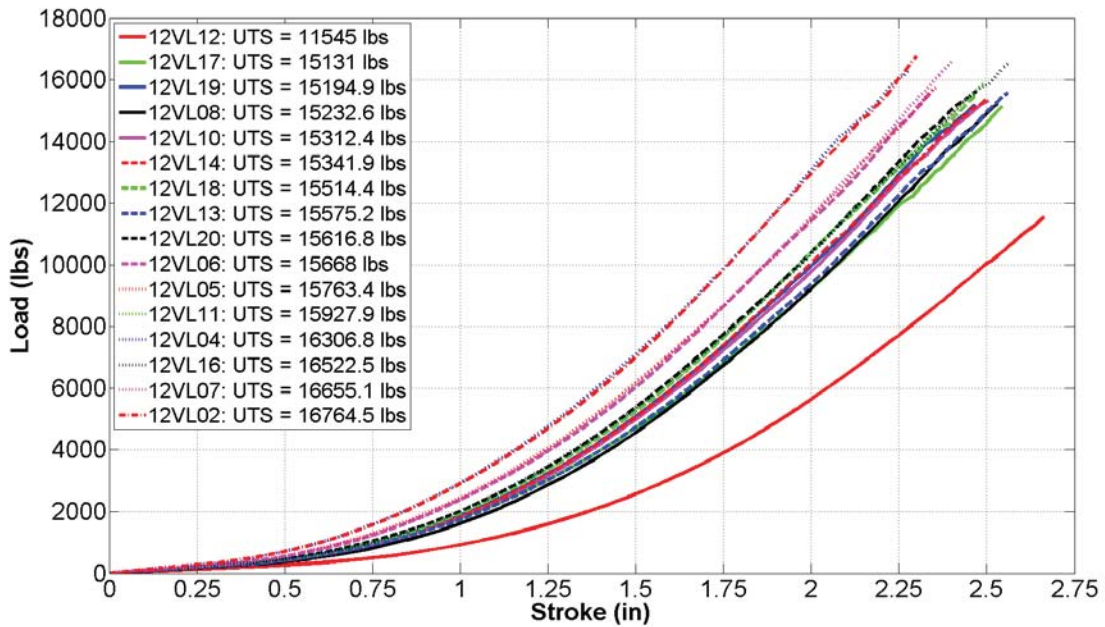
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Figure 11. 12K Kevlar average load-stroke plot for 15 rolls. Average UTS also shown in legend. Each curve is a 5-specimen average, normalized to 0.5% of the UTS average.

Figure 12. 12K Vectran average load-stroke plot for 16 rolls. Average UTS also shown in legend. Each curve is a 5-specimen average, normalized to 0.5% of the UTS average.

C. Load and Displacement Rate Effects for Different Specimen Lengths

Two of the major differences between the accelerated and large-scale, real-time test setups were the specimen length and the load-up rate. The accelerated tests use 10-inch test sections, loaded at the ASTM-D6775 standard rate of 3 in/min, used for the UTS tests, while the real-time tests in building 1293 are 74-inches grip-to-grip and loaded at approximately 1500 lbs/s via the overhead crane. These two parameters were explored in a series of tests on both 6K and 12K webbings. The results of testing 6K Kevlar and Vectran to failure at 0.1, 1, and 10 in/min displacement rate are presented in Table 4 and Fig. 13. Over two orders of magnitude difference in displacement rate caused essentially no change in the load-stroke behavior for each material. The 6K Kevlar did show a decrease in UTS at 0.1 in/min, but all other cases for both materials held similar average UTS values within the variance of the material. These tests were performed on the shorter 10-inch test sections only.

Table 4. 6K Vectran and Kevlar displacement rate test comparison for short specimens.

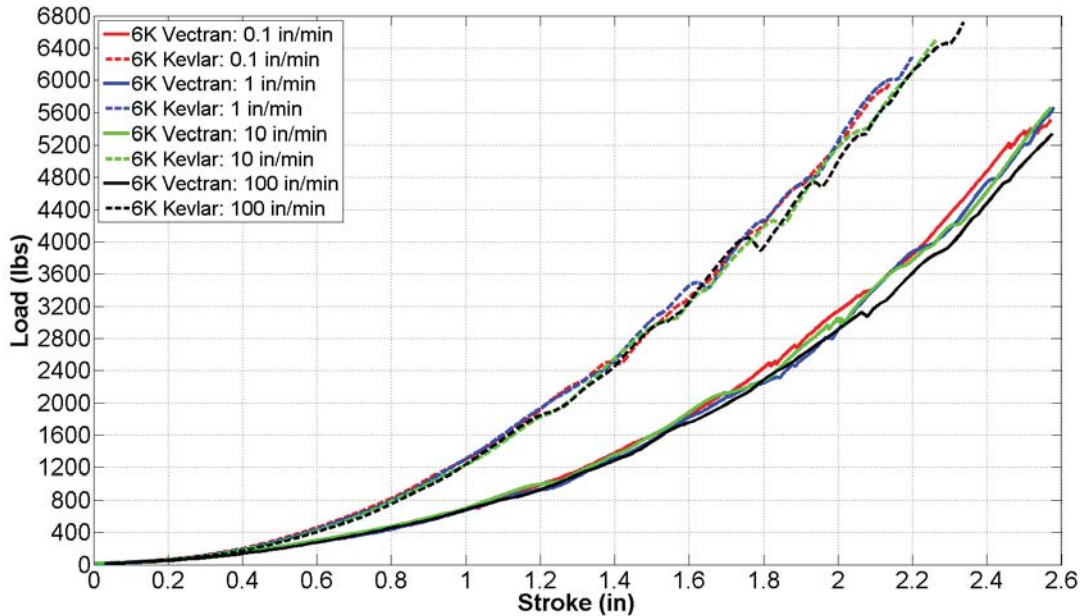| Rate	6K Kevlar		6K Vectran	
(in/min)	Avg UTS (lbs)	Std Dev (lbs)	Avg UTS (lbs)	Std Dev (lbs)
0.1	6236	93	5837	163
1	6732	136	6008	236
10	6869	131	5798	167

Figure 13. 6K Vectran and Kevlar displacement rate test comparison for short specimens.

A second series of tests performed on 12K Vectran explored differences in both load and displacement rate for long and short test specimens. These tests were performed in the shorter 55-kip test stand and the tall 110-kip test stand. The results of these tests fall very much in line with those of the 6K webbings and are shown in Figs. 14 and 15. Fig. 14 shows a comparison of short and long specimens tested at the ASTM D6775 standard 3 in/min displacement rate versus two load rates; 150 lbs/s and 600 lbs/s. The long and short specimens for each rate display negligible differences in their stiffness curves, however there is a slight shift of the 600 lbs/s curves to the right (i.e. more compliant). In Fig. 15, displacement rates of 0.1, 1 and 10 in/min were tested, with negligible differences again between the short and long specimens. In these cases there was a slight shift of the curves to the left with increasing displacement rate along with a higher variance in the curves. When rapidly loaded, the decrimping and fiber binding may become more chaotic, with regard to when the fibers are fully locked versus a slow load up, possibly leading to this observed variance. The differences observed in these curves suggest the load or displacement rate and the

specimen length have relatively minor effects on the material behavior, given the inherent variability, particularly in the 12K Vectran.
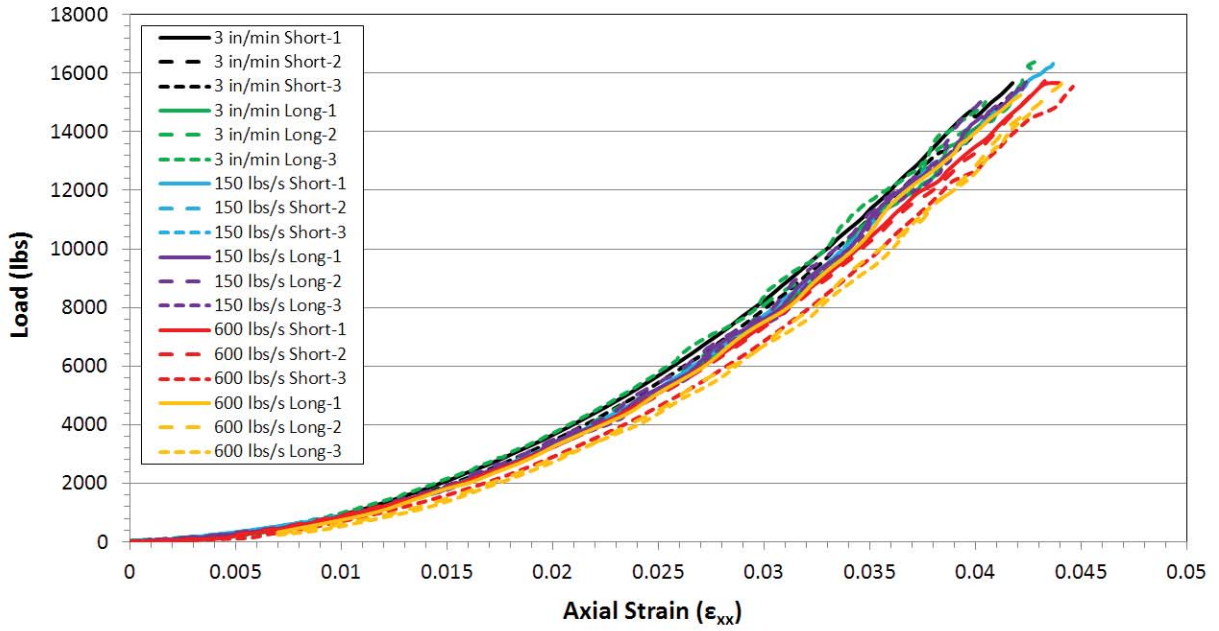

Figure 14. 12K Vectran displacement and load rate test comparison for short and long specimens.
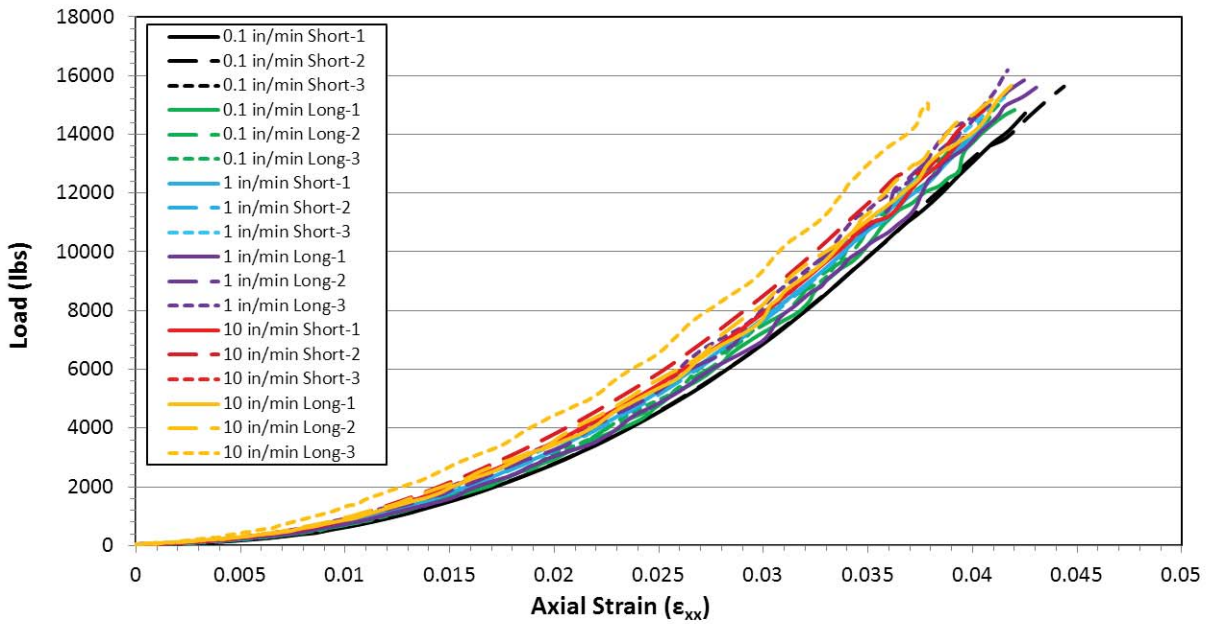

Figure 15. 12K Vectran displacement rate test comparison for short and long specimens.

D. Preconditioning Effects on Load versus Displacement Behavior

Inflatable flight articles and webbing materials will typically be load tested prior to launch either to verify strength performance or for leak testing of full-scale articles. Load cycling the webbing, also known as preconditioning, has a significant, and time-dependent effect on the stiffness curve. These effects were studied in a very limited test series during the creep test program on four 6K Vectran webbings with sewn looped ends. The specimens were 95-inches in length, loop-to-loop and were loaded to 20, 30, 40 and 50% UTS in the tall test stand. The oven was slid out of the way to provide the maximum specimen length. Each plot in Figs. 16 to 19 represents a single specimen that was loaded to a set % UTS, multiple times over the course of 1.5 years. It should be noted that *only the ramp-up is shown* in the figures to more easily compare the slopes over time. The stroke data is also normalized to 10 lbs initial load (i.e. zero stroke is set at 10 lbs). Between tests the specimens were kept in a UV-opaque bag, in an air-conditioned laboratory.
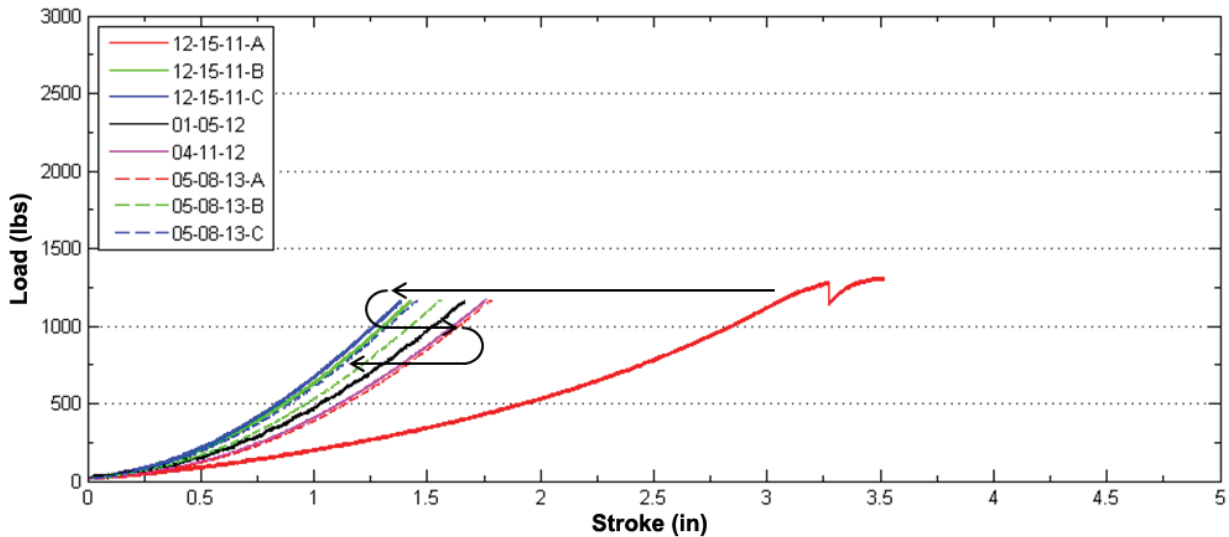
Figure 16. 6K Vectran load cycles to 20% UTS performed periodically over the course of 1.5 years.
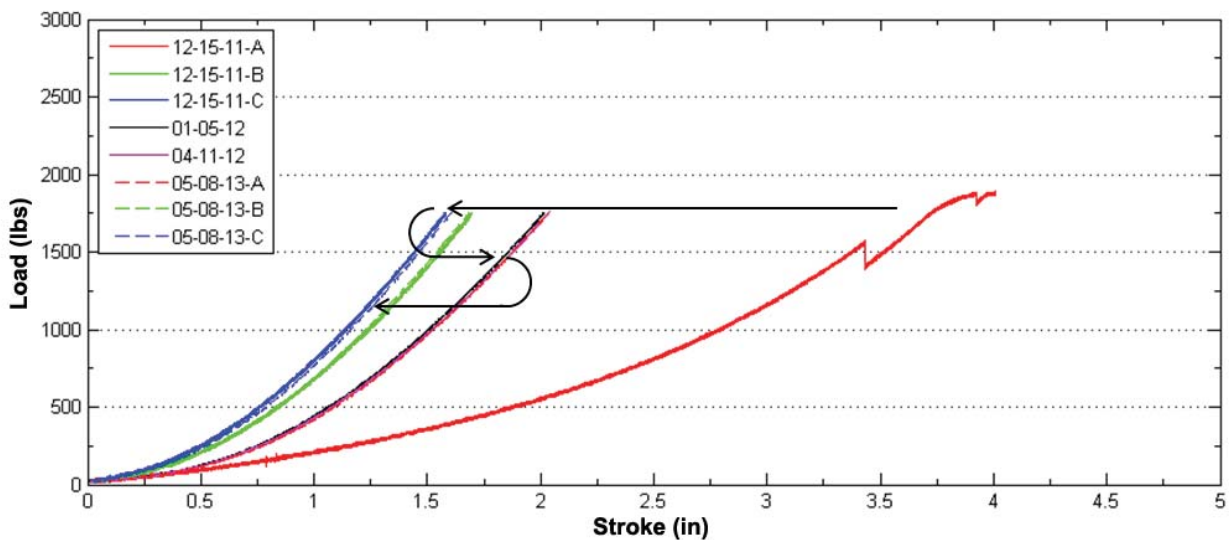
Figure 17. 6K Vectran load cycles to 30% UTS performed periodically over the course of 1.5 years.
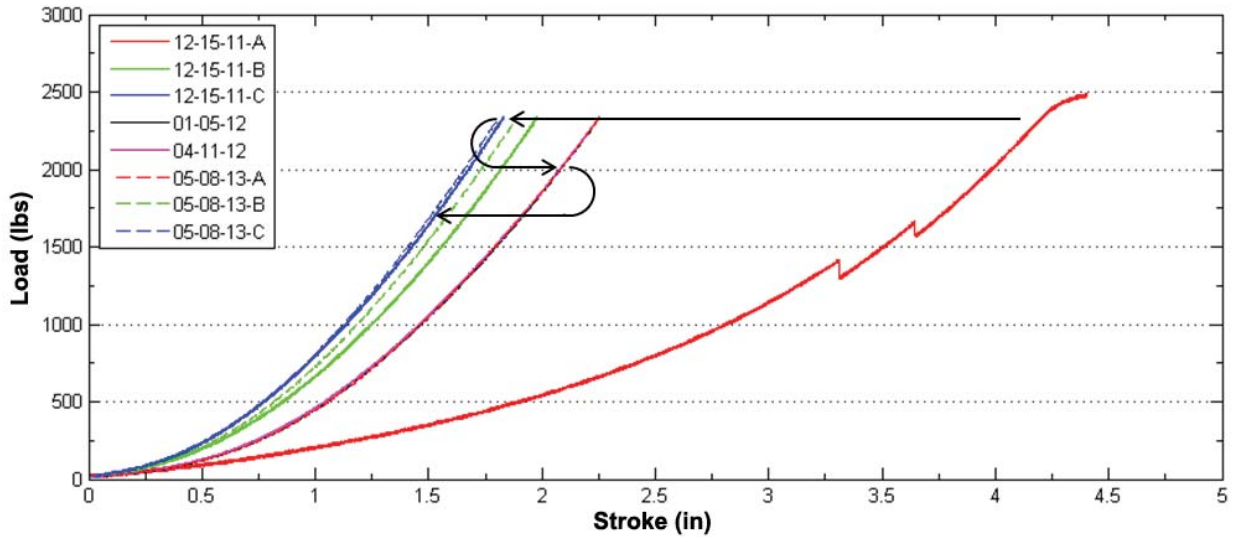
Figure 18. 6K Vectran load cycles to 40% UTS performed periodically over the course of 1.5 years.
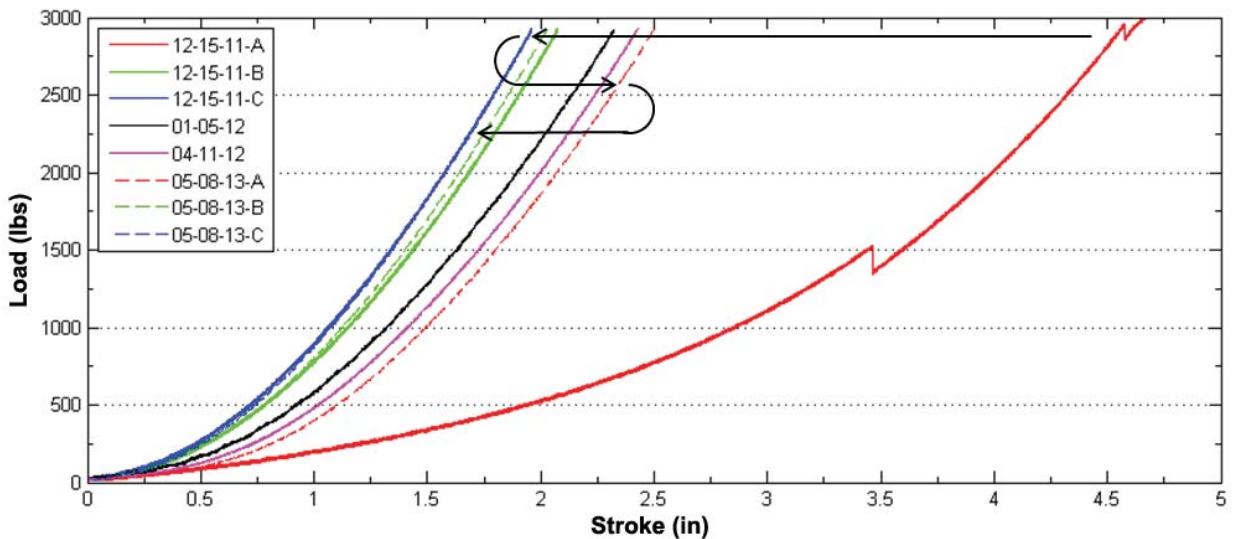

Figure 19. 6K Vectran load cycles to 50% UTS performed periodically over the course of 1.5 years.

Initially, three cycles were performed on 12-15-11 to the specified load level. The first cycle is always much more compliant than the subsequent cycles due to the webbings' initially looser weave. The first loading causes decrimping, crimp-interchange and fiber jamming to occur that tightens the weave and produces stiffer load-deflection behavior in the later cycles. The fiber jamming also causes a semi-permanent length change in the specimens that is only partially recovered over time if left unloaded. By the third cycle, the curve approaches a limit whereby additional cycling will not shift the curve any further left. This is seen at all tested load levels. On 01-05-12 and 04-11-12 a single cycle was performed on each specimen. The plots illustrate that there was some relaxation that occurred over this time period, shifting the curves to the right. Approximately 22 to 26% of the length change that occurred initially was recovered for the 50% down to the 20% UTS load cases respectively, with slightly greater recovery for the lower loaded cases. A year later, three more load cycles were performed on the specimens, with the first cycle again either shifting the curve slightly to the right (50% case) or staying approximately the same (20 to 40% cases). By the third cycle, however the stiffness curves returned to the left-most limit originally attained in the first series of tests. It should be noted that all four specimens follow the same initial curve, but every cycle after that

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follows a curve specific to the % UTS tested. The lower % UTS tests produce more compliant secondary curves versus the higher % UTS tests, which is in line with a reduced amount of initial decrimping.

These tests illustrate the difficulty in predicting the stiffness behavior of these webbings if any preconditioning has been performed, as the behavior is dependent on the load level, number of load cycles and time between cycles. All creep specimens used under this program were pristine, to avoid the additional effects of preconditioning. In the course of developing the creep test approach however, some samples were loaded multiple times prior to creep testing due to problems with the test program. These few samples lasted significantly longer than their pristine counterparts, suggesting preconditioning may actually increase creep life. This has not been verified with a comparative test series as of yet, but would be an area for future study.

IV. Accelerated and Real-Time Creep Test Results

The current test program has performed, and is presently running, real-time creep tests on all four material variants (6K and 12K Kevlar and Vectran) over a range of % UTS values, however accelerated testing has concentrated on the 12K materials, in particular the 12K Vectran. This is due to a programmatic request for creep data on these webbings because of a current NASA flight program in coordination with Bigelow Aerospace, and in part due to difficulties experienced in measuring strain on the 6K samples. The speckle pattern, painted on the 6K specimens for strain measurement in the accelerated creep tests, degrades during the tests at elevated temperatures due to fiber twisting, resulting in the loss of the test data. This problem was recently issued as an InnoCentive[TM] challenge that uses crowd sourcing to gather solutions from a network of solvers from a multitude of backgrounds and countries. Several promising solutions were awarded prizes and will be tested over the next few months. This issue has not been observed with the 12K specimens and given the timeframe of the test program the initial comparative tests were performed using only the 12K webbings. All test cases executed to date are shown in Fig. 20, where the numbers by the symbols represent the number of tests performed at that % UTS for the given variant. Real-time tests are represented by diamonds, with blue diamonds representing tests that are still ongoing. Stars represent the accelerated creep tests.
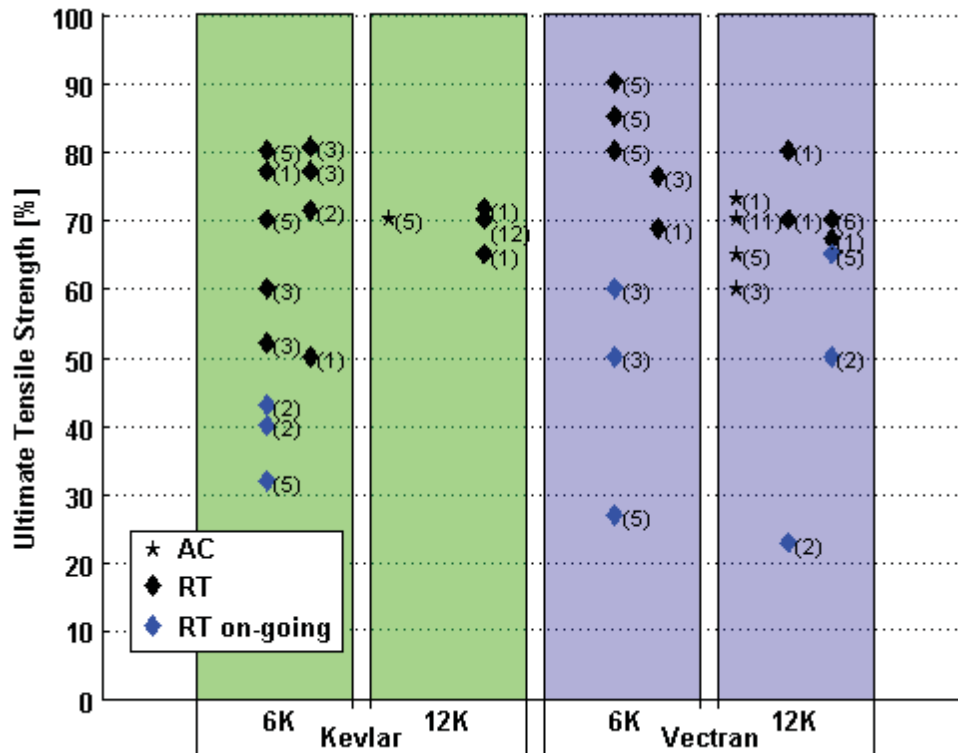

Figure 20. % UTS Creep Tests Performed versus Material Type.

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A. Time-To-Failure versus % UTS Plots

One of the most useful sets of data from these tests is the time-to-failure (TTF) versus the % UTS load for each material variant. For the comparisons of the 12K master creep curves later in this section, a highly accurate strain measurement is required throughout the duration of the tests. This may not always be available to future studies and indeed the 6K webbings tested did not have the photogrammetry or laser radar measurement system available. The TTF plots only require the final failure time and the applied load, yet provide great insight into the predictability of long term failure at different applied loads and the variability in failure times that can be expected, which are often the primary goals in performing these tests. Real-time creep test times-to-failure are given in Fig. 21 for 6K Vectran and Kevlar specimens that were tested at a high percentage of UTS. These tests were performed in the MTS load frames on short, 10-inch test section webbings to provide some quick estimates of real-time creep life for a small inflatable module being tested at NASA JSC. These specimens were tested at higher percentages of the UTS to get failures within a few days. The data is fitted with a logarithmic curve to estimate the TTF of specimens at lower applied loads. This approach works well for data that shows low variance, such as the 6K Kevlar, however it becomes more challenging for the 6K Vectran data that exhibits much greater variance in TTF. Separate curves are fit through the minimum, average and maximum values at each % UTS tested and provide a prediction band for each material variant. For the 6K Kevlar these curves are very similar and the predication band is narrow. The 6K Vectran however displays a wide band of TTF values, almost up to an order of magnitude at 80% UTS. Conservatively, one could take the minimum line and determine a safety factor that moves it further to the left (i.e. reduces the predicted TTF for a given % UTS). This conservatism would have to be weighed against the level of variance observed and the confidence in the predicated range. Care must also be taken in extrapolating such a curve too far to the right, which assumes all the data at lower loads would fall within the predication band. This is one of the primary reasons that lower % UTS real-time tests are also being performed under this program to the extent possible given facility and time constraints.
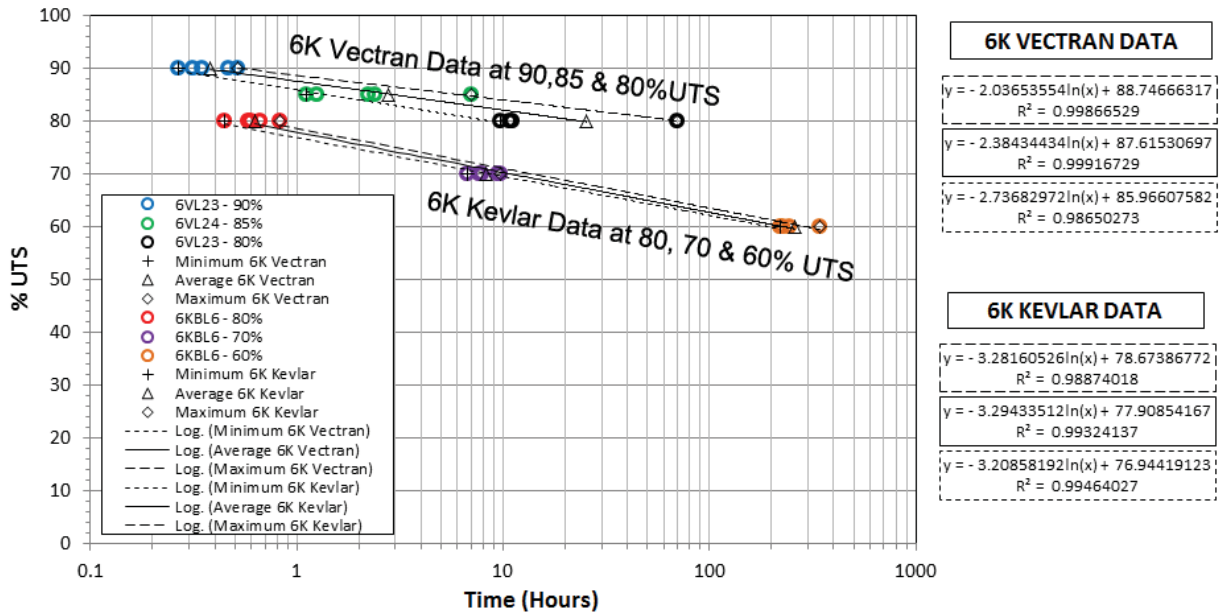

Figure 21. Time-to-failure versus % UTS for 6K Real-time Creep Tests.

B. Accelerated and Real-Time Creep Test Comparison

A series of accelerated creep tests on 12K Vectran were performed at loads from 60 to 70% UTS and two specimen sets at 65 and 70% UTS were compared to a parallel series of real-time tests performed in the large-scale creep test facility. The primary series of accelerated tests used a 1500 lbs/s load rate to mirror the rate used in the real-time tests, and were performed in the small load frame with a 10-inch test section. The master creep curves for 60, 65 and 70% UTS are shown in Fig. 22. The creep strain is the strain that occurs after the initial load-up to the test % UTS and is on the order of 5% of the total strain to failure of the webbing for 12K Vectran. One 70%, and two 60% UTS specimens were lost due to unexpected hydraulic shutdowns and were removed from the data set.

The major details that are observed are the branching of the curves for each specimen at different points, the large variance in TTF at a given % UTS and the dramatic increase in predicated TTF between 70% and 60%. The branching of the master creep curves has been regularly observed in all webbing creep tests performed under this study. It is believed, as was discussed in the introduction, that local failures in the webbing are the probable cause of the branching, as non-uniform stresses in the fibers result in some being more highly loaded and failing first. This increases the stresses in the remaining fibers and the master creep curve reflects that with a change in slope until it reaches a steady state once again or propagates a failure. The large variance in TTF is most likely a reflection of the large variance in strength observed for 12K Vectran. High variance in the strength results in some specimens being effectively creep tested at a higher or lower percentage of that particular webbing's UTS. For example if the average UTS is 15,000 lbs with a ±9% variance, then a specimen loaded to 70% average UTS is in reality in the range, 64 to 77% UTS. Observing the difference in TTF over the 60 to 70% range tested, illustrates the large effect on TTF that a small change in applied load has.
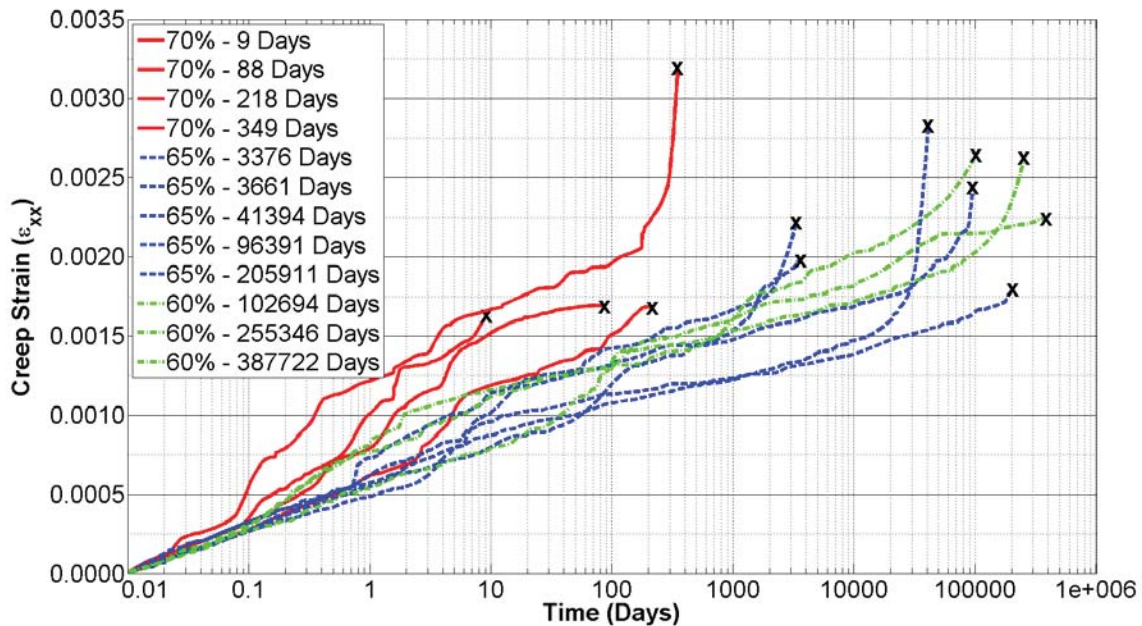

Figure 22. 12K Vectran master creep curves from accelerated creep testing at 60, 65 and 70% UTS. These tests were all performed at 1500 lbs/s load rate with short (55-kip) specimens.

After this test series it was decided to run two more sets of accelerated creep tests on the 12K Vectran at 70% but at the ASTM-D6775 standard displacement rate of 3 in/min and in both the short and tall load frames to determine if the rapid load rate and a short test section may be affecting the results. The results of this study are presented in Fig. 23 and show that the longer specimens do appear to have slightly less creep strain than their shorter counterparts. However, the significant reduction in load-up speed (from 7 seconds to about 45 seconds at 3 in/min) and increase in test section length (110-kip samples in green) has essentially no effect on the TTF. It should be noted that the strain for the longer test samples is measured over a 10 to 15-inch speckled section in the middle of the 74-inch total (grip-to-grip) specimen. The short 10-inch test section is from grip-to-grip, thus edge effects may be increasing the recorded strains slightly. The difference also looks inflated here due to the scale but is on the order of 1 to 2% of the total strain.

The comparison of the 65% and 70% accelerated creep tests with the parallel real-time tests are shown in Figs. 24 and 25. A large variability in results is even more prevalent in the real-time creep test data, with two of the 70% samples breaking in less than a day, one in a month and one after more than two months. The latter two specimens fall within the prediction band of the accelerated tests at 70%. The first two may be examples of propagating failures due to some initial local stresses. Setting up an accelerated test in either load frame is relatively straightforward and the specimen alignment can be carefully controlled. The real-time tests are significantly more challenging to setup due to the scale of the apparatus, the use of the overhead crane to lower the weights and the requirement of using a forklift to position the person loading the sample. Loading the custom Mil-T-87130 grips is also more challenging than the sedam grips used in the accelerated tests, requiring a different and longer wrap. Any of these factors may
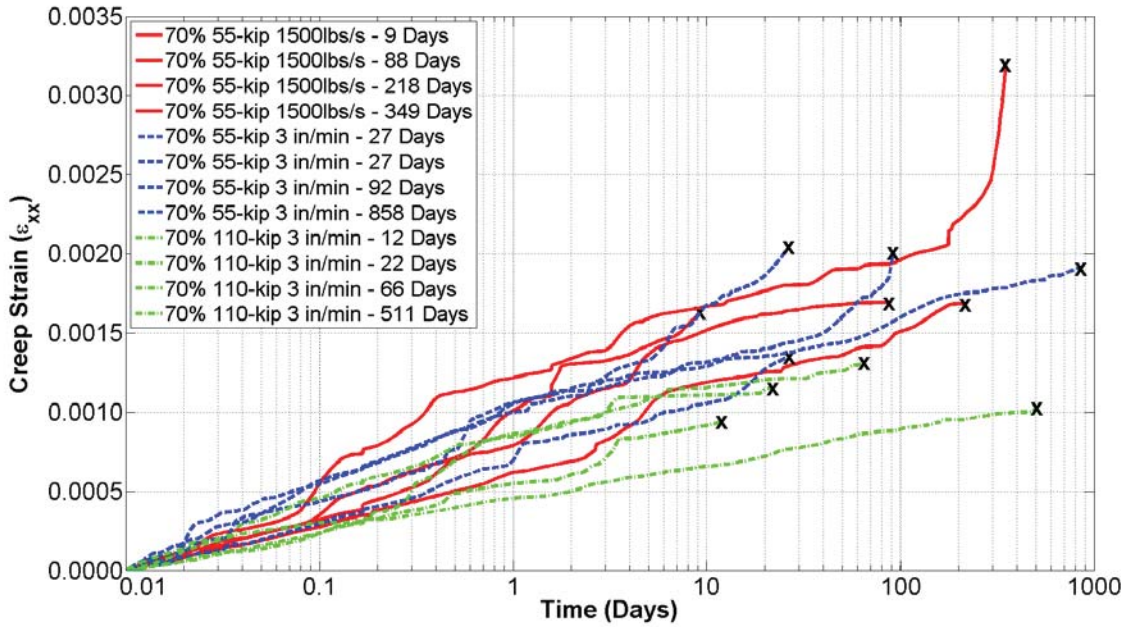
Figure 23. 12K Vectran 70% UTS master creep curves from accelerated creep testing. These tests include 1500 lbs/s load rate and 3 in/min displacement rate tests with short (55-kip) and long (110-kip) specimens.
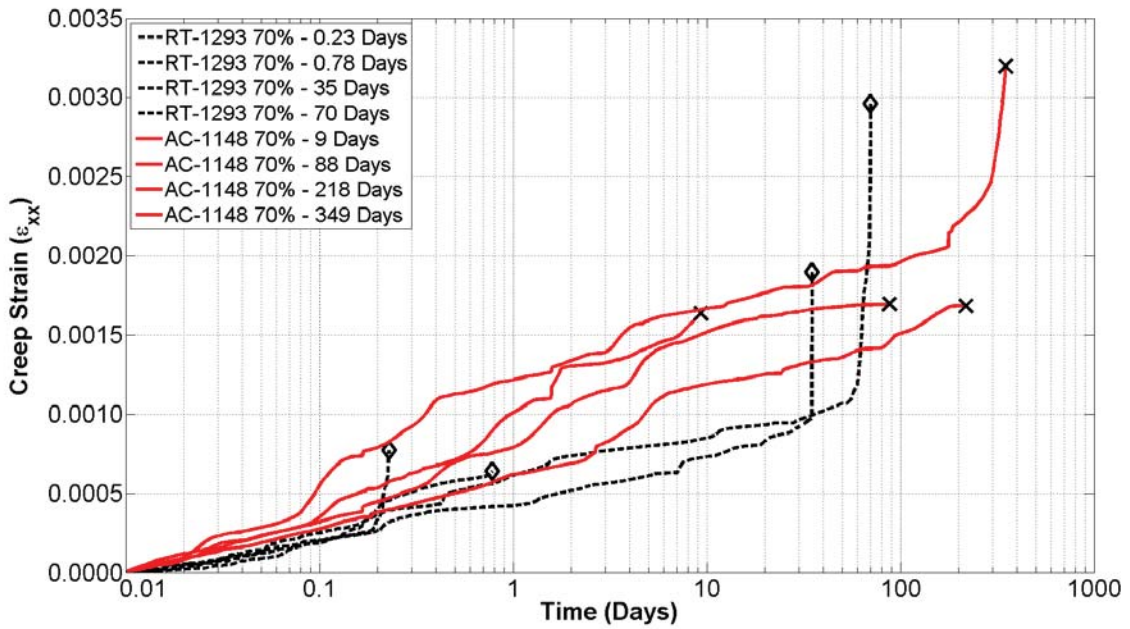

Figure 24. 12K Vectran 70% UTS load, accelerated versus real-time creep tests at 1500 lbs/s.

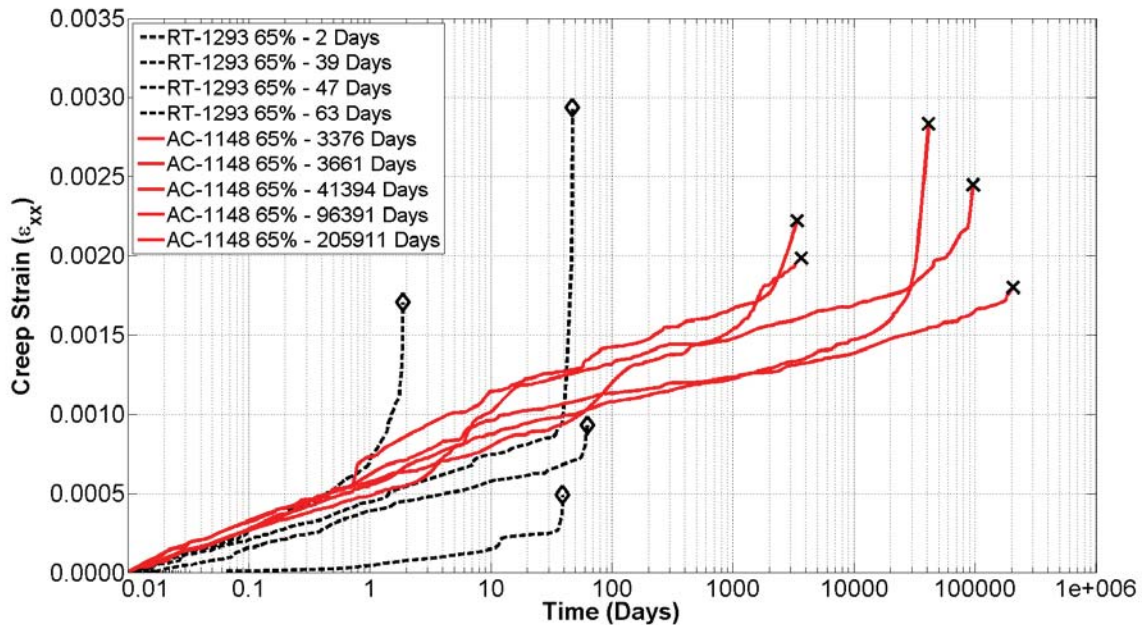American Institute of Aeronautics and Astronautics

Figure 25. 12K Vectran 65% UTS load, accelerated versus real-time creep tests at 1500 lbs/s.

contribute to slight initial misalignments in the webbing that might increase the likelihood of a premature failure. An additional challenge is that it is impossible to determine through examination of the failed specimen whether such a misalignment was the cause of failure as a creep failure still occurs and there is no visible difference at the failure location between specimens. The 65% UTS creep tests show the most marked difference between the accelerated and real-time tests. There is little change in the real-time TTF compared with the 70% UTS cases, yet several orders of magnitude change in the accelerated TTF results. Without further testing and comparisons of the other variants that have lower variability it is difficult to pinpoint the extreme discrepancy in the 65% UTS creep results.

C. Challenges in Correlating Accelerated and Real-Time Creep Tests of High-Strength Webbings

The major challenges in correlating accelerated (AC) and real-time (RT) creep tests are maintaining a stable thermal environment and accounting for differences in the required test setup and facilities. Potential factors that may be affecting the creep test correlation are listed in Table 5. The differences in load rate and specimen length have already been explored and found to have negligible or minor effects on the creep life. UV light is always a concern for long-term tests with polymer webbing but the UV environment in the two lab spaces was examined and metered and should have minimal effects on the test specimens. It is of note that real-time specimens are exposed for much longer periods, and possibly to incident sunlight when the large bay doors are occasionally opened in the large-scale real-time test lab. The accelerated tests have the benefit of a precision environmental chamber, while the real-time creep tests are in an open laboratory space. It was noted during the collection of real-time data that the temperature in the lab cycled over a 24-hour period between approximately 60 and 80°F and on occasion would rise higher on some days when the bay doors were opened. A test series will be conducted in the next year to compare real-time creep in the tall load frame with a carefully controlled base temperature versus a series with small thermal oscillations to quantify this effect. An additional result of performing elevated temperature steps during the accelerated creep testing is some drying of the fibers and emission of sizing oils. Sizing is used during manufacture to lubricate the fibers, and is evident on the grips after accelerated creep tests. Slippage, due to the sizing lubricating the grips at these elevated temperatures, was the primary reason in going to a stitched end loop on the accelerated test specimens. This emission along with additional drying may increase inter-fiber friction, which may affect the creep life. This is a difficult property to examine, but it has been proposed that thermally treated, real-time specimens that are heated to a set temperature for several hours could be compared with regular real-time creep test specimens. It is unlikely that this will be explored under the current test program however due to time constraints. As has been discussed in previous sections, the size of the test apparatus, the difficulty in setting up the real-time tests in a repeatable and consistent manner and the differences, availability and cost associated with the

instrumentation and required facilities of a large number of real-time specimens all increase the difficulty of correlating the two creep test approaches.

Table 5. Potential characteristics of test setup that may account for differences between real-time and accelerated creep test results.

Factor	Difference in Real-Time and Accelerated Creep Test	Conclusion
1	Specimen length: 6-ft in RT tests vs. 10-inch in AC tests	No effect
2	Load Rate	Minor effect
3	UV effect in real-time tests	Minimal for Vectran
4	Temperature cycling in real-time tests	Will Test
5	Elevated thermal environment (drying effects)	Intrinsic to Test
6	Stepped Isothermal Method Post-Processing for AC. (Additional steps are required to process the strains of the accelerated tests into equivalent RT strains)	Possibly needs update to methodology or is not suitable for these webbings

The last factor that was identified, as a possible source of discrepancy is the Stepped Isothermal Method (SIM) currently used for the post-processing of the accelerated creep tests. This method is based on the assumption of linearly viscoelastic behavior. Most polymers are linearly viscoelastic at lower stress and strain levels. In webbing architectures however, there is a large region of 'architectural' strain in this low-stress region, up to about 50% UTS that involves decrimping and fiber locking. Therefore, it is not until higher stress levels are attained that the stress-strain behavior reflects that of the polymeric material itself rather than the architecture of the woven strap. It is in this region that the webbing may exhibit non-linear viscoelasticity, which is suggested by the strain being only partially recoverable. Previous tests[5-8], however have indicated that the SIM approach does indeed work at the fiber level for Kevlar and Vectran, suggesting that the core material behavior is predominantly linearly viscoelastic, even at higher % UTS load levels. Accounting for the differences and non-linearity due to the architectural properties of the webbing at lower % UTS loads may well be more challenging and possibly intractable. Currently all accelerated tests have been run at 50% UTS or higher. Running an accelerated test at a low % UTS load would require many more, higher temperature steps, which may cause additional impacts on the material behavior from thermal effects and longer test times.

V. Conclusions and Future Work

This paper presents some of the findings of an ongoing study into the time-dependent behavior of high-strength Kevlar and Vectran webbings, used in the restraint layers of inflatable space structures. Four webbing variants, manufactured to Mil-T-87130 specifications were tested; 6K and 12K Kevlar, and 6K and 12K Vectran. The test facilities, instrumentation and methodology for real-time and accelerated creep tests were detailed with major differences noted in the scale and approach required for both. Several exploratory test series were presented that provided insight into the variability of the stiffness and strength of the webbings, and the time-dependent effects of load up rate, load cycling and time between loading. Finally a comparison of accelerated and real-time creep tests performed on 12K Vectran webbing was presented and illustrated inconclusive results as to the applicability of the current SIM approach used for accelerated creep testing. Multiple factors were identified that may have an impact on the discrepancy in the creep test results, some of which have been explored and some of which will be tested in the next few months. The results of these tests are providing a wealth of information on the time-dependent behavior of high-strength webbings and are highlighting some of the many facets that must be considered when designing structures using these materials.

Creep testing will continue into the first quarter of 2014, and some of the factors identified in Table 5 will be explored, however a critical area that has not yet been explored is working with the webbing manufacturers themselves to see if the straps can be manufactured to be more consistent with lower variance in strength. These webbings wouldn't just be manufactured to a minimum strength but a set statistical variance. The feasibility of such an approach depends on the cost to incorporate these design changes into the manufacturing process, which may be too costly to the manufacturer to make it worthwhile, given the small number of custom runs currently needed to produce these modules. It would in all likelihood require a level of effort and funding used in the development of a military specification (Mil-Spec) to yield the design and manufacturing capability to produce high precision, high-strength webbings. This may be necessary however, if greater confidence in material behavior and lower margins are required of future missions that employ inflatable modules.

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