NASA/TM–2020-220561

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February 2020

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Abstract

NASA is developing technologies for proposed lunar and Mars space exploration missions. Enhanced habitation systems are one element of both missions. Inflatable modules are being studied as potential habitats due to their inherent low mass and small launch volume. One goal of inflatable module research is quantification of the safe-life and end-of-life creep-strain spectrum. Full-scale pressurized inflatable modules are large, costly, and difficult to experimentally study. Therefore, material subcomponents are often studied as an alternative. An experimental thermally controlled long-term creep study of Vectran™ webbings for application to inflatable modules is presented. Vectran fibers have high strength and low creep properties. High strength webbing materials are desirable for the load bearing restraint layer of inflatable modules because they are strong, flexible, and lightweight. Characterization of the creep behavior, safe-life, and end-of-life of webbing specimens will help quantify comparable life properties for inflatable modules.

Several experimental multiple-year creep studies of webbing specimens in uncontrolled thermal environments have been conducted at NASA Langley Research Center. Experimental data obtained exhibits the classic creep-strain curve due to load, coupled with unique sinusoidal variation due to variation in temperature and humidity over daily and annual time periods. Results also have indicated that specimens fail within a year if the applied load is greater than 50 percent of the rated load.

The primary goal of this study is to eliminate thermal effects from the creep data for a group of webbing specimens, and to allow uncontrolled thermal effects to influence the creep data of a second group of webbing specimens. Comparison of both sets of data will define how temperature influences creep data. A unique creep test facility was fabricated to facilitate the generation and comparison of the two sets of data. The facility consists of five creep test stands with an integrated heating and cooling system, and four creep test stands exposed to external environmental or ambient conditions. The facility contains displacement, temperature, humidity, and load sensors. Test specimens consist of one-inch wide, 48-inch long Vectran webbings rated at 12,500 pounds-per-inch.

Experimental thermally controlled creep-strain data has been generated for two groups of webbing specimens. Applied load for all test stands was above 9000 lbs and greater than 50 percent of the rated load. Temperatures varied between 58 ˚F and 83 ˚F for the four test stands exposed to ambient conditions. Associated creep data exhibited the classic creep-strain profiles. The temperature was set to 72 ˚F for the five test stands in the controlled temperature environment. Creep data for tests with temperature control also exhibited the classic strain profiles. Data indicated that if the load is greater than 50 percent of the rated load then thermal effects do not manifest. Therefore, creep tests with loads less than 50 percent of the rated load are planned for in the near future.

Nomenclature

AT	=	ambient temperature
BEAM	=	Bigelow Expandable Activity Module
CT	=	controlled temperature
CTE	=	coefficient of thermal expansion
CHE	=	coefficient of hygroscopic expansion
FS	=	factor of safety
ISS	=	International Space Station
HVAC	=	heating, ventilation, and air conditioning
LaRC	=	Langley Research Center
LVDT	=	linear voltage displacement transducer
LCP	=	liquid crystal polymer
M/L	=	mass per unit length
MMOD	=	micrometeoroids and orbital debris
NASA	=	National Aeronautics and Space Administration
UTS	=	ultimate tension strength

I. Introduction

Inflatable space structures have been utilized in various aerospace applications [1-9] for over 50 years. Human rated inflatable space modules are currently being developed by NASA and private companies for potential weight and launch volume savings. An illustration of a proposed inflatable habitat is shown in Fig. 1a. Inflatable modules are desirable because they can be stored compactly, and deployed to a large volume for on-orbit, lunar, or Mars surface exploration activities. The shell of an inflatable structure (Fig. 1b.) consists of several material layers including; micrometeoroids and orbital debris (MMOD) shielding, restraint to support pressure loads, and flexible bladder to contain the air. An inflated restraint layer module is shown in Figs. 1c, and a deflated restraint module is show in

Fig. 2a. The restraint layer module consists of hundreds of orthogonally woven high strength webbings as shown in Fig. 2b. An individual webbing is shown in Fig. 2c.

Along with desirable characteristics for space exploration, inflatable modules have material and structural shortcomings. Prior work has indicated that webbings exhibit creep behavior [6-9]. The pressure load of an inflatable module can cause individual webbings to creep, degrade, and fail. Structural analyses of inflatable structures is inaccurate at the local level due to the imprecise orthogonal weave pattern of the webbings. In addition, failure of one or two webbings may or may not affect the performance of an inflatable module. These factors limit the appeal of inflatable modules for space missions. Therefore, the experimental study and characterization of the creep behavior of webbings helps validate material and structural performance, and analysis models of inflatable modules.

Creep is the progressive deformation of a material held at a constant load. Creep behavior has three classic stages; primary, secondary, and tertiary (Fig. 3). Primary creep is a transient stage during which the material deforms at a high strain rate. The primary creep stage is typically of short duration. Secondary creep is a steady-state stage where the webbing material exhibits near constant creep strain rates over an extended time period. The tertiary stage typically consists of material necking, which reduces the cross-sectional area of the specimen, leading to high local stresses and a rapidly increasing strain rate until failure. The Poisson necking effect is small for webbings, therefore the tertiary stage is not prominent.

The primary goal of this study is to eliminate thermal effects from the creep data of a group of webbing specimens, and to allow thermal effects to influence the creep data of a second group of webbing specimens. A comparison of both sets of data will be conducted to define how thermal conditions influence webbing creep data and life. A unique creep test facility was fabricated to facilitate the generation of the two sets of data. The test facility, experimental test methodology, and comparison of results will be described in detail.

II. Experimental Campaign

A. Test Specimen Description

High strength Vectran webbing material was selected for experimental testing in this study as it is commonly used in inflatable space modules [1]. A typical roll and a segment of Vectran webbing are shown in Figs. 4a and 4b. Vectran webbing fibers have desirable high strength and low creep properties. The Vectran webbing material utilized in this study was nominally rated at 12,500 lbs/inch, henceforth referred to as 12.5 K Vectran. Vectran is a viscoelastic synthetic material that exhibits nonlinear behavior over time while under constant load. Vectran material is typically manufactured in runs of several thousand yards from which rolls of 25 to 100 yards are cut. Vectran material manufacturers provide a minimum strength rating per roll, which is typically conservative. The database of mechanical properties for woven materials for space applications is substantially smaller than the comparable database of mechanical properties for metallic or composite materials. Therefore, an ultimate tensile strength (UTS) value was calculated per roll of material utilized.

Vectran material has a negative coefficient of thermal expansion (CTE) and a positive coefficient of hygroscopic expansion (CHE). CTE is a thermal property which characterizes the degree of expansion or contraction of a material when heated or cooled, and CHE is a chemical property which characterizes the degree a material can attract water molecules from the surrounding air through absorption or adsorption. CTE and CHE values per roll were not provided by the manufacturer.

A typical webbing specimen is shown in Fig. 5a. All webbings specimens were highly flexible, flat, 1-inch wide, nominally 48 inches long, and had two end loops for installation into pin-clevis fixtures. An end loop is generated by bending a length of material backwards over the material and stitching an 8-inch region together while leaving an opening. A diamond stitch pattern, which is very efficient for load transfer [6], was utilized to stitch the material (Fig. 5b). The webbing material consists of vertical and horizontal yarns woven together in a defined 0° and 90° angle pattern (Fig. 5c). A micrograph of the material is shown in Fig. 5d. Two test groups with comparable specimens were defined for study. Group I consisted of nine test specimens and, Group II consisted of six test specimens. Specimens in Group I were constructed from one roll of material, and specimens in Group II were constructed from a separate roll of material. UTS and load values for Groups I and II are presented in Table I. Test specimens were cycled 5 times to 25% UTS in a load machine prior to testing to lower the degree of material stretch during testing.

B. Environmental Creep Facility

The design and fabrication of a low-cost and small volume creep test facility, relative to the size and cost of previously constructed full-scale creep test facilities [7-9] was an objective for this study. The creep test facility components for the current study were designed to fit within standard office size rooms, cost less, and require less maintenance and setup time. The finalized and fabricated test facility consisted of nine lever-arm creep test stands, five of which were connected to an heating, ventilation, and air conditioning (HVAC) system, and a sensor network. The test hardware and sensors were assembled within three offices, referred to as rooms A, B, and C, which were each 10 ft by 12 ft by 8 ft in size, and in a dormant thermally uncontrolled high bay test facility. Room A, was identified for ambient creep testing, room B was identified for controlled creep testing, and room C was identified for data acquisition. The test facility lacked an HVAC control system, therefore during a test series, webbings in room A were effected by daily and seasonal changes in the environment.

The creep test stands consisted of a support frame, lever-arm, metal weights, and upper and lower webbing restraint fixtures. Drawings, of the side (Fig. 6a) and front (Fig. 6b) of a test stand and components are shown in Fig. 6. Four test stands were assembled in room A (Fig. 7), and five test stands were assembled in room B. A front view of two test stands in room A is shown in Fig. 8a. An environmental chamber was integrated into each test stand in room B. A side view of one test stand with an environmental chamber is shown in Fig. 8b. A programmable HVAC unit was installed in room B to maintain a set temperature of 72 ˚F within each environmental chamber. The HVAC unit was connected to the five environmental chambers by an air duct system. The HVAC system, air duct system, and test stand weights are shown in Fig. 9a. The environmental chambers are shown in Fig. 9b.

The data acquisition system was installed in room C, and was programmed to record displacement, temperature, humidity, and load cell data every ten minutes. Each test stand had two transducers to measure webbing displacements, and a load cell to measure the applied load. Each test stand in room B had an environmental chamber with four temperature sensors and a humidity sensor. A load cell (Fig. 10a), a temperature and humidity sensor (Fig. 10b); and two displacement transducers (Fig. 10c) are shown in Fig. 10. Displacement transducers are located on the stationary lower fixture, hence as the upper fixture translates up the transducer heads are extended and generate a displacement value.

C. Experimental Results and Discussion

Prior long term steady-state creep testing - Thermal effects have been observed in long term (years) creep test studies of Vectran webbing materials when the environment is not controlled [7-9]. Fig. 11 displays displacement data from a 12.5 K Vectran webbing specimen from a previous study [8] in an ambient environment loaded to 22% UTS over a 5.4 year test period. The curve in Fig. 11 exhibits a global sinusoidal wave pattern with six peaks and valleys, due primarily to seasonal changes in temperature and to a lesser degree humidity. Over the five year test period, facility temperatures decreased to a minimum range of 35 °F to 40 °F during the January and February time period, and increased to a maximum range of 85 °F to 90 °F during the June and July time period. Fig. 12 displays a segment of the displacement data from the same webbing over a 57 day period. The 57 day period was taken from the last quarter of the fifth year of the test data. The curve exhibits a local wave pattern due to daily changes in temperature and humidity. Temperature variations per day over the 57 day time period are smaller and less predictable, when compared to seasonal variations. The global and local displacement creep curves are inversely related to the annual and daily ambient temperatures, due to the negative coefficient of thermal expansion (CTE) of the webbing material. Figs. 13 and 14 display the comparable temperature and humidity curves over the 57 day test period, respectively. The identified global and local displacement wave patterns are assumed to have a detrimental effect on the experimental determination of the ideal webbing material creep life. Mitigation of displacement variations due to thermal variation over time is desired through long-term environmentally controlled testing. An example of the longitudinal variation in displacement of a webbing specimen due to environmental effects is illustrated in Fig. 15. Additional information on environmental effects on webbing creep life can be found in Ref. 8.

Data from nine webbing specimens in Group I – Group I was identified as the initial test group, of several anticipated test groups, with the highest load value. Test groups with progressively lower load levels are scheduled in the future as time and test material permit. Group I consisted of nine webbing specimens loaded to 69% of UTS. Five of the specimens were tested in a controlled environment (#1 - #5), and four were tested in an ambient environment (#6 - #9). Previous studies [6-9] indicated that material failure would occur rapidly at the high load levels, potentially within a one to two week period.

Fig. 16 displays displacement data, and Fig. 17 displays load cell data for webbing #9. Both displacement curves in Fig. 16 exhibit a linear increase in displacement over a six day period until webbing stitch failure. The small steps in the curve are due to fiber and yarn breakage during the test. The local thermally induced wave patterns, identified in Fig. 13, are absent. Noticeably, the load curve in Fig. 17 decreased over time, and the effects of yarn breakage are highlighted by the sharp jumps and steps in the load curve. This is anomalous behavior because the load should remain constant over the duration of the test period. The decrease in load was determined to be a test stand design flaw, caused by the generation of a small off-set angle from vertical, as the lever-arm rotates over the test period. The decrease in load was determined to be small enough, relative to the applied load, to continue with the study.

Specimen failure generally consists of material and stitch stretching, local fiber and yarn breakage progressing to stitch breakage (Fig. 18a), and complete diamond stitch failure (Fig. 18b). Failures occurred in the joining stitch not across the width of the material.

Fig. 19 displays the temperature values from the facility and the chamber containing specimen #2. Fig. 20 displays the humidity values from the facility and the chamber containing specimen #2. Environmental conditions within the chamber are within +/- 1 degree of 74.5 ˚F and within +/- 6 % of a mean humidity value over the test period. Temperature and humidity values were consistent in all environmental chambers over the test period for specimens in Group I.

Fig. 21 displays displacement data, and Fig. 22 displays load cell data for webbing #3 in a controlled environment. Both displacement curves in Fig. 21 exhibit an increase in displacement over a two day period until webbing failure. The small steps in the curve are due to yarn breakage. Local thermally induced wave patterns are absent. The controlled environmental conditions are expected to reduce the amplitudes of the local wave patterns, not totally eliminate them. As expected, the load curve in Fig. 22 decreased over time.

Fig. 23 displays displacement data from the nine webbing specimens in Group I. Fig. 24 displays strain data for the nine webbing specimens in Group I. Specimen test duration or life varied from a minimum of one day to a maximum of 11 days. All creep displacement curves exhibited positive slopes over time. Five of the specimens exhibited high strain values and failure within 3 days. All strain values were below 1%. Note, a large percentage of material strain was removed through specimen load cycling prior to test start. In general, the specimens with the shortest life experienced the highest strains. None of the displacement creep curves exhibited the local thermally induced wave pattern, exhibited in Fig. 13, due to the magnitude of the applied load and the short test duration. Data from previous studies [8, 9] indicated that loads well above 50% UTS cause large deformation, severe fiber and yarn breakage, and material yielding, which leads to webbing failure. Table II contains specimen length, test duration, load decrease, and environmental values for the nine specimens in test Group I.

Data from six webbings specimens in Group II - Group II was identified as the second test group with the second highest load value. Group II consisted of six webbing specimens loaded to 63% of UTS. Three of the specimens were tested in a controlled environment (#1 - #3), and three of the specimens were tested in an ambient environment (#4 - #6).

Fig. 25 displays displacement data, and Fig. 26 displays strain data for the six webbing specimens in Group II. One specimen experienced failure after four days, and four specimens experienced failure after 15 days. All creep curves exhibited positive slopes over time. All strain values were below 1%. In general, the specimens with the shortest life experienced the highest strain. This is consistent with specimens in Group I. None of the displacement curves exhibited a local wave pattern due to temperature variation due to the magnitude of the applied load and the short test duration. This is consistent with test results from specimens in Group I. Table III contains specimen length, test duration, load decrease, and environmental values from the six specimens in Group II.

Ambient and thermally controlled creep data from Group I and II has been presented. Due to the high-load levels and subsequent short life, discernable differences in creep life are not evident. Therefore, creep tests with loads less than 50 percent of the rated load, where thermal effects manifest, are planned for in the near future.

Concluding Remarks

A test facility for environmentally controlled creep testing has been custom designed and constructed as part of this study. Functionality, cost, size, and ease of use of the facility was a priority in this effort. Webbing material for potential use in inflatable habitats was tested in two rooms within a high bay test facility without an HVAC system. One room was designated for ambient environmental testing with four test stands, and another room was designated for controlled environment testing with five test stands. The creep test stands were designed and manufactured at NASA LaRC. The test stands were designed to be low cost, have a small foot print, and consist of off-the-shelf components. All of the test stands designated for ambient testing had integrated displacement transducers and load cells. All of the test stands designated for controlled testing had an integrated environmental chamber, temperature and humidity sensors, displacement transducers, and load cells.

Two groups of 12.5 K Vectran webbing specimens were tested. Group I consisted of nine specimens subjected to a 69% UTS (9800 lbs) load, and Group II consisted of six specimens subjected to a 63% UTS (9400 lbs) load. Five of the test specimens in Group I were subjected to a controlled set temperature of 72 ˚F, and the remaining four were subjected to ambient conditions. Three of the test specimens in Group II were subjected to a controlled set temperature of 72 ˚F and the remaining three were subjected to ambient conditions. Test specimens in Groups I and

II experienced material elongation and yielding, fiber and yarn breakage, and failure in the diamond stitched region of the specimens. Test data shows that webbing specimens in Groups I and II had a short life of less than 16 days. The shortest test lasted one day. Test data indicated that webbings in the Group II had a longer life than Group I due to the lower load level. However, no significant difference was noticed within the displacement, strain, or life data of the controlled versus ambient groups.

The thermal effects are expected to become noticeable once the applied load values are lowered to a range between 50% and 55% UTS. Future plans include additional updates to the hardware and sensors of the test facility to improve operability. Future enhanced habitation modules utilizing inflatable systems are anticipated for space exploration missions. Quantification of safe-life and end-of-life creep strain behavior for webbing materials in a controlled environment will help predict the long-term behavior of human-rated inflatable modules, reducing mission risk and increasing confidence in the use of inflatable structures.

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Acknowledgements

The authors wish to thank personnel in the following branches at NASA LaRC for their support in design, fabrication, assembly, and testing; Structural Mechanics & Concepts Branch, Material Experiments Branch, Structural Dynamics Branch, Mechanical Experimental Equipment Branch, Aerospace Composite Model Development Section, and LITES II contractors.

Figures

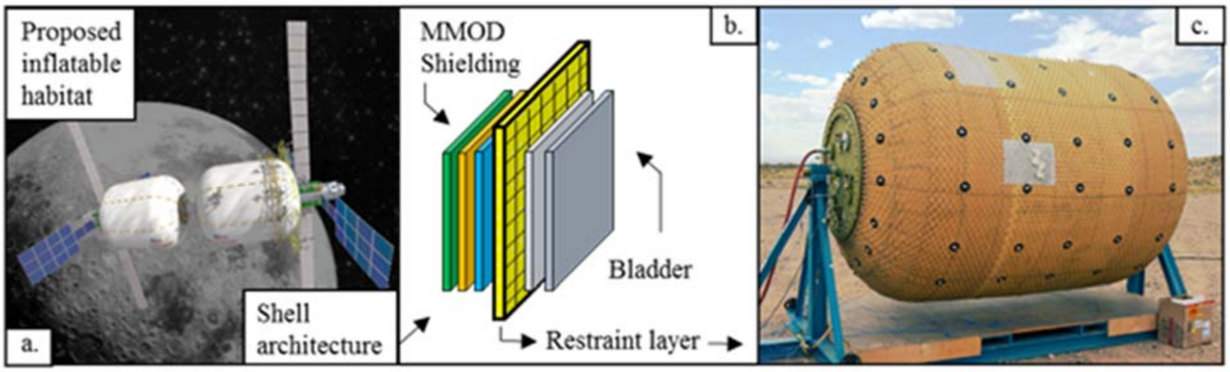

Figure 1. (a.) Image of a proposed inflatable space vehicle, (b.) typical layers of an inflatable space vehicle shell, and (c.) an inflated restraint module.

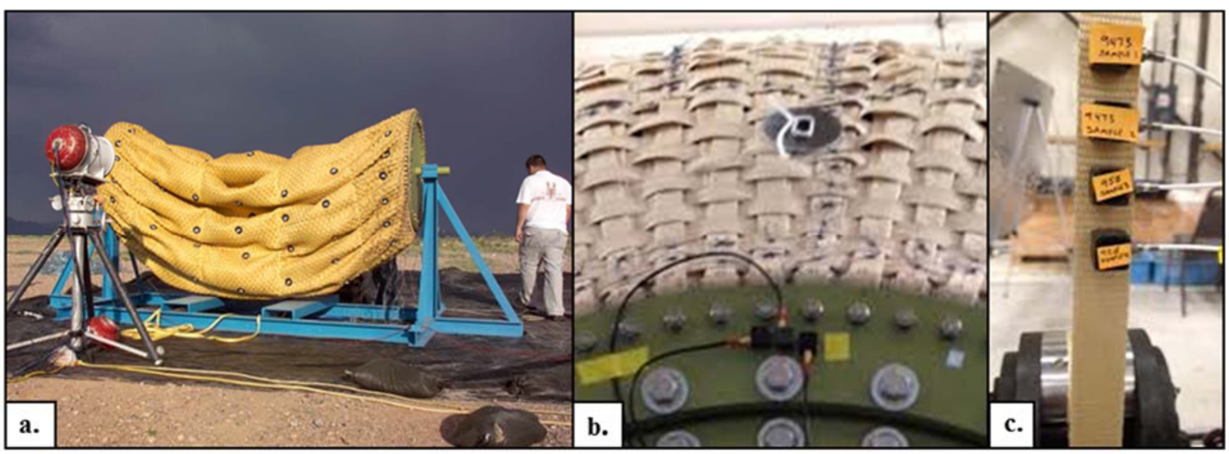

Figure 2. (a.) Deflated restraint layer module, (b.) interwoven webbings, and (c.) individual webbing.

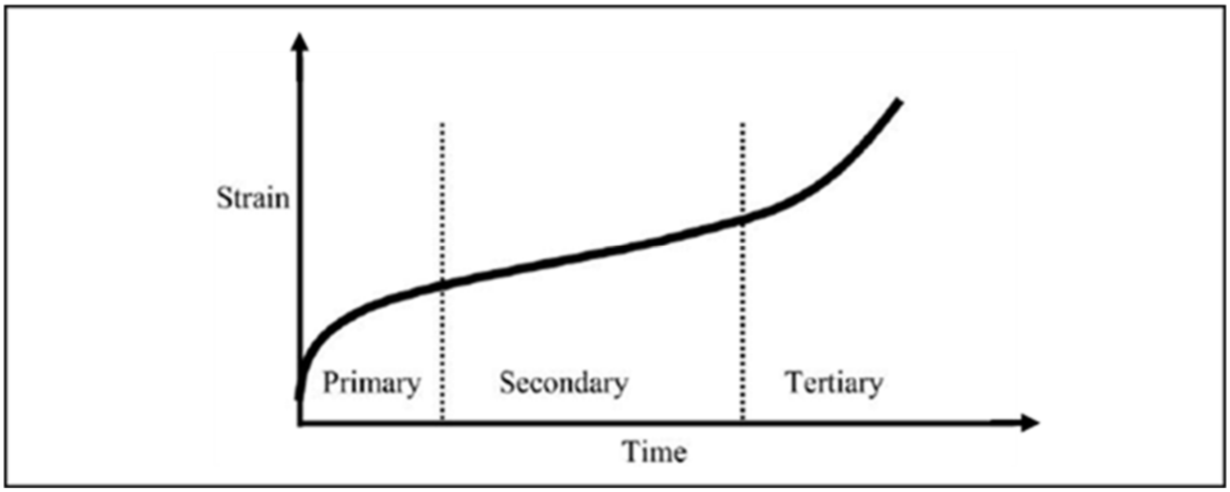

Figure 3. The three stages of classic elastic material creep.

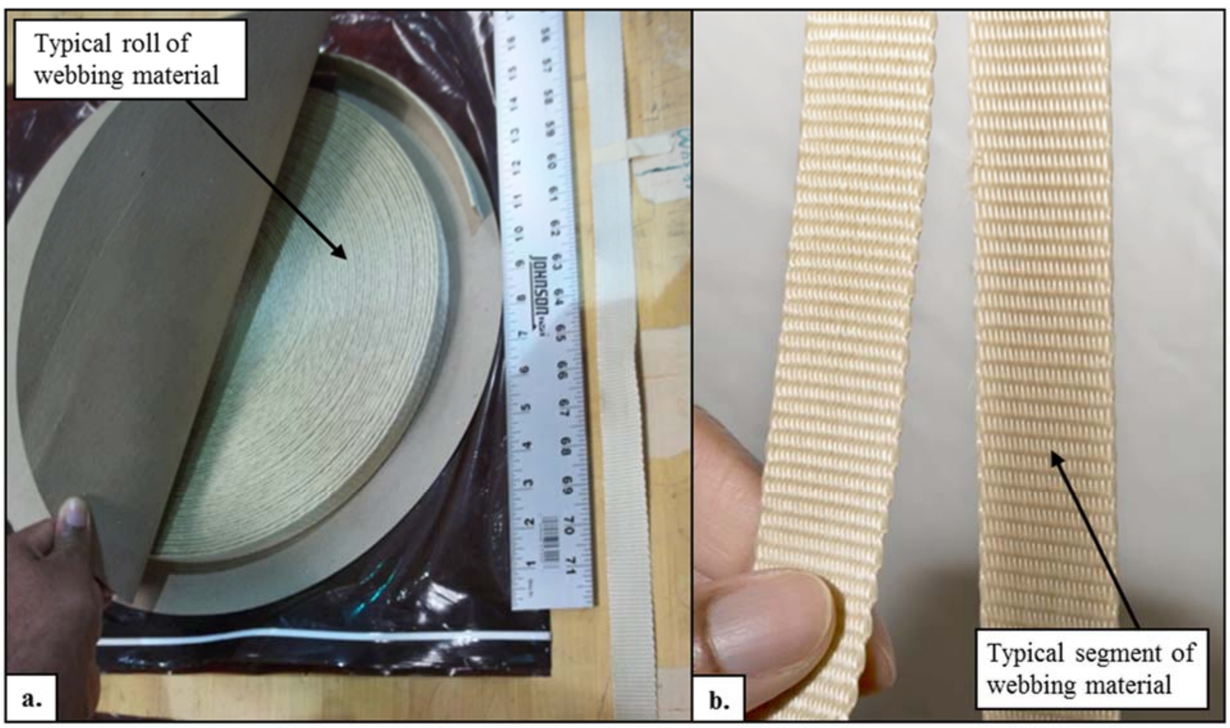

Figure 4. Vectran webbing material, (a.) typical roll and (b.) webbing segment.

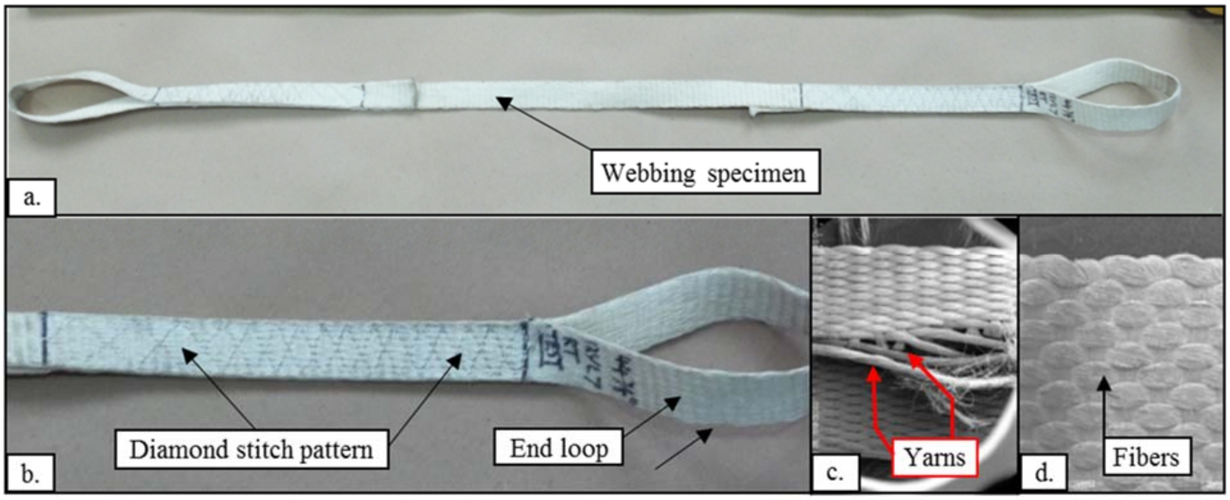

Figure 5. (a.) Webbing test specimen, (b.) stitch and end loop, (c.) yarns, and (d.) micrograph of fibers.

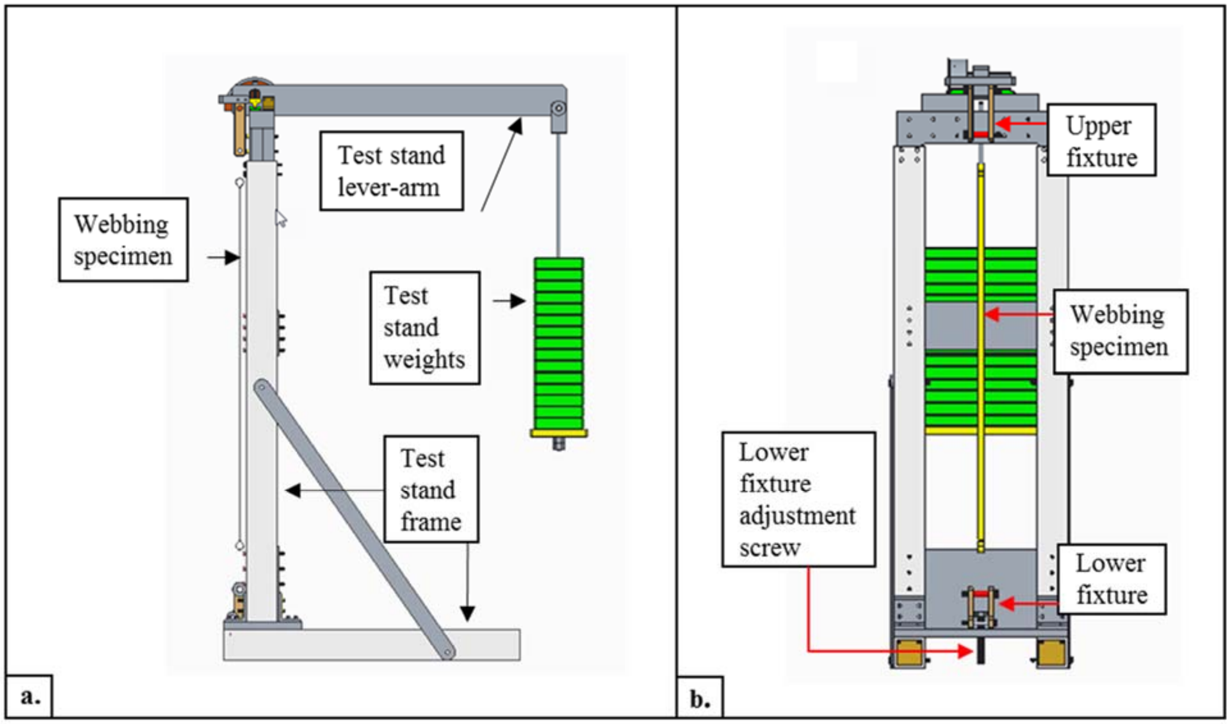

Figure 6. Drawings of a lever-arm creep test stand and components, (a.) front and (b.) side.

Figure 7. Four low-cost small-volume lever-arm creep test stands in room A.

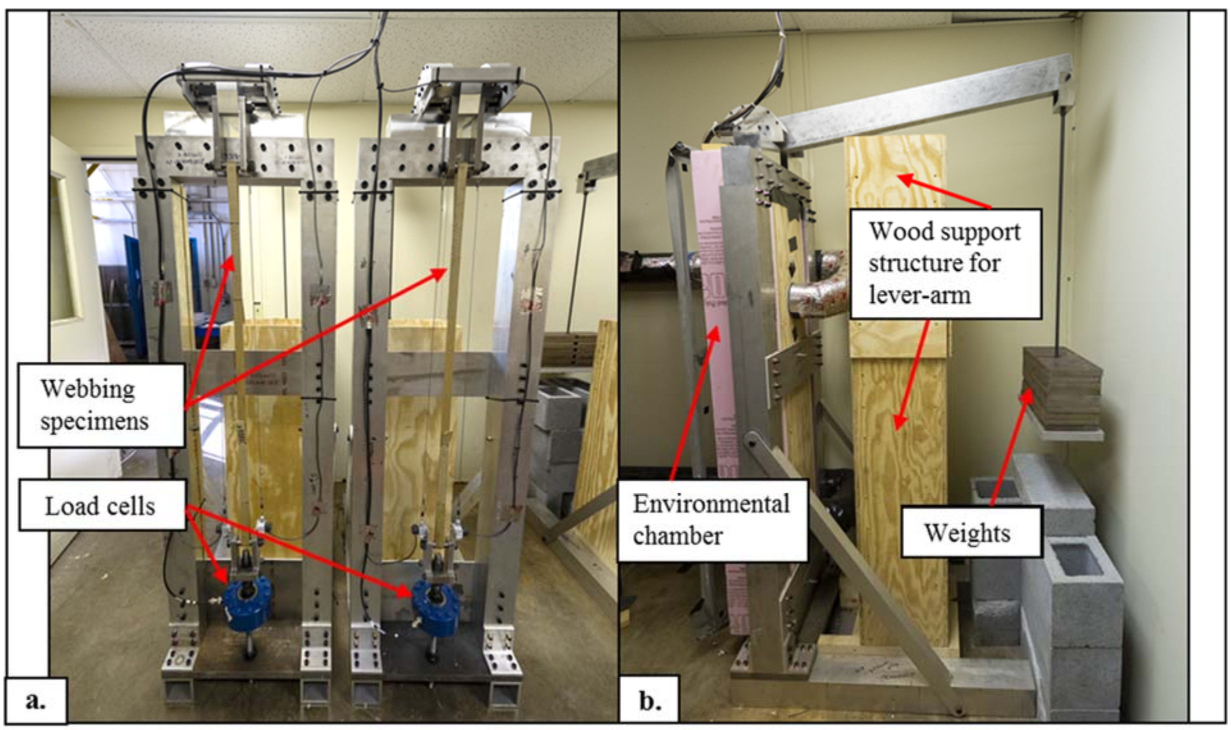

Figure 8. Lever-arm creep test stands, (a.) front and (b.) side.

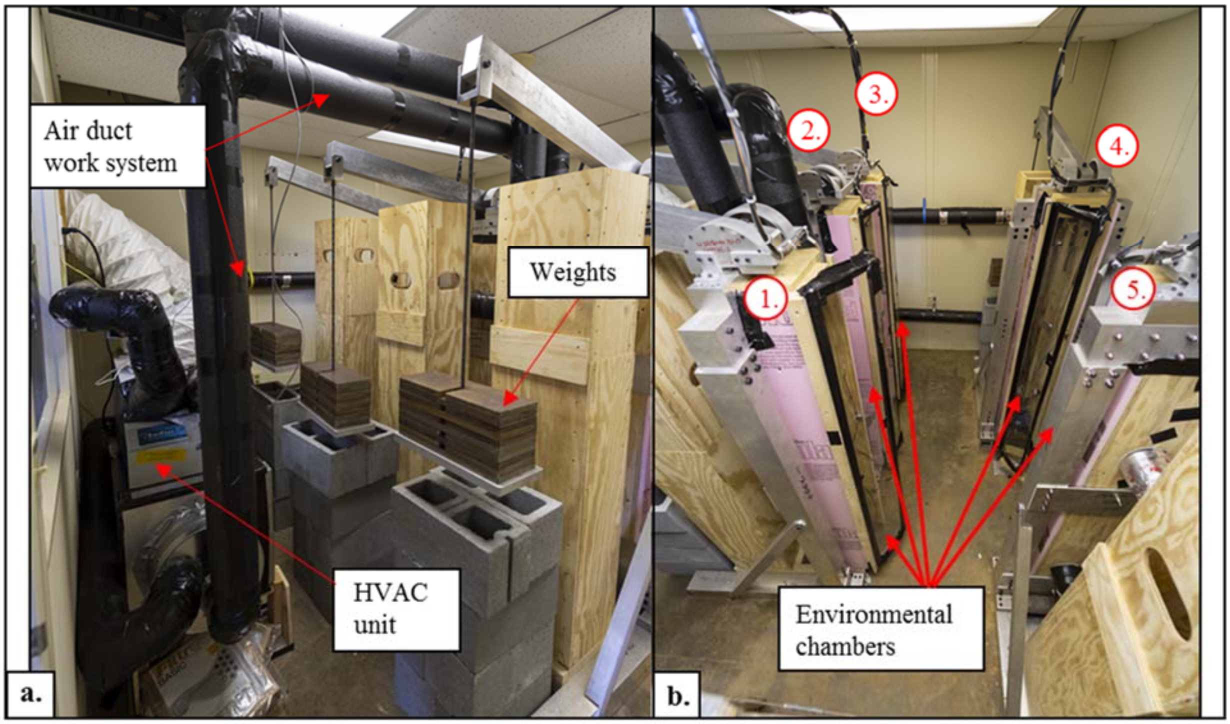

Figure 9. (a.) HVAC system, air duct work system, and (b.) environmental chambers in room B.

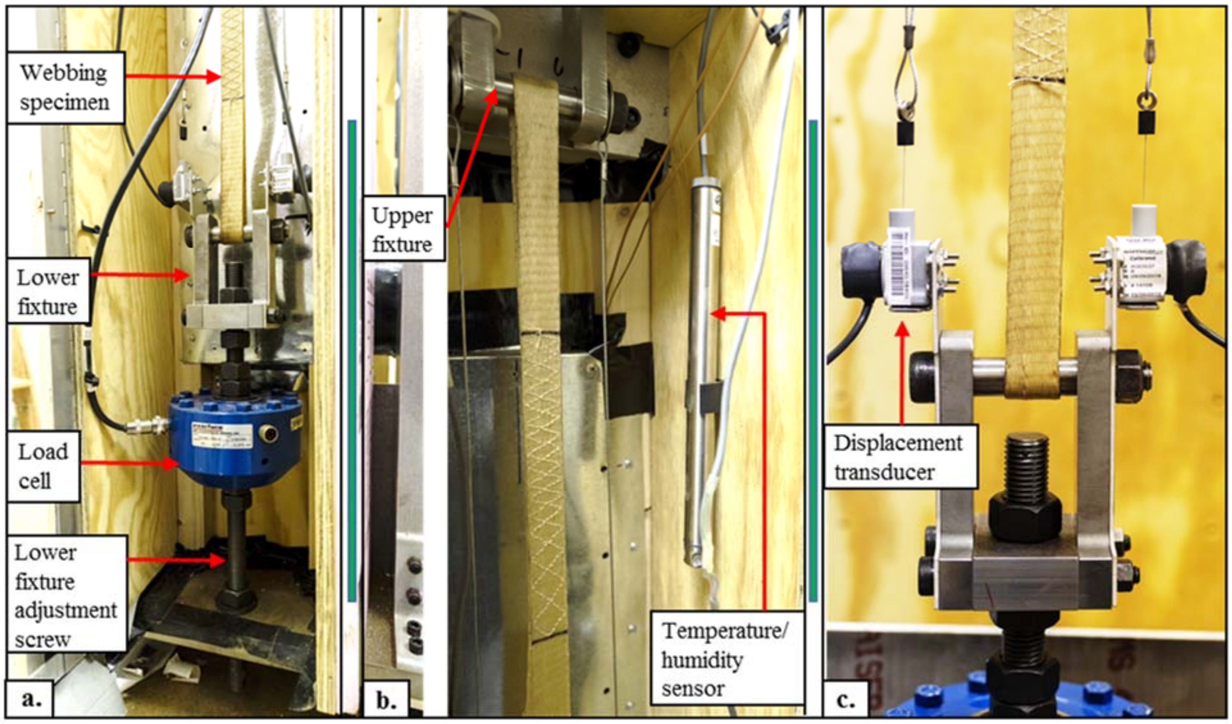

Figure 10. (a.) Load cell, (b.) temperature and humidity sensor, and (c.) displacement sensors.

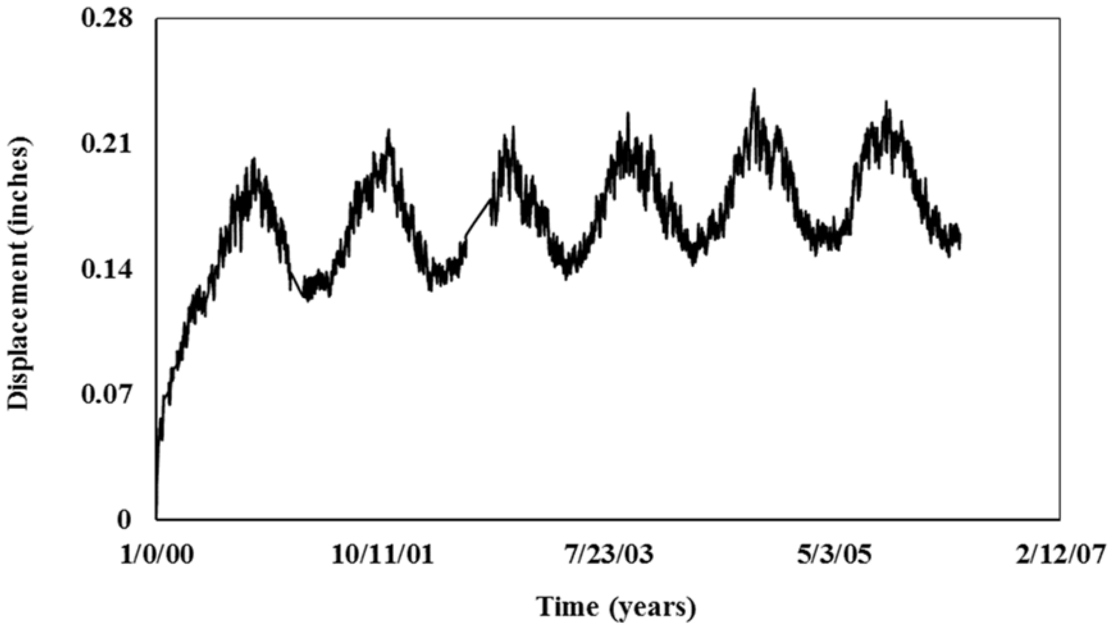

Figure 11. 5.4 years of creep displacement data with ambient global thermal effects.

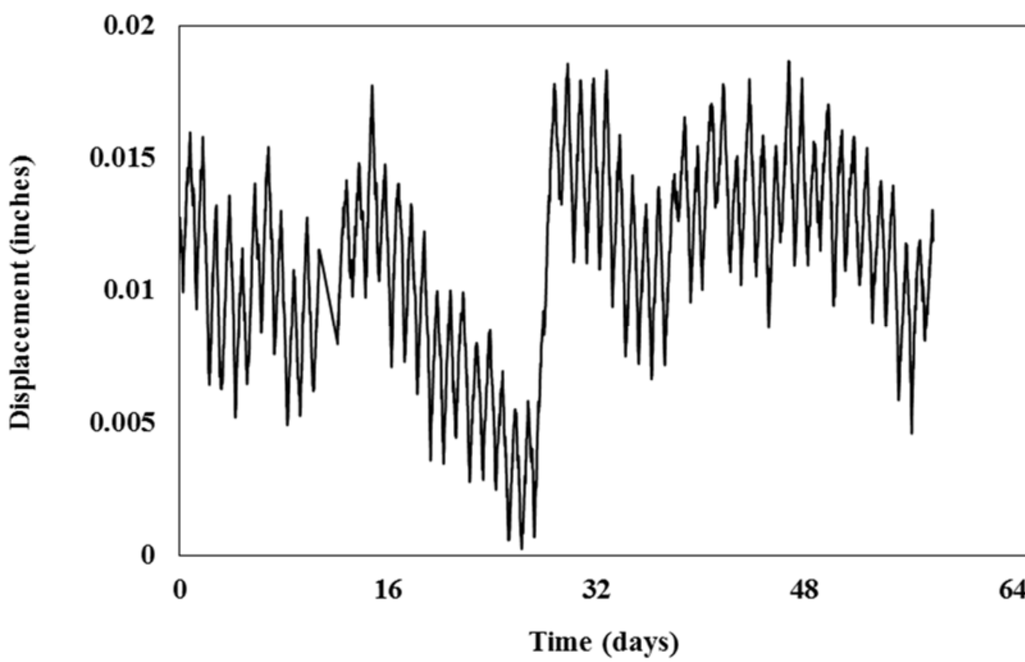

Figure 12. 57 days of creep displacement test data with ambient daily thermal effects.

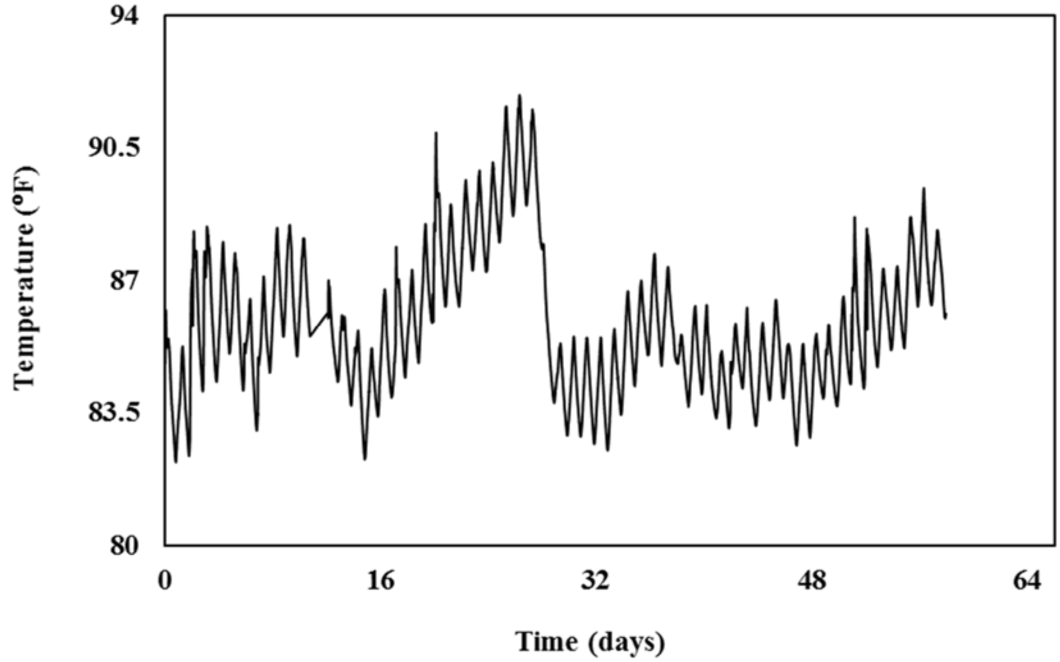

Figure 13. 57 days of ambient temperature data within the test facility.

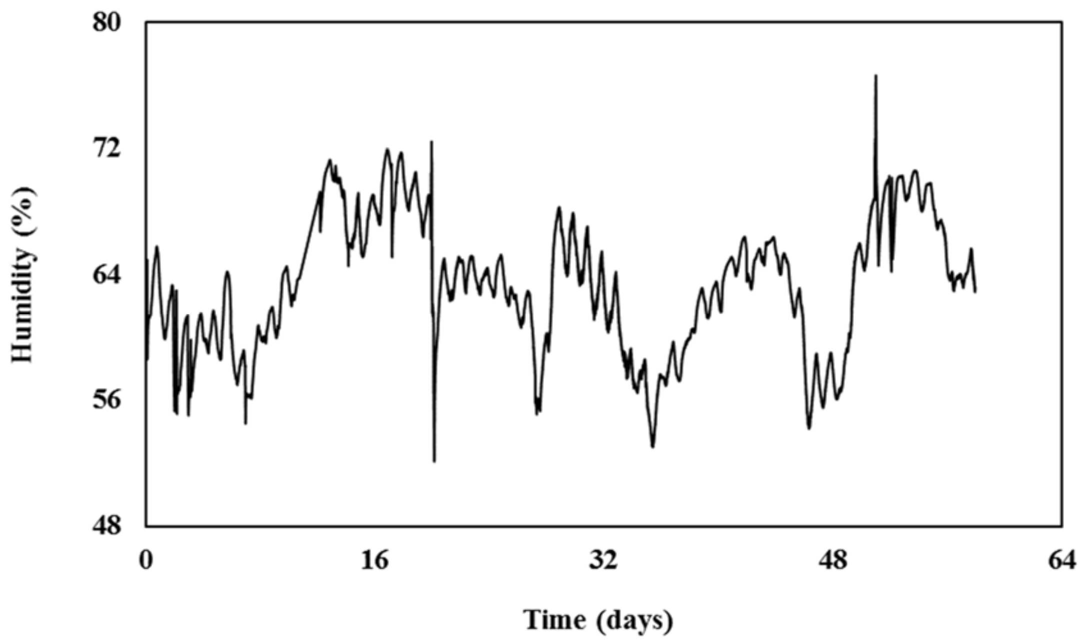

Figure 14. 57 days of ambient humidity data within the test facility.

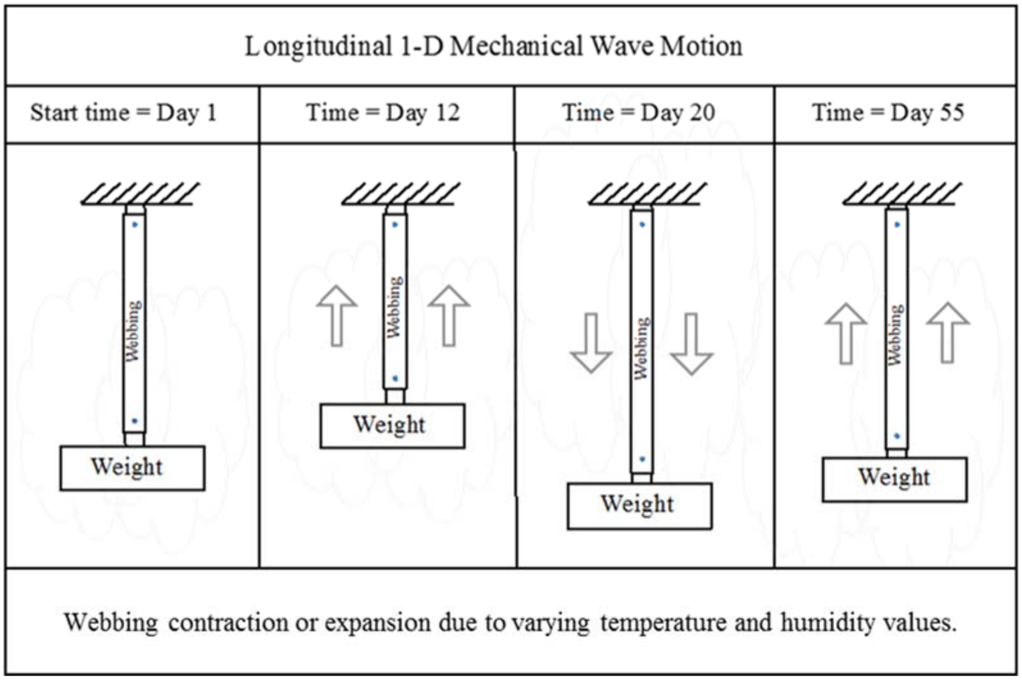

Figure 15. Longitudinal displacement motion of webbing due to environmental variations.

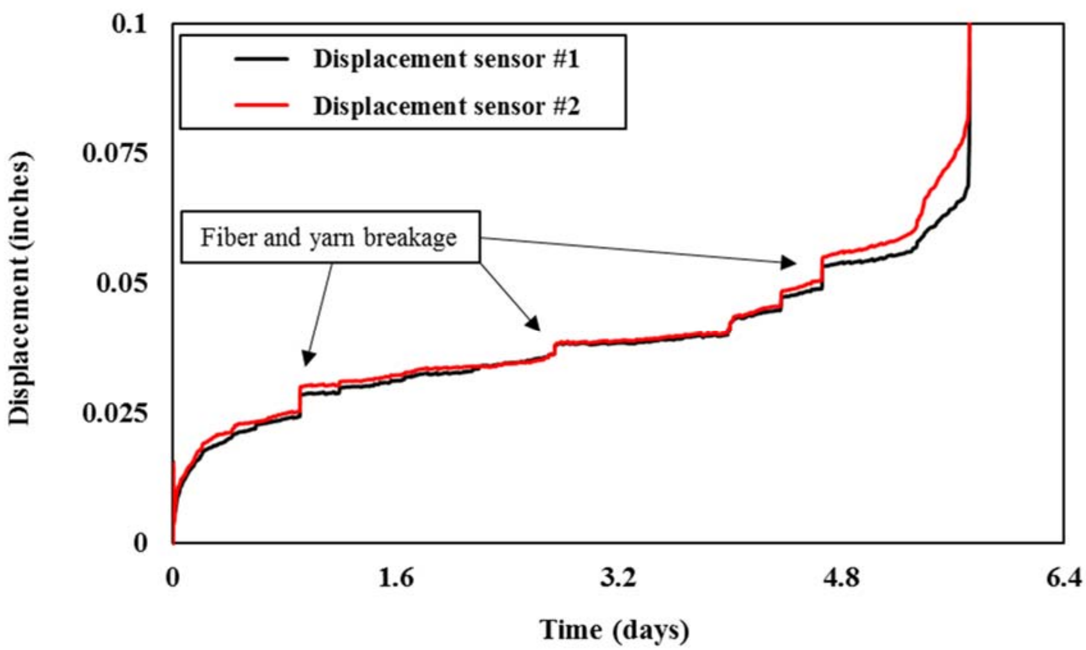

Figure 16. Displacement of two sensors versus time for specimen #9, Group I.

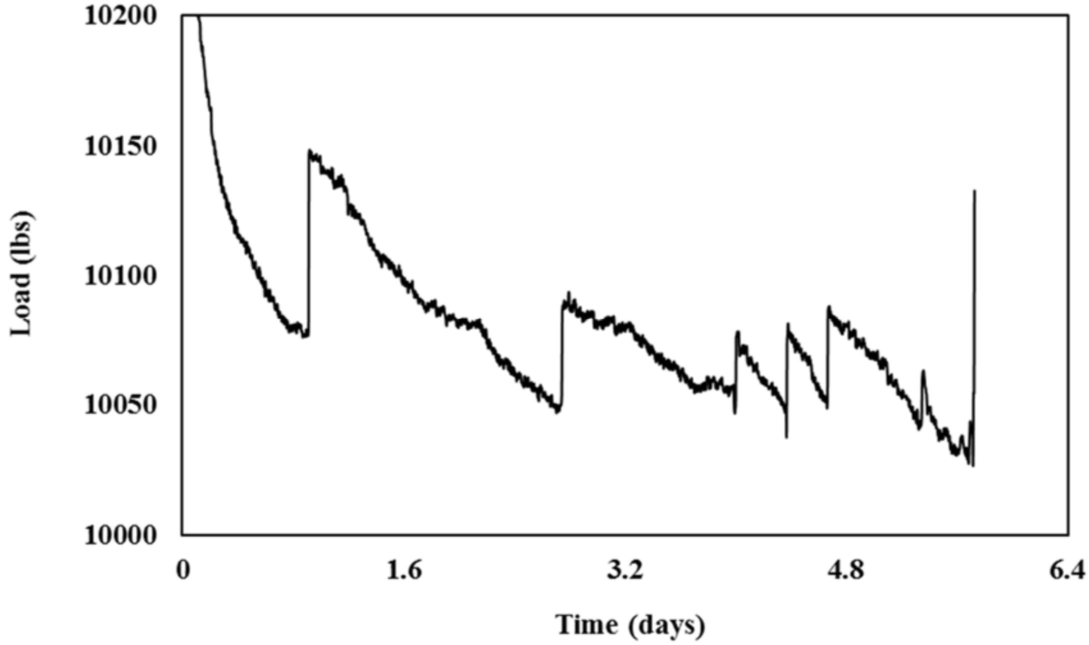

Figure 17. Load versus time for specimen #9, Group I.

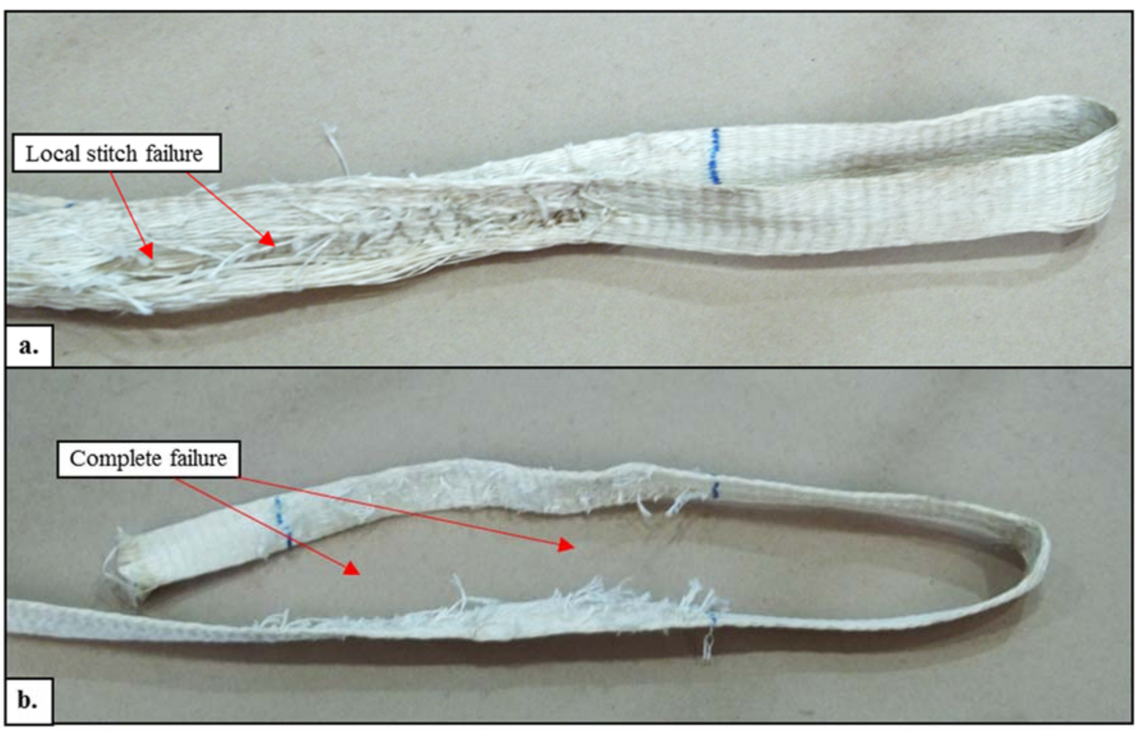

Figure 18. Webbing specimen, (a.) local stitch failure, and (b.) complete failure.

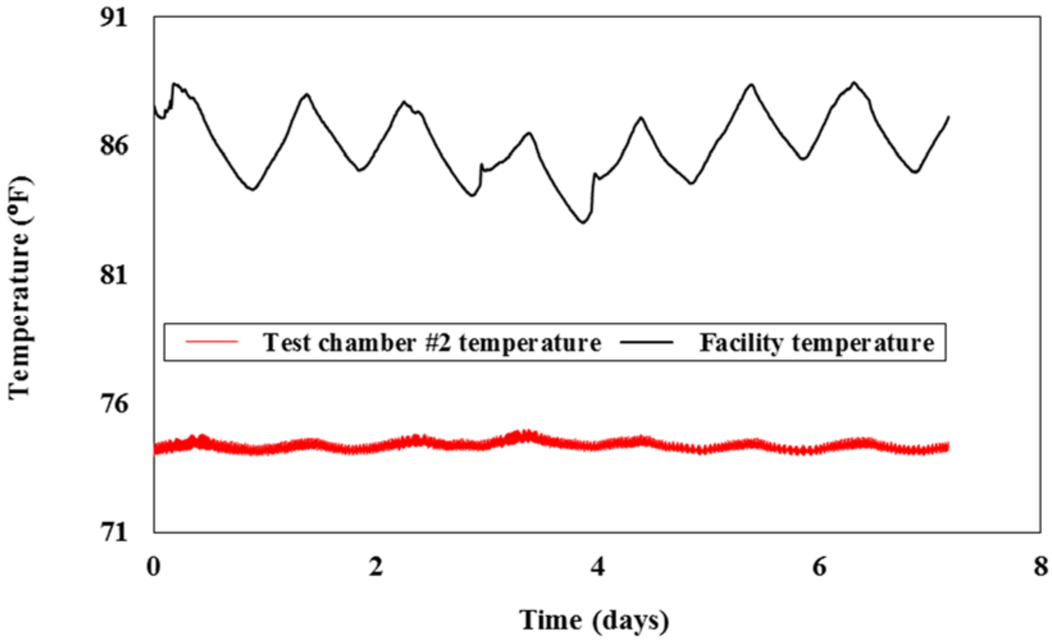

Figure 19. Temperature data from facility and environmental chamber for test specimen #2, Group I.

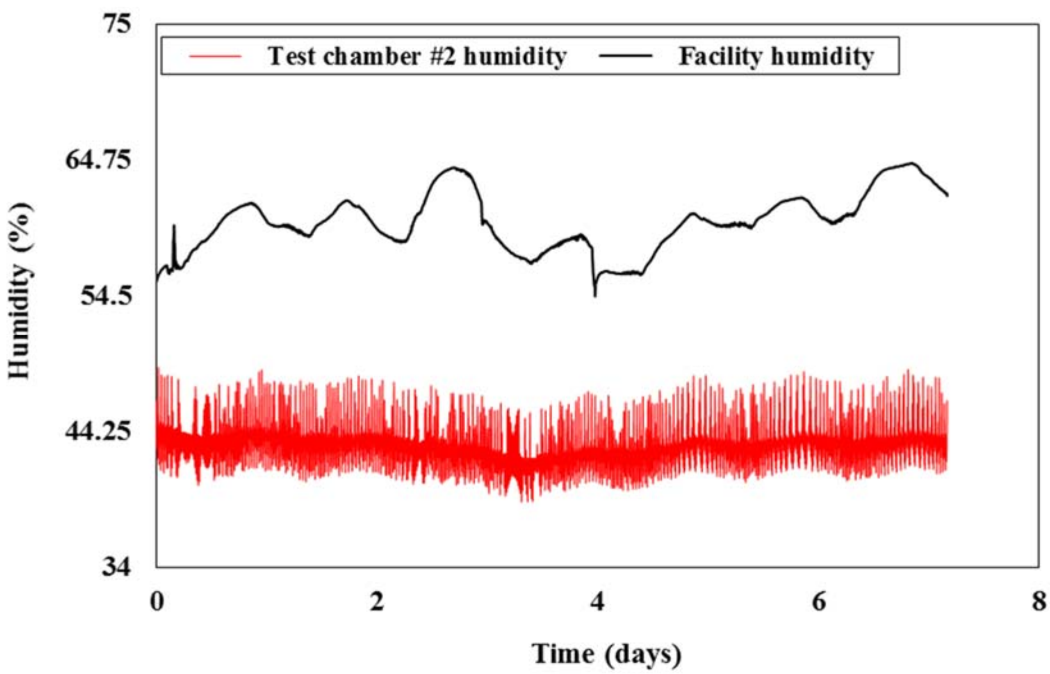

Figure 20. Humidity data from facility and environmental chamber for test specimen #2, test Group I.

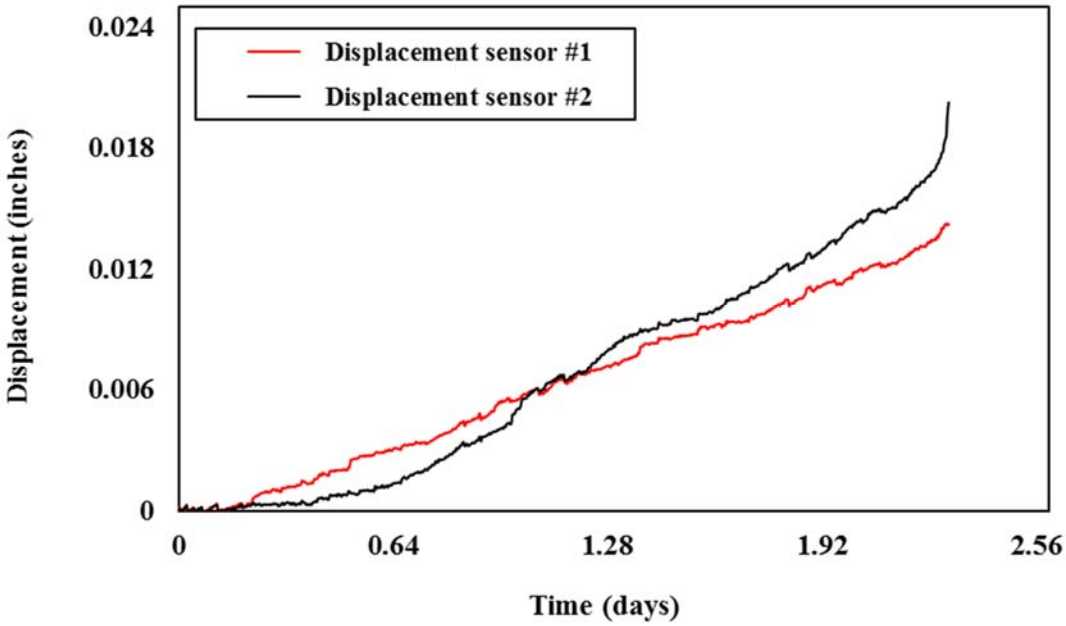

Figure 21. Displacement of two sensors versus time for specimen #3, Group I.

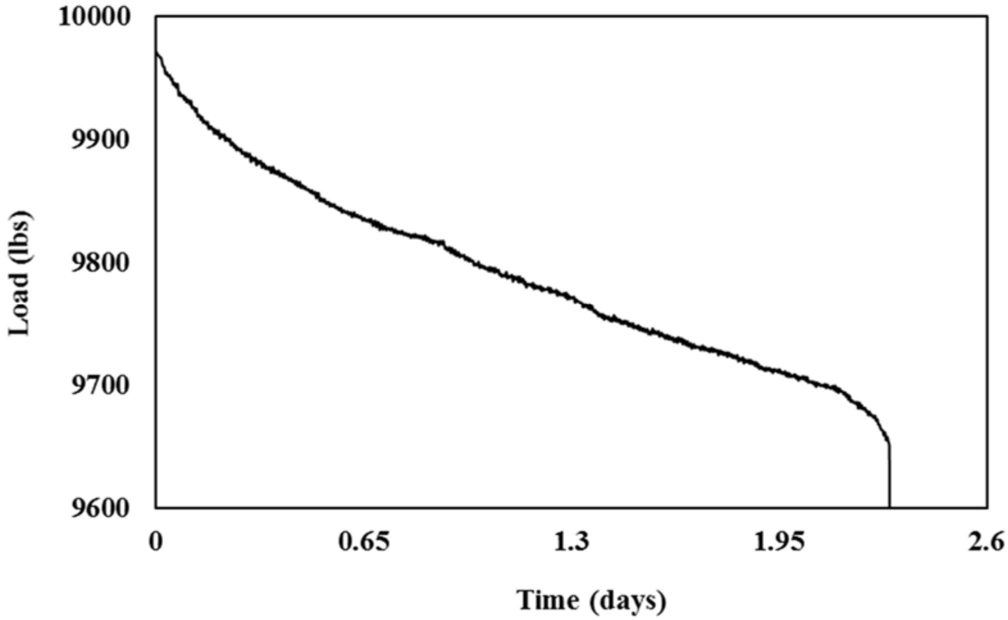

Figure 22. Load versus time for specimen #3, Group I.

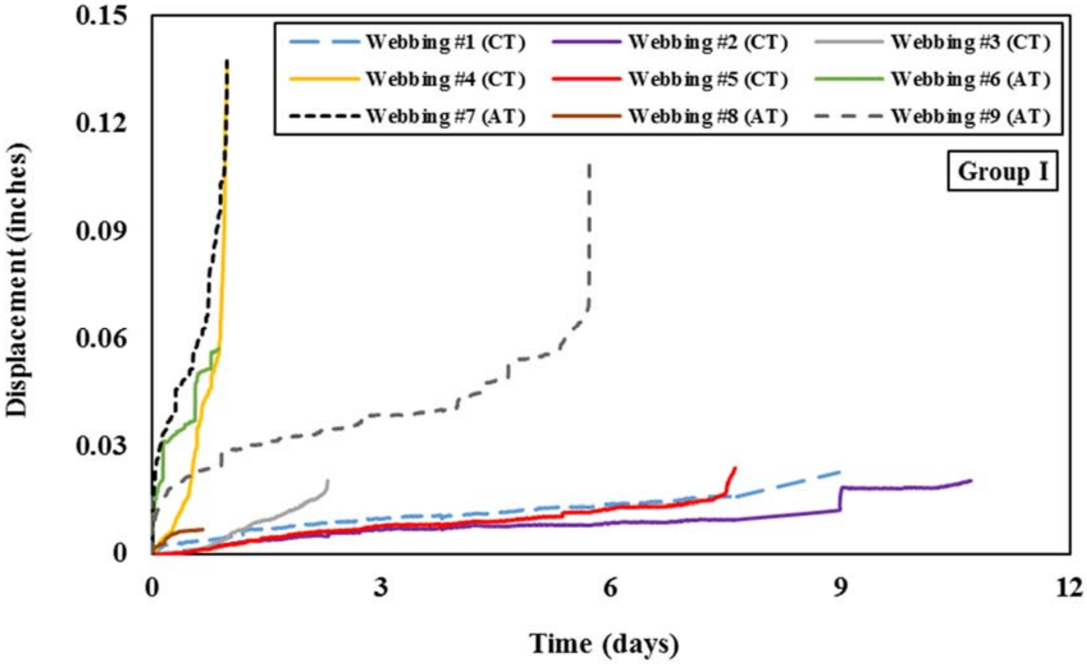

Figure 23. Displacements versus time of all webbing specimens in Group I.

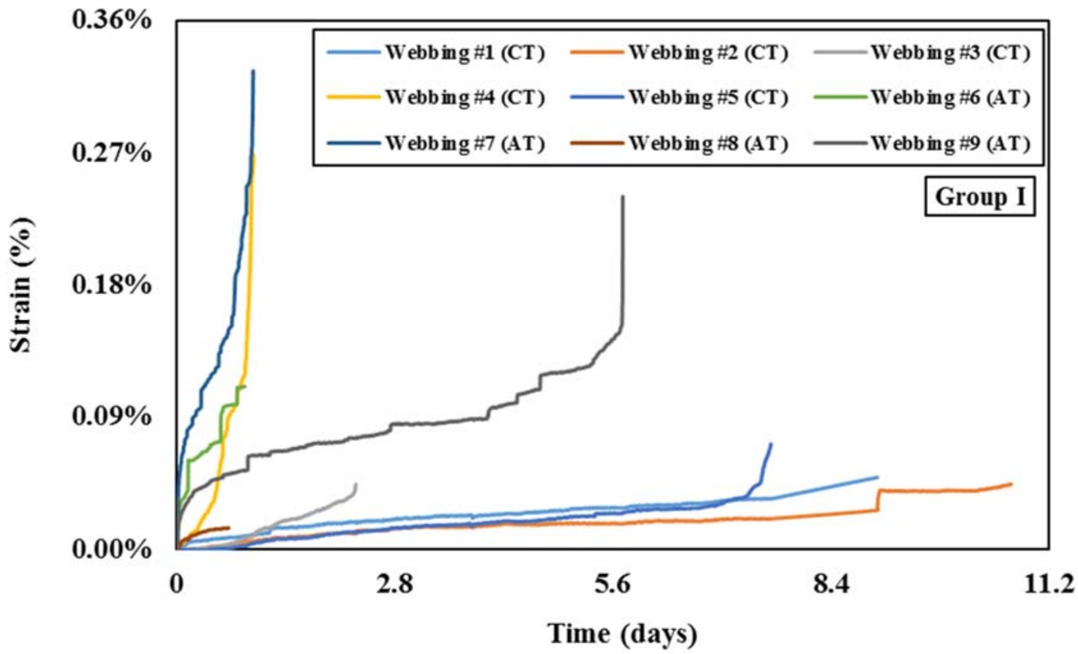

Figure 24. Strain calculations versus time of all webbing specimens in Group I.

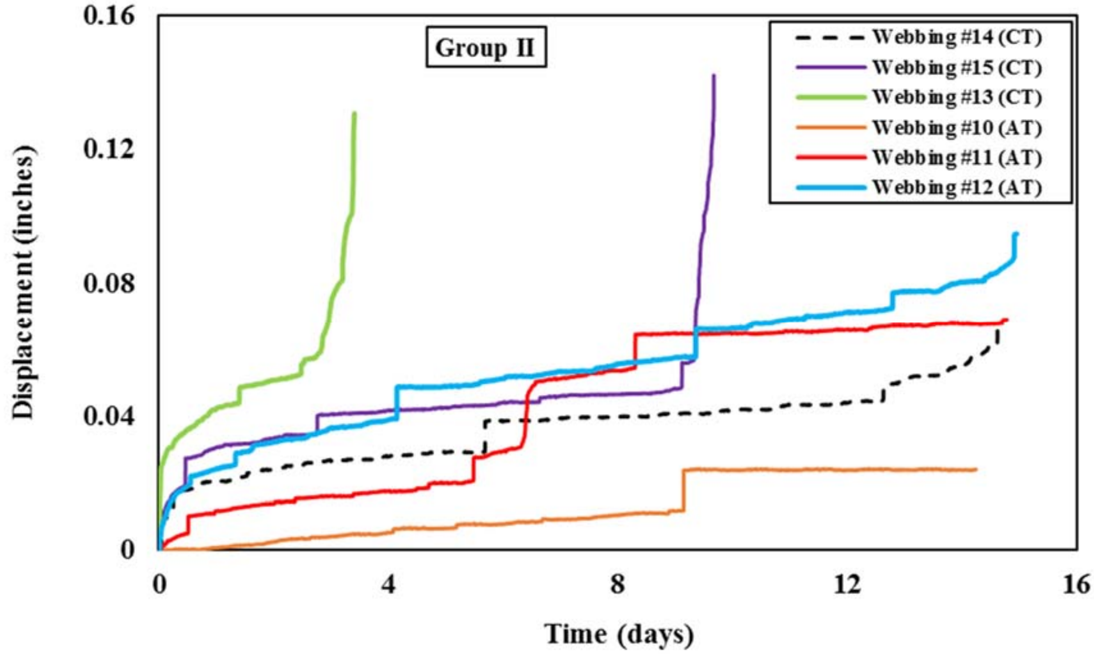

Figure 25. Displacements versus time of all webbing specimens in Group II.

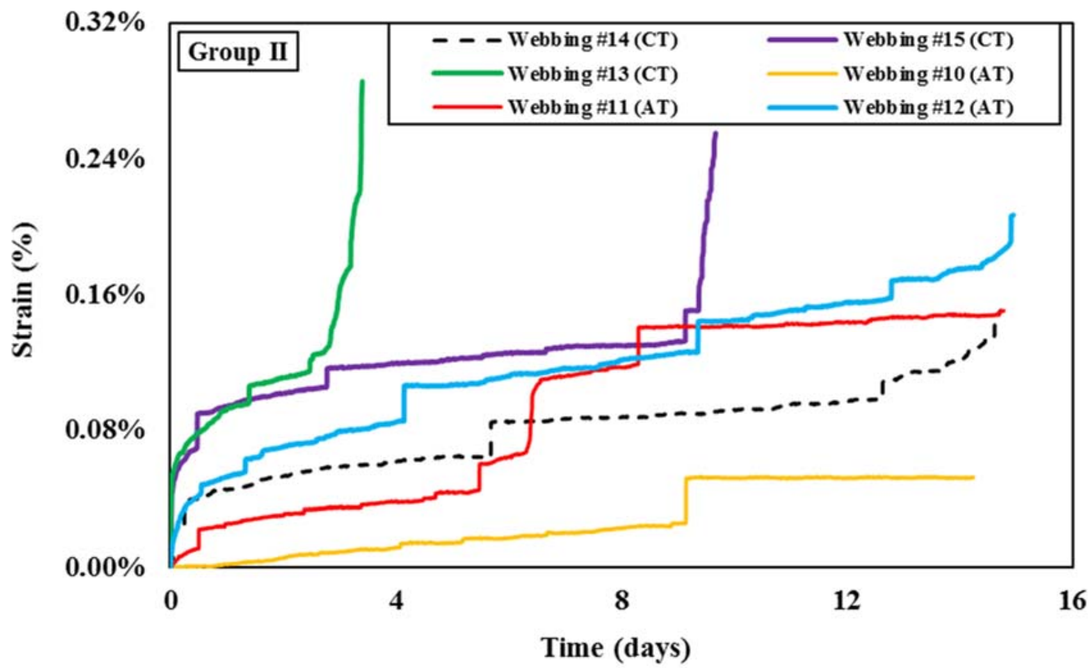

Figure 26. Strain calculations versus time of all specimens in Group II.

Tables

Table 1. UTS and applied load values for webbing Groups I and II.

Material	Group	UTS value (lbs)	Applied UTS %	Applied load (lbs)
12.5 K Vectran	I	14,255	69	9800
12.5 K Vectran	II	14,924	63	9400

Table II. Specimen # and associated load range, test duration, and environmental test condition from Group I.

Material Group & Load	Specimen #	Specimen length (inches)		Nominal load range (lbs)	Nominal test duration (days)	Nominal environmental conditions range	
		Original	Conditioned			Temp, F	Humidity, %
Group I Load 9800 lbs 69% UTS	1	44.	45.75	10050-9800	9	69-71.5	39-60
	2	44.125	45.75	10050-9700	10.7	74.4-75	39-48
	3	44.	45.8125	9950-9650	2.3	71-72	38-50
	4	44.125	45.25	10000-9700	1	73-74	39-55
	5	44.125	45.6875	10240-9900	7.6	73-74.8	40-51
	6	44.125	45.875	10430-10250	.9	82-88	54-64
	7	44.0625	45.8125	10700-10540	1		
	8	44.0625	45.75	10640-10010	.66		
	9	44.125	45.125	10200-10000	5.7		

Table III. Specimen # and associated load range, test duration, and environmental test condition from Group II.

Material Group & Load	Specimen #	Specimen length (inches)		Nominal load range (lbs)	Nominal test duration (days)	Nominal environmental conditions	
		Original	Conditioned			Temp, F	Humidity, %
Group II Load 9400 lbs 63% UTS	14	44.1875	45.75	9390-9220	14.7	73.5-75	39.-50.5
	15	44.125	45.55	9360-9200	9.8	70.5-72	40.5-51.5
	13	44.125	45.8125	9350-9206	3.4	72.4-74.3	41.3-63.
	10	44.125	45.875	9347-9130	14.2	82.4-92.	53.-68.
	11	44.1875	45.875	9600-9430	14.8		
	12	44.125	45.875	9720-9560	15.		

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*
1- 02- 2020

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Controlled Environmental Effects on Creep Test Data of Woven Fabric Webbings for Inflatable Space Modules

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Kenner, Winfred S.; Jones, Thomas C.; Le Boffe, Vincenzo M.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
089407.09.23

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-21118

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA-TM-2020-220561

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 39
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT
NASA is developing technologies for proposed lunar and Mars space exploration missions. Enhanced habitation systems are one element of both missions. Inflatable modules are being studied as potential habitats due to their inherent low mass and small launch volume. One goal of inflatable module research is quantification of the safe-life and end-of-life creep-strain spectrum. Full-scale pressurized inflatable modules are large, costly, and difficult to experimentally study. Therefore, material subcomponents are often studied as an alternative. An experimental thermally controlled long-term creep study of VectranTM webbings for application to inflatable modules is presented. Vectran fibers have high strength and low creep properties. High strength webbing materials are desirable for the load bearing restraint layer of inflatable modules because they are strong, flexible, and lightweight. Characterization of the creep behavior, safe-life, and end-of-life of webbing specimens will help quantify comparable life properties for inflatable modules.

15. SUBJECT TERMS
Creep; Displacements; Inflatable Modules; Temperature effects; Vectran webbings

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
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