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Determination of Modulus of Elasticity as a Function of Temperature for an Isogrid Tube

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Abstract
This paper presents the preliminary results from an experiment performed to determine the temperature dependence of the modulus of elasticity for a thermoplastic isogrid tube. To do this, the isogrid tube was subjected to axial tensile loads of 0-100 lbf and strain was measured at room and at elevated temperatures (from 75-200 °F) using two protocols. The first protocol allowed the tube to cool between tests while in the second protocol the tube was ramped through a series of temperatures and held at a temperature long enough to load and unload the tube. Elevated temperature tests did not exceed 200 °F since the reported glass transition temperature for the isogrid tube is 210 °F. The strain rate was constant for all tests at a rate of 0.008 in./min. The isothermal tests resulted in an average modulus of 2.34 x 10^6 PSI (16.1 GPa). The results from elevated temperature test for the two protocols used indicated that the modulus begins to decrease at temperatures approaching 100.0 °F. An instrumented aluminum tube was also subjected to axial loads at room temperature to verify the test apparatus.

Introduction
Inflatable booms are being considered as structural elements for a number of large-scale orbital missions such as the Next Generation Space Telescope (NGST), Space Solar Power (SSP), lightweight microwave antennas and solar arrays[1-4]. Inflatable booms are attractive for use on large spacecraft because of their lightweight and compact size when stowed and their structural efficiency when deployed.

One type of inflatable rigidizable boom under consideration for future missions is the isogrid composite tube. The isogrid tube is constructed from a graphite rib structure, in which the ribs form equilateral triangles with one another, and are imbedded in a thermoplastic resin. A thermoplastic material becomes pliable when heated above its glass transition temperature (TG). Structures such as cylindrical booms that are made from thermoplastic materials may be softened by heat and packaged compactly. They are deployed on-orbit by reheating them and introducing an inflation gas inside the structure. The structure rigidizes as it is cooled below the TG.

Currently though, the thermal-structural properties of isogrid tubes are not well understood over a wide range of temperatures. These must be known before such structures can be incorporated into the design of future spacecraft.

Thus, the purpose of this research is to determine the modulus of elasticity of the tube as a function of temperature, with particular emphasis on measurements near the glass transition temperature of the thermoplastic matrix.

After a brief discussion of previous work investigating rigidizable columns, details of the experimental apparatus and instrumentation will be presented along with the experimental protocols used and results. The results will be discussed and the investigation summarized.

Previous Work
The development of large, deployable, efficient structures is an enabling technology for many future spacecraft missions. These missions include large deployable antennas, sunshields, solar arrays, and solar sails. In particular, inflatable, rigidizable circular columns are under consideration as primary structural supports because of their light-weight and relatively small stowage volume[5].

Several types of cylindrical tubes have been under consideration as load bearing supports for use on future

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missions. Darooka and Jensen discuss different tube configurations, as well as advantages and disadvantages of each, in detail in ref 6. Two types of tubes discussed by the authors are laminated and isogrid tubes. Laminated tubes were to be used in the cancelled Inflatable Sunshield in Space (ISIS) mission[1,7]. For this experiment the booms were to have been constructed from a Kapton® inflation bladder, a layer of graphite imbedded in a heat cured epoxy, a Kapton® restraint layer, and a multi-layer insulation sleeve. An isogrid tube is constructed from a graphite rib structure, in which the ribs form equilateral triangles with one another, and are imbedded in a thermoplastic resin. The graphite-resin may be wrapped in a protective Kapton® layer. Although isogrid tubes are not as easy to produce as the laminated tubes, they are stiffer due to the rib structure

According to Freeland et. al.[8] the ideal rigidization system must have six properties. They must be: 1.) stiff after rigidization (have high modulus of elasticity), 2.) flexible prior to rigidization (allows for packing in a very small volume), 3.) maintain shape during rigidization, 4.) exhibit no thermal expansion on orbit, 5.) resistant to degradation in the space environment, and 6.) rigidization process must be reversible to allow for testing.

Currently there are several rigidization mechanisms available. An overview and discussion of each is presented by Derbés[9]. One rigidization mechanism that meets several of the criteria defined by Freeland et. al. above is the thermoplastic isogrid tube. An advantage of the thermoplastic rigidization mechanism is that it is reversible. Thermoplastics are rigid below their glass transition temperature, but become flexible above this temperature. Thus, it can be tested, heated to allow it to be packaged, heated again for deployment, and then rigidizes upon cooling. Thermoplastics can also be used to produce stiff, high strength structures that have coefficients of thermal expansion near zero[5].

Because isogrid tubes are relatively stiff, have near zero coefficient of thermal expansion, have a reversible rigidization mechanism they are worthy of further study for use on future missions. Although methods exist for analyzing isogrid structures[10,11] and structural as well as thermal characterization tests have been published[12,13], the structural properties of isogrid tubes have not been measured over a wide range of temperatures. Thus, the Modulus of Elasticity as a function of temperature was measured in this research. This data is important because it gives insight into the thermal-structural behavior of the boom, which may be necessary for the successful on-orbit implementation of similar booms.

Test Setup

In order to determine themo dulus of elasticity of an isogrid tube as a function of temperature, a testing mechanism was designed and built. An isogrid tube was also instrumented with sensors to provide data about strain and temperature during tensile tests.

The test setup is described in this section, including: the test specimen, the test frame, radiant heating system and instrumentation.

Test Specimen

The test specimen shown in Fig. 1 was provided by NASA Langley Research Center's Ultra-Lightweight and Inflatable Structures Group (UIS). The test specimen is a thermoplastic column that has properties of softening for compact packaging when its temperature is raised above TG. The manufacturer's specified glass transition temperature for the thermoplastic tube is 210 °F. The tube is approximately 50 inches length and 4 inches in diameter. The wall thickness of the test article varied slightly according to location as displayed in Table1. The locations varied by 90° increments around the circumference of the boom. The test article consisted of the composite column with plates on either end for mounting in the test fixture. Component masses of the tube are given in Table 2.

Test Stand

The test stand was constructed from 6061 aluminum and is shown in Fig. 2. The approximate dimensions of the frame were 21 in. x 21 in. x 72 in. The isogrid boom was mounted horizontally on the test frame and attached to the back plate. Six studs located on the back plate were used to bolt the specimen securely into place. Axial loads were applied using a linear motion system. This motion system consists of two gears and threaded rod driven by a Servo motor and gearbox as shown in Fig. 3. A 2 in. spur gear was attached to the motor's drive shaft. A mated 3 in. diameter gear was attached to a thrust bearing that was recessed into a 6.0 in. square x 11.5 in. high aluminum column. The column was bolted to a 1 in. thick aluminum plate and provided a rigid mount for the motion gears. A block containing an alignment bushing was attached to the top of the aluminum column as shown in Fig. 3. This block ensured proper linear alignment once axial loads were applied. A second plate 0.5 in. x 12in. was used to mount the motor. This plate was slid into place, allowing proper mating of the gears and secured into place with 9/16-18 bolts. The axial load was applied via a threaded rod with a pitch of 20 threads per 1 in. The threaded rod passed through a threaded bushing in the center of the drive gear. The bushing rotated with the drive gear, thus, the threaded rod moved axially without rotation. The threaded rod passed through the bushing and connected to one end of the load cell. Another threaded rod extended from the load cell on the other side and screwed into the center of one of the end caps.

Motion Control
Motion was accomplished using a servo-motor attached to a 20:1 gear box. The motor was controlled by a personal computer via an RS-232 Port. The motion system was controlled to provide a constant strain rate of 0.008 in/min. The system was capable of producing approximately 200 in-lb of torque. Feedback was provided to the motion system by the load cell.

Radiant Heater
The radiant heating system was constructed from 12-0.25 in. dia. quartz heat lamps. Two different length bulbs were used. The two lengths were 29 in. lamps rated at 480 V and provided a maximum heat flux of 2500 W and 20 in. lamps rated at 240 V that produced a maximum heat flux of 1600 W. The bulbs were mounted inside a 18 in. dia. x 52 in. long x 0.06in. thick stainless steel housing, which served as a reflector. The housing in relation to the rest of the test stand is shown in Fig. 4. The lamps were connected in two circuits. In the first, the six individual 480 V bulbs were connected in parallel and in the second circuit two 240V bulbs were connected in series and then three sets of two bulbs were connected in parallel. A silicon controlled rectifier (SCR) power controller provided 480V power to the two lamp circuits. A 4-20 mA control signal was provided to the SCR using a proportional-integral-differential (PID) controller. Figure 4 also shows a picture of the test apparatus with radiant heater. Temperature feedback was provided to the PID controller from a Type T thermocouple mounted to the tube. A piece of aluminized Kapton® was glued to the back plate of the test stand to reflect the heat back to the tube. A reflective aluminum panel was placed over the heater shell opening as to minimize heat loss due to convection.

Instrumentation
The instrumentation used for this project consisted of four strain gages, thirteen thermocouples, and a force transducer. Four axial strain gages were mounted around the boom circumference at 90° intervals at boom's center. The strain gages were mounted in accordance with manufacturers specifications[14]. The adhesive used is rated to 210 °F. The gages were mounted directly to the protective Kapton® layer that encapsulated the tube. In addition to the strain gages, three sets of thermocouples were mounted along the boom length. Each set consisted of four thermocouples mounted around the boom circumference at 90° intervals as shown in Fig. 5. The thermocouple sets were mounted 6 in. from each end of the boom as well as at the center of the boom length. In order to monitor the temperature for the elevated temperature tests, a type T thermocouple was mounted on the middle of the tube at the top. This thermocouple was attached to a PID temperature controller and provided feedback to control the rate of temperature increase. A force transducer, which was previously described, wasuse d to measure the applied loads.

All the transducers were connected to the data acquisition board through a signal conditioner. The data acquisition was controlled with a program developed in LabVIEW. This program also controlled the motion system described previously.

Experimental Procedures

In this section, test procedures for room and elevated temperature tests are described. Two different protocols were used for elevated temperature tests. This was done to determine if the heating process effected the temperature dependence of the modulus.

Prior to the isothermal and elevated temperature testing of the isogrid boom, tests were performed on an instrumented aluminum tube so that the test stand, heater, and instrumentation could be validated. Once the instrumentation components measured accurate temperatures and strain rates for the aluminum tube, we installed the isogrid boom.

Isothermal Tests
To begin isothermal testing, the strain gages were zeroed and a tensile load was applied at a constant strain rate of 0.008 in/min up to a force of 100 lbf. The tube was then unloaded and the strain gages were monitored to ensure that no hysteresis occured. The eight strain gages as well as the twelve thermocouples were represented on an interface in LabVIEW. For all tests, the maximum load was 100 lbf. The data was converted into a spreadsheet for further analysis.

Elevated Temperature Tests
Two different protocols were used for elevated temperature tests. This was done to determine if the temperature dependence of the modulus was independent of the heating process. The two protocols are described below.

Protocol 1

For this protocol the PID controller was programmed to heat the tube so it was brought to temperature, the load was applied at temperature, and the tube was then allowed to cool naturally to room temperature.

The PID controller was programmed to increase temperature to attain the desired set-point at a rate of approximately 2 °F/min. Once at the desired temperature of the test, the strain gages were zeroed and observed until there was to no change in the strain reading over time (approximately 10 minutes). Once the strain gages were stable, the motion was started and axial tensile loads were applied up to 100 lbf. Once 100 lbf was attained the tube was unloaded. Once the test was finished, the heater was turned off the tube was allowed to cool naturally to room temperature. This procedure was used for testing at temperatures of 100.0 °F, 120.0 °F, 140.0 °F, 160.0 °F, and 180.0 °F.

Protocol 2

For this protocol the tube was brought to temperature and not allowed to cool between tensile tests. The temperatures were consecutively increased between the load tests until reaching the maximum testing temperature.

Again, the PID Controller was programmed to heat the tube to a desired temperature at a rate of approximately 2°F/min. This temperature was then held for twenty-five minutes. During this time the strain gages were zeroed and observed until they were stable. Once the strain gages stabilized, the axial tensile loads were applied up to 100.0 lbf. The tube was then unloaded and the strain gages checked to see that they returned to near zero. After 25 minutes, the temperature was increased. The tests were performed at 120.0 °F, 140.0 °F, 160.0 °F, 180.0 °F, 190.0 °F and 200.0 °F. After the axial load was applied at the 200.0 °F the tube was unloaded and allowed to cool naturally. During cooling loads occurred. The tube appeared to shrink, resulting in tensile loads. Thus the tube was unloaded using the motion control system if the load exceeded 6.5 lbf.

Results and Discussion

The magnitude of the stress the tube was subjected to is based on the relation:

$$\sigma = \frac{P}{A} \tag{1}$$

where P is the load acting through the tube cross sectional area, A. The cross sectional area for determining the stress was calculated by performing a linear interpolation between the average tube thickness and diameter of each tube end. The modulus was determined from the slope of the stress-strain curve:

$$E = \frac{\sigma}{\varepsilon} \tag{2}$$

where E is the modulus and ε is the strain. The value used for the strain was the average of the four strain gages.

Prior to testing the isogrid tube tests were performed on a seamless 6061 aluminum alloy tube. This was done to tests the instrumentation and experimental apparatus. The tube had an outside diameter of 4 in., a wall thickness of 0.065 in, and was 48.0 in. in length. The mean value for the modulus at room temperature was 10.09 x 10^6 PSI, which is a 0.9 % difference from the published value[14] of 10.00 x 10^6 PSI. Data for the aluminum tube are presented in Table 3. Data for six tests at room temperature for the isogrid tube are presented in Table 4. The mean value is 2.34 x 10^6 PSI (16.13 GPa) with a standard deviation of 0.01 x 10^6 PSI (.07 GPa), showing good repeatability in the data.

The elevated temperature results from the two protocols show that the modulus significantly decreases as temperature increases in Figure 6. The modulus decreases above temperatures of 100.0 °F. The modulus has little variation between the two protocols up to temperatures of 140.0 °F.

Tests performed at room temperature were repeatable and the results were consistent. Of six tests the mean value was 2.34 x 10^6 PSI (16.1 GPa). The maximum variation was .37%. At elevated temperature, the data for the modulus shows good agreement below 140.0 °F. The modulus begins to decrease near 100.0 °F and at 140°F the modulus showed a decrease of 7.26 %. The tests results did diverge above 140.0 °F. The results from the tests using protocol 2 at 160.0 °F measured a modulus of 1.74 x 10^6 PSI (11.997 GPa), which was 3.05% higher than that determined from the data from protocol 1. At 180.0 °F the modulus determined from the data collected using protocol 2 was 1.52 x 10^6 PSI (10.460 GPa). This was 4.45% higher than that determined from the data collected using protocol 1.

At temperatures above 180.0 °F using protocol 2 the modulus did not decrease with increasing temperature. Without a second series of tests to verify this data no conclusions can be drawn from this data. Unfortunately a second set of data was notcollect ed due to damage to the column. It is possible that the glass transition temperature, of the thermoplastic, which was specified to be 210.0 °F, changed due to the repeated thermal cycling or was specified incorrectly. It is also possible that the stress transfer between the thermoplastic and the protective Kapton® layer became inefficient as the thermoplastic became rubbery near the glass transition temperature. Thus, the strain gage may have become ineffective at measuring the expansion of the underlying thermoplastic composite and the strain gage attachment method may require improvement.

For reference, the thermal history of the isogrid tube is shown in Table 5 and Figure 7. The diagram includes thermal cycling of the strain gages as well as the thermal cycles for tension testing. No load was applied for the cycling of the strain gages, and the loads for the tensile tests were applied up to 100 lbf.

Summary

An experiment to measure the modulus of elasticity as a function of temperature for an isogrid tube was described. Details were given on the experimental apparatus including the test stand, motion control system, instrumentation and heating system. The tensile modulus at room temperature was determined to be 2.34 x 10^6 PSI (16.13 GPa). Two protocols were used for elevated temperature testing. Preliminary data show that at temperatures up to 140.0 °F there was good agreement between the two protocols. The modulus began to decrease near 100.0 °F and at 140.0 °F it showed a 12.5% decrease from the room temperature value. For temperatures above 140.0 °F there was some deviation between data in the two protocols. Damage to the test article prevented verification of the two test methods.

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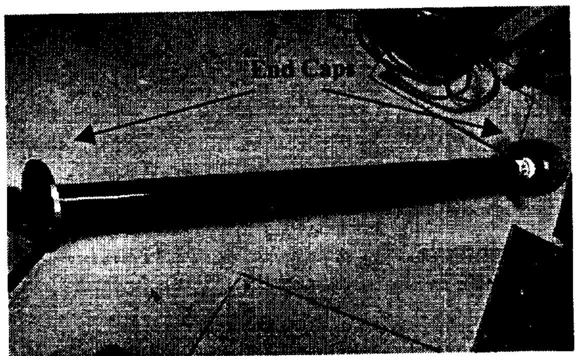


Figure 1. Isogrid tube test specimen with end caps.

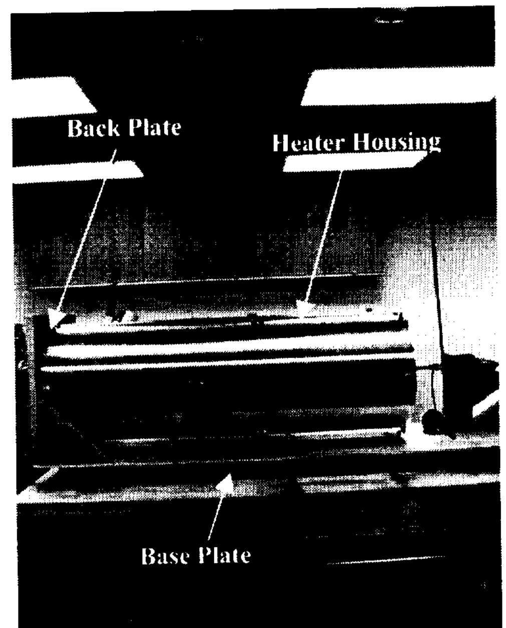


Figure 2. Test stand side view.

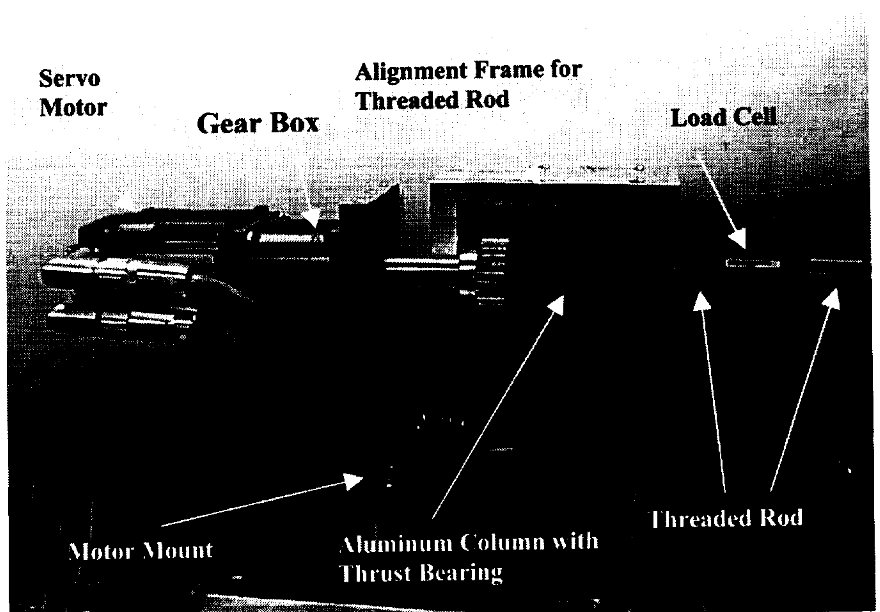
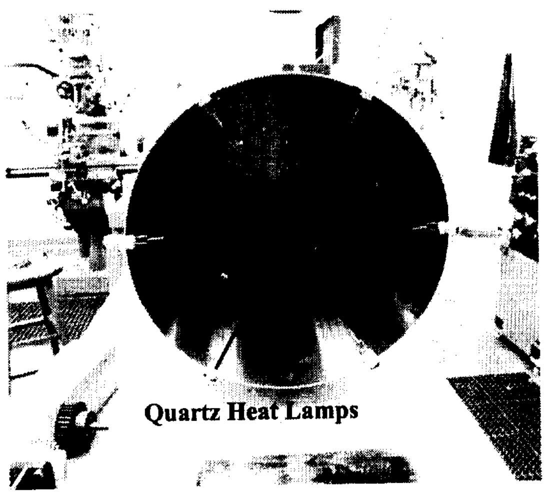


Figure 3. Side view of linear motion system.



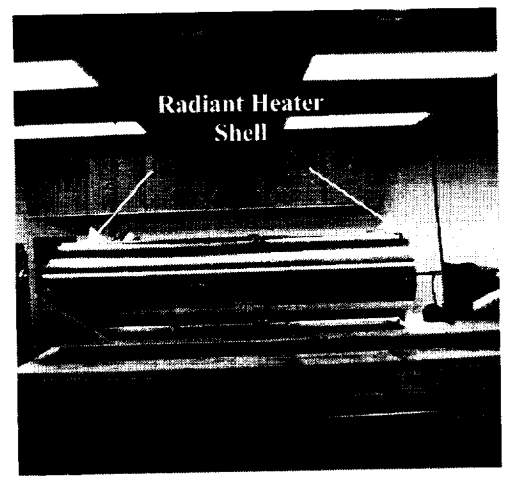


Figure 4. Side and front view of radiant heater

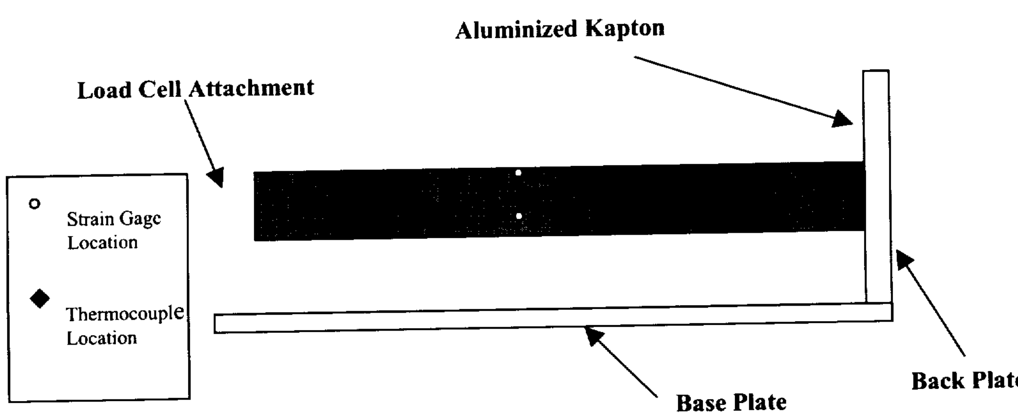


Figure 5. Strain gage and Thermocouple location.

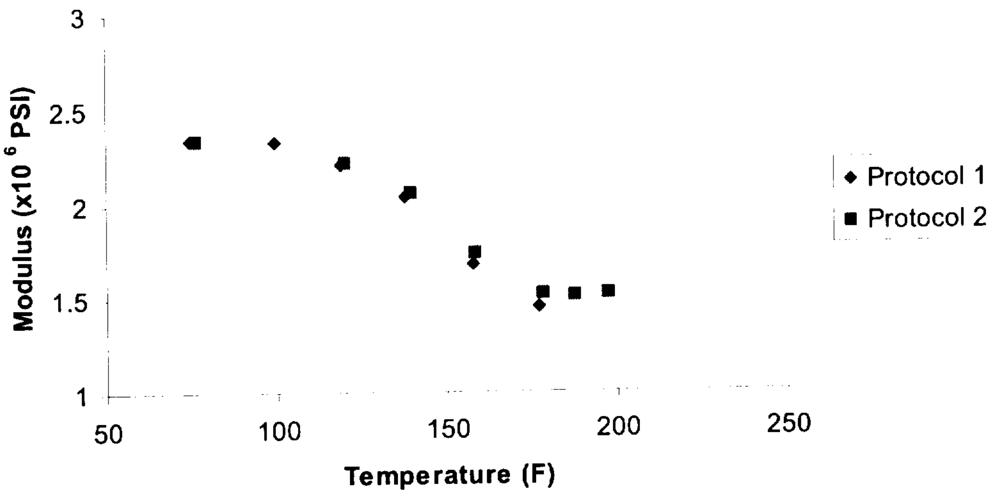


Figure 6. Modulus of Elasticity vs. Temperature for the two protocols of the elevated temperature tests.

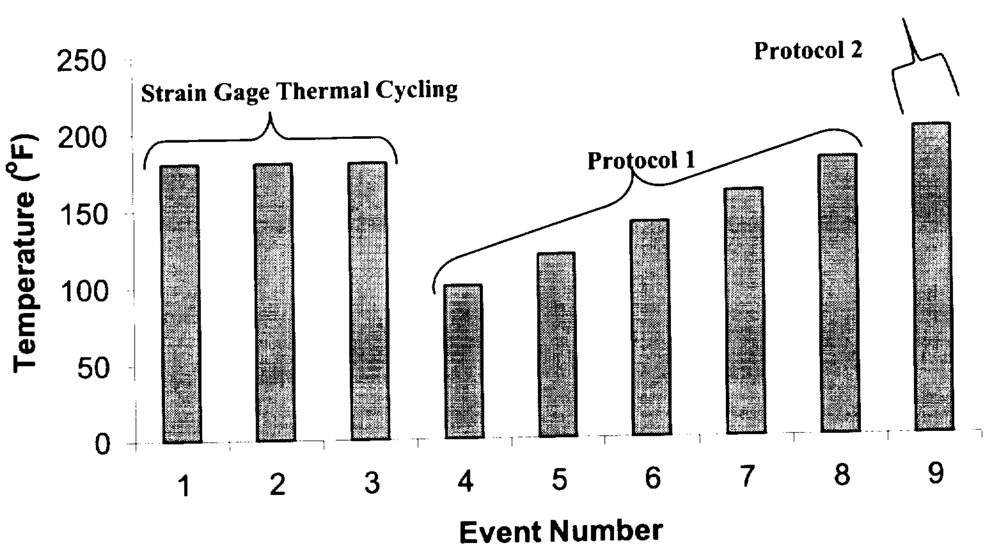


Figure 7. Thermal History of the test article including strain gage verification as well as elevated temperature tests.

Table 1. Wall thickness of the test article at various locations.

End 1 Attached to load cell		End 2 Mounted to back plate	
Location	Thickness (in)	Location	Thickness (in)
1	0.016	1	0.015
2	0.015	2	0.015
3	0.021	3	0.020
4	0.020	4	0.021

Table 2. Approximate mass of the test article components

Tube Weight (lbs.)	0.42
End Cap (lbs.)	0.61
Tube/End Caps Weight (lbs.)	1.65

Table 3: Modulus of Elasticity for 6061 Aluminum Tube.

Trial	Modulus for Isothermal Tests PSI(Gpa)
1	10.05×10^6 (69.18)
2	10.12×10^6 (69.63)
3	10.05×10^6 (69.18)
4	10.17×10^6 (70.01)
5	10.09×10^6 (69.46)
6	10.07×10^6 (69.32)
Average	10.09×10^6 (69.46)
Standard Deviation	0.0 5 (0.344)

Table 4. Room Temperature Modulus of Elasticity of Isogrid Tube.

Trial	Modulus for Isothermal Tests PSI (GPa)
1	$2.34\text{x } 10^6$ (16.11)
2	$2.33\text{x } 10^6$ (16.01)
3	$2.35\text{x } 10^6$ (16.19)
4	$2.35\text{x } 10^6$ (16.18)
5	$2.34\text{x } 10^6$ (16.07)
6	$2.35\text{x } 10^6$ (16.15)
Average	$2.34\text{x } 10^6$ (16.13)
Standard Deviation	$0.01\text{x } 10^6$ (0.07)

Table 5: History of elevated temperatures for the isogrid tube.

Thermal Excursion Event	Temperature °F/min	Description	Heating Rate °F/min	Temperature Holds	Load Testing and Duration (Load to 100lbf.)
1	180	Strain Gage Verification	1.2	45 min at 130F, 5 min at180F	none
2	180	Strain Gage Verification	2	30 min at 130F, 30 min at 180F	none
3	180	Strain Gage Verification	2	30 min at 130F, 30 min at 90F	none
4	100	Load Test	2	10 min at 100F	Tensile Test for 10 min
5	120	Load Test	2	10 min at 120F	Tensile Test for 10 min
6	140	Load Test	2	10 min at 140F	Tensile Test for 10 min
7	160	Load Test	2	10 min at 160F	Tensile Test for 10 min
8	180	Load Test	2	10 min at 180F	Tensile Test for 10 min
9	200	Load Test	2	30 min at 200F, 30 min at 160F during cool down	Tensile Test for 10 min

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13. ABSTRACT *(Maximum 200 words)*

Experiments were performed and results obtained to determine the temperature dependence of the modulus of elasticity for a thermoplastic isogrid tube. The isogrid tube was subjected to axial tensile loads of 0-100 lbf and strain was measured at room and elevated temperatures of 100, 120, 140, 160, 180, 190, and 200 °F. These were based on tube manufacturer specifying an incorrect glass transition temperature of 210 °F. Two protocols were used. For the first protocol the tube was brought to temperature and a tensile test performed. The tube was allowed to cool between tests. For the second protocol the tube was ramped to the desired test temperature and held. A tensile test was performed and the tube temperature ramped to the next test temperature. The second protocol spanned the entire test range. The strain rate was constant at 0.008 in/min. Room temperature tests resulted in the determination of an average modulus of 2.34 x 106 Psi. The modulus decreased above 100 °F. At 140 °F the modulus had decreased by 7.26%. The two test protocols showed good agreement below 160 °F. At this point the glass transition temperature had been exceeded. The two protocols were not repeated because the tube failed.

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