DESIGNING FOR DURABILITY USING AN E-GLASS REINFORCED SRIM URETHANE COMPOSITE

Scott L. Coguill
University of Wyoming
Laramie, Wyoming 82071

Dan Houston
Ford Motor Company
Dearborn, Michigan 48121

ABSTRACT

The durability of a SRIM Urethane composite are evaluated and the results are used to develop a design guide to aid in the use of this material. Test methods for static, fatigue, creep and impact testing are described in detail. The Oak Ridge National Laboratory developed these methods for durability testing. The raw test data from an earlier study are summarized and generalized in the form of design equations. The scope and limitations of these design equations are discussed. This material evaluation and data summary process provides a means for designing for durability using an E-glass reinforced SRIM Urethane composite.

1. INTRODUCTION

For this study a minimum amount of static, fatigue, impact and creep testing were performed to determine the durability of an E-glass reinforced SRIM urethane composite. The composite consisted of molded plaques fabricated using performs produced by the P4 process. The reinforcement was Owens Corning 433 BF, 2760 TEX chopped roving and the resin used was Bayer Baydur 420 IMR Urea/Urethane. Two foot square plaques were molded and supplied to the test laboratory.

The test methods used are outlined below and were based upon the specifications developed by Oak Ridge National Laboratory [1]. Table 1 and 1a list the test matrix and a complete description of the plaques supplied for testing. The results of the testing are summarized and generalized as design equations in Section 3 of this report. The specific test results can be found in Ref. [2].

Table 1. Minimum Test Matrix

Test Type	Number of Tests						Plaque
	Air/50% RH				Water Soaked		
	-40°C	23°C	50°C	120°C	23°C	50°C	
Tensile	4	4	4	4	4	4	TZP-1
Compression	4	4	4	4	4	4	TZP-5
Shear	4	4	4	4	4	4	TZP-5
Fatigue							TZP-6
Fatigue	8	8		8	8		
Tensile	3	3		3			
Creep							TPZ-7
Tensile		14	4	4	6		
Compression		4		4			
Damage Tolerance							TZP-8 TZP-12
Impact		8					
Tensile		12					
Compression		12					

Table 1A. Plaque Description

Plaque Number	Full Description
TZP-1	A3-27; 1.94/3.82 PC 1 hr 270°F
TZP-5	A3-22; 1.94/3.76 PC 1 hr 270°F
TZP-6	A3-21; 1.94/3.74 PC 1 hr 270°F
TZP-7	A3-20; 1.94/3.74 PC 1 hr 270°F
TZP-8	A3-18; 1.96/3.74 PC 1 hr 270°F
TZP-12	A3-15; 1.96/3.76 PC 1 hr 270°F

2. TEST METHODS

2.1. Tensile According to the ORNL document, plaque reference tests were to be performed to evaluate the plaques for acceptance. The reference tests consisted of four tensile tests on specimens randomly selected from each plaque. Straight-sided, 25.4 mm by 254 mm long blanks were cut from the plaques using a water-cooled abrasive, 0.1 mm aluminum oxide wheel. Next, a water-cooled router with a diamondimpregnated bit was used to route the specimens to the final dog-boned shape with a gage section width of 20.32 mm as specified in the ORNL document. The reference tensile specimens were then gaged with axial strain gages, EA-06-250BF-350 for plaques TZP-1, -5, -8, -12 and gages CEA-06-500UW-350 for TZP-7. The various gages were used based on the type planned for use for the subsequent static or creep tests. All gages were from Measurements Group Inc. The gages were adhered with M-Bond 200 adhesive, cured at room temperature. The tests were performed in a universal test frame at a rate of 2 mm/minute. Modulus was calculated over the strain range of 500-2500 $\mu\varepsilon$. Results from these plaque reference tests can be viewed in Table 3. As per the ORNL document, plaque acceptance was based on the criteria defined by the multiple strength or stiffness values lying within the standard deviation of data from all plaques. Plaque TZP-12 slightly exceeded the acceptance criteria but was judged usable for impact testing. The impact results are used for a relative comparison within a plaque and were not as dependent upon the other plaques.

Static tensile tests were performed on specimens that were cut from Plaque TZP-1. Per Table 1, the tests were conducted under several environmental conditions. Those specimens that were to be tested in wet conditions were placed in a tank filled with distilled water and left at room temperature, nominally 23°C, and allowed to soak in the water for 1000 hours. Total weight gain per sample ranged from 0.35 percent to 0.98 percent. An ATS model environmental chamber with a -300°C to 300°C temperature range was used for all of the non-ambient static tensile tests. The -40°C tests were achieved using liquid nitrogen to cool the environmental chamber surrounding the test fixture and specimen. The elevated temperature tests were also performed using this type of test chamber using circulated hot air. The tensile tests were performed per the specifications in the ORNL document. Three load-controlled cycles between stress levels of 5% and 25% of ultimate tensile strength were run to obtain the initial modulus measurement. Thereafter, the specimen was loaded at a constant displacement rate to failure. Biaxial strain gages, CEA-06-250UT-350, were used to measure strain for modulus and Poisson's ratio determination. Those specimens run at 23°C and 50°C had the gages adhered with M-Bond 200 cured at room temperature. The specimens run at 120°C and -40°C had the gages adhered with M-Bond 600, cured at 121°C for 2 hours. Results of the tensile durability tests are in Ref. [2]. Static design recommendations for this material are presented in Section 3.2. Figures 1 and 2 show the various test set-up and the environmental test chamber.

2.2 Compression Compression tests were performed per the ORNL guide. Specimens were prepared from Plaque TZP-5. Specimens were fabricated 25.4 mm wide by 133.4 mm long and were tabbed with 57.2 mm long tabs of G-11 glass/epoxy material. A paste adhesive, Tech Kits A-12, was used to adhere the tabs. The adhesive was cured at 66°C for 1 hour. Strain gages, EA-06-250AE-350, were adhered to both sides of the specimens using the same adhesive regime as used for the tensile specimens, and the tests were run at the same environmental conditions as the tensile specimens. Using an IITRI compression test fixture, the tests were run at a rate of 1mm/minute. The non-ambient environmental conditions were achieved using the same ATS chamber as previously described. Results of the tensile durability tests are in Ref. [2]. Static design recommendations for this material are presented in Section 3.2. Figure 3 shows the IITRI test fixture.

Figure 1. Tensile test set-up.

Figure 2. ATS environmental test chamber used for elevated and sub-ambient tests.

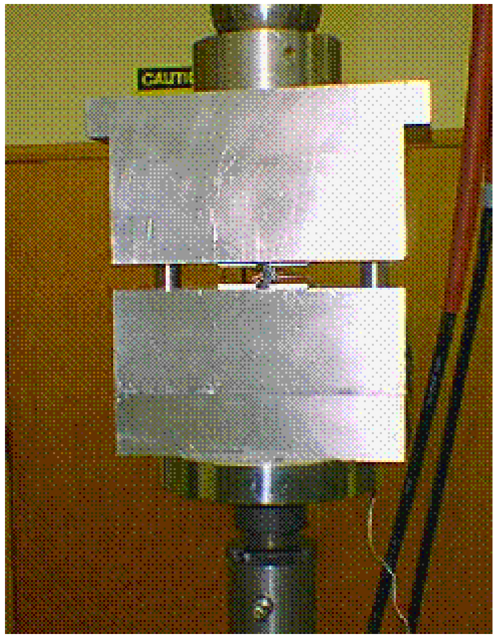

Figure 3. IITRI compression fixture.

2.3 Shear Shear tests were performed per the ORNL guide using a V-notched beam (Iosipescu) test specimen and fixture. Figure 4 shows the test fixture. Shear specimens were prepared from plaque TZP-5. Specimens were fabricated 19.1 mm wide by 76.2 mm long and were tabbed with 31.8 mm long tabs of G-11 glass/epoxy material. A paste adhesive, Tech Kits A-12 cured at 66°C for 1 hour was used to adhere the tabs. Strain gages, N2A-00-C032A-500, were adhered to both sides of the specimens using the same adhesive regime as used for the tensile specimens. Again, these tests were run at the same environmental conditions as the tensile and compression specimens. Tests were run at a rate of 1 mm/minute. The non-ambient environmental conditions were achieved using the same ATS chamber as previously described. Results of the tensile durability tests are in Ref. [2]. Static design recommendations for this material are presented in Section 3.2.

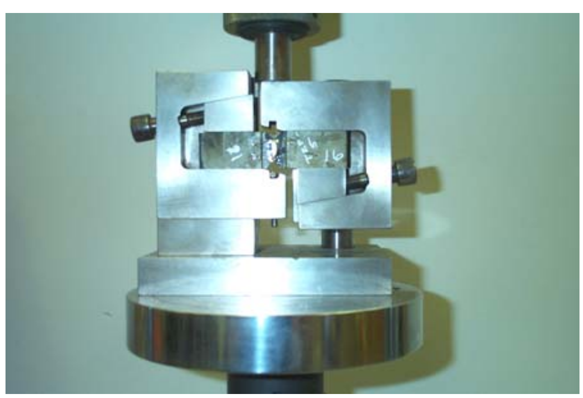

Figure 4. V-notched beam shear test fixture.

2.4 Fatigue- Tensile Tensile fatigue specimens were prepared from plaque TZP-6 in the same manner as the static tensile specimens. As Table 1 indicates, 3 specimens were statically tested to obtain the ultimate strength that was then used to calculate the fatigue loads for testing. All specimens, both static and fatigue, underwent an initial strain profile to determine the modulus. For the fatigue specimens, the strain data were obtained using an extensometer. Figure 5 demonstrates the test set-up with the extensometer in place.

The fatigue test conditions were the same as the static tensile tests with the omission of the 50°C wet and 50°C dry conditions. Specimens for the 23°C wet tests were pre-soaked for 1000 hours in room temperature water. Tests were performed with the specimen immersed in room temperature water throughout the entire fatigue profile. This set-up can be viewed in Figure 6. Elevated temperature tests were achieved by placing a zone heater around the specimen. Figure 7 shows this test set-up. The -40°C tests were conducted with an individual cooling chamber surrounding the gage section of the specimen. This set-up can be viewed in Figure 8. Test frequency was determined from the following formula, provided in the ORNL document:

$$F=(kS_{ult})/(S_{max}-S_{min})$$

Individual results of the static test performed to determine the ultimate load for fatigue can be found in Ref. [2]. Fatigue response design recommendations can be found in Section 3.3.

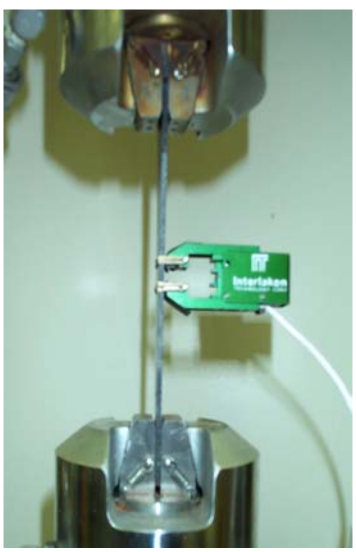

Figure 5. Room temperature tensile test set-up with extensometer for fatigue pre-test profile.

Figure 6. Wet tensile fatigue test set-up.

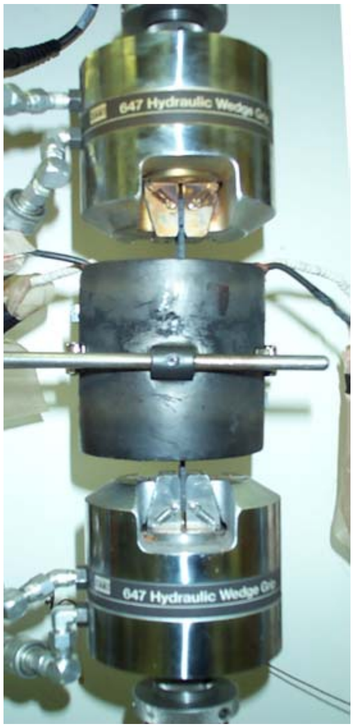

Figure 7. Elevated temperature tensile fatigue test set-up.

Figure 8. Sub-ambient temperature tensile fatigue test set-up.

2.5 Creep-Tensile Two types of creep tests were performed, namely tensile and compressive, using plaque TZP-7. The tensile creep specimens were prepared in the same manner as all other tensile specimens. All of the specimens underwent a preliminary strain profile procedure to establish the modulus using strain gages, CEA-06-500UW-350. These gages were adhered with M-Bond 600, cured at 121°C for 2 hours. The initial profile was performed on a universal test frame.

The tensile creep tests were then conducted in a CMRG designed multi-specimen creep testing apparatus. This piece of equipment is capable of testing up to 20 tensile creep specimens simultaneously, using individual leveraged weights for each specimen. Time versus strain data was collected per specimen. Tests were also conducted at non-ambient conditions as requested in this study. Figure 9 shows the creep apparatus.

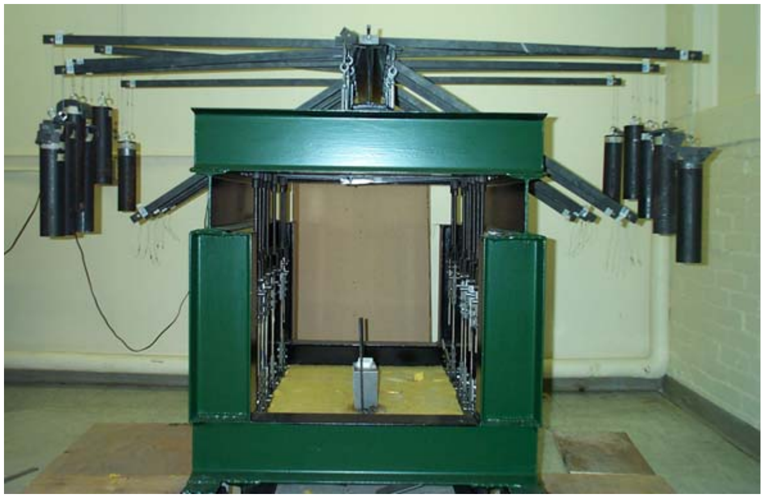

Figure 9. Creep testing apparatus

As Table 1 indicates, tensile creep tests were to be conducted not only in standard ambient conditions, but at elevated temperatures and submerged in water. The same cast-in-place cup arrangement as used for the fatigue specimens was used for the specimens tested at 50°C, wet conditions. Refer to Figure 6 to view this set-up. The elevated temperature tests were performed using individual heat pads with aluminum cover plates to accommodate heat dispersion. These heaters were placed only in the gage section of each specimen. The entire specimen and fixture were insulated. Figures 10 through 12 show the test set-ups for these tests. Strain was monitored throughout the duration of the tests, using the same strain gages as were used for the initial strain profile. Laboratory conditions were maintained at 23°C and 40% relative humidity throughout the duration of the creep testing. The strain versus time data that was collected had a linear response of the form:

$$\varepsilon = bt^n$$

Where: $\varepsilon =$ Creep Strain
$b =$ Power Constant
$t =$ Time
$n =$ Power Constant

$$b = A\sigma$$

Where: $A =$ Power Constant
$\sigma =$ Creep Stress

The power constants measured for each test specimen are found in Ref. [2]. Summaries of the tensile creep responses are presented in Sections 3.4.1, 3.4.2, and 3.4.3.

2.6 Creep-Compression The compressive creep tests were also performed in the same multi-specimen creep apparatus. However, the compressive creep specimen was unique to this test. The specimen was 25.4 mm wide by 31.8 mm long. The ends were ground flat and parallel to insure proper loading. The fixture consisted of the same style recommended in the ORNL document. The only exception was instead of potting the specimen in the fixture, sets of screws were used to secure the specimen in the fixture. The fixture was then attached to the testing apparatus using the same type of upper and lower blocks that were pulled upward and downward by linkages shown in Figure 13.

The compressive creep tests were also performed at ambient and at 120°C. This was accomplished using individual environmental chambers that enclosed not only the specimen and fixture but the testing linkage as well. Strain gages, CEA-06-500UW-350, were used to monitor the strain response throughout the creep test. Individual specimen test results are listed in Ref [2]. Summaries of the tensile creep responses are presented in Sections 3.4.4 and 3.4.5.

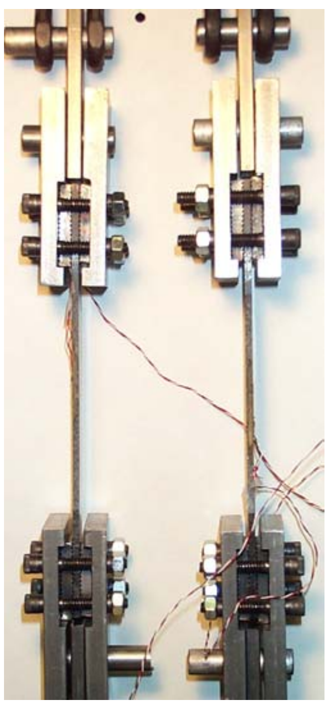

Figure 10. Tensile creep specimens.

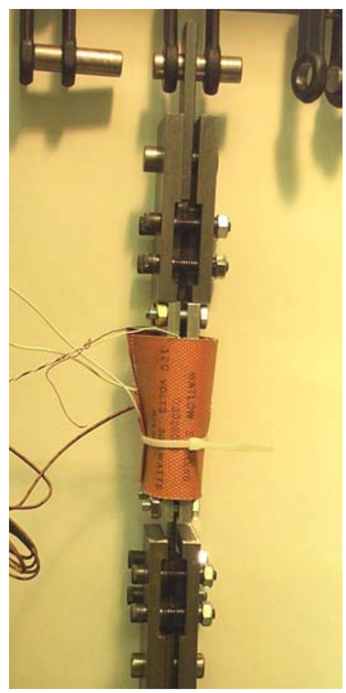

Figure 11. Tensile creep specimens with heaters.

Figure 12. Elevated temperature insulation for tensile creep tests. with heaters in place.

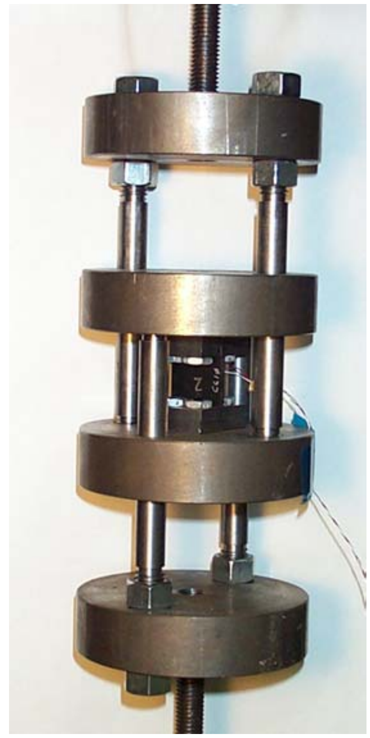

Figure 13. Compressive creep test fixture and linkage.

2.7 Damage Tolerance The tensile- and compression-after-impact specimens were prepared from plaques TZP-8 and-12. The tests were performed using an Instrumented Drop Weight Impact Tower rather than with an air-gun and pendulum described in the ORNL guide to induce the damage to the specimen. A 16.8 kg drop-weight was used. Attached to the weight was a 12.7 mm diameter hemispherical steel impactor point. The tower was equipped with a rebound mechanism to prevent multiple impacts per specimen. The tower also used a light beam and trigger flag arrangement with a high-speed digital oscilloscope to measure the velocity of the falling mass immediately prior to impact. Impact energy was determined using the mass of the dropped weight and the velocity of the mass immediately prior to impact. Specimens were initially prepared to 229-mm square. The specimens were secured in a clamped ring assembly having a 203-mm diameter opening and impacted in the center as can be seen in Figure 14. After the plaques were impacted, each was C-scanned to inspect the damage area. Those scans can be viewed in Ref [2].

Three tensile specimens were then cut from the damaged plate per the ORNL recommendation of one in the center and two from the opposing edges. The tensile specimens were all cut to 25.4mm wide strips. The center specimen was left straight sided and the two edge specimens were dogboned to a final gage section width of 20.3 mm and tested without tabs. The center specimen was tabbed.

Three compression specimens were also cut from an impacted plaque. All three specimens were tabbed with G-11 fiberglass/epoxy material and cut to a final dimension of 25.4 mm wide by 133.4 mm long. These specimens were tested in an IITRI compression test fixture. Damage tolerance design considerations are presented in Section 3.5.

Figure 14. Impact test set-up with panel in place.

3. DESIGN GUIDE

3.1 Introduction The test results from this study can be best summarized as a set of design guides for use when designing products utilizing this particular SRIM Urethane composite. The following recommendations provide a guideline when designing for static and fatigue loads, assessing damage tolerance and predicting long term creep response. The TZP panels have a degree of anisotropy resulting in a weak and a strong orientation. The durability testing was performed in the weak direction to produce the most conservative results. The following data predominantly represents the properties of this material in the weak direction.

3.2 Static Mechanical Properties The following information in Table 4 is a reprint of the Automotive Composites Consortium material properties data sheet for the TZP SRIM Urethane composite. In this table, the weak direction is the zero degree direction. Static test data presented in Ref. [2] provided a limited amount of data for correlation purposes but not nearly enough data to be statistically significant. Therefore the following table is recommended for design purposes.

Table 4. Automotive Composites Consortium Material Properties Data Sheet for the TZP SRIM Urethane Composite

RESIN	BAYER BAYDUR *420IMR Urea/Urethane*
REINFORCEMENT	OC E-Glass *433 BF,2760 TEX, P4 NCC, Pretex 110*
PROCESSING DATES	Molded and Postcured 10/30/99 Troy Tooling
FIBER VOL. (VOL%(WT%))	29.2 (46.8)
SPECIFIC GRAVITY	1.599
CLTE (°C x E-6) (range 30-80°)	15.2 @0°, 10.2 @ 90°
REF TEMP T75 (°C)	116
DATA ARCHIVE	Code : TZP (full characterization 420/433/Pretex, FP2 box)

TENSILE PROPERTIES

	TEMPERATURE (°C)	-40	sd	25	sd	120	sd
STRENGTH (MPa)	0°	188	18.3	173	16.0	119	15.1
	90°	255	24.2	224	29.3	164	11.9
	average	222	40.4	199	34.9	141	26.6
MODULUS (GPa)	0°	14.1	0.055	10.5	0.98	6.9	0.55
	90°	15.1	1.56	12.9	10.3	9.7	1.04
	average	14.6	1.28	11.7	1.57	8.3	1.64
FAIL STRAIN (%)	0°	2.07	0.29	2.20	0.17	2.06	0.25
	90°	2.34	0.35	2.22	0.13	1.9	0.29
	average	2.20	0.34	2.21	0.15	2.02	0.27
POISSON'S RATIO	0°	0.280	0.028	0.294	0.032	0.290	0.051
	90°	0.353	0.029	0.373	0.031	0.395	0.071
	average	0.316	0.046	0.333	0.051	0.343	0.081

COMPRESSION PROPERTIES

	TEMPERATURE (°C)	-40	sd	25	sd	120	sd
STRENGTH (MPa)	0°	298	22.5	211	12.9	69	6.3
	90°	357	22.9	269	24.3	84	7.4
	average	326	37.2	242	35.4	77	9.9
MODULUS (GPa)	0°	12.4	0.52	10.4	0.77	6.7	0.68
	90°	14.8	1.19	13.2	1.34	9.4	0.99
	average	13.7	1.52	11.8	1.81	8.0	1.59
FAIL STRAIN (%)	0°	2.95	0.39	2.45	0.33	1.13	0.22
	90°	2.78	0.12	2.03	0.24	0.95	0.07
	average	2.87	0.30	2.24	0.345	1.04	0.18

SHEAR PROPERTIES

	TEMPERATURE (°C)	-40	sd	25	sd	120	sd
STRENGTH (MPa)	0°	212	11.8	158	9.1	66	10.1
	90°	204	13.8	167	14.7	48	28.9
	average	208	13.3	163	12.7	57	23.0
MODULUS (GPa)	0°	5.03	1.15	3.6	0.50	3.0	0.51
	90°	4.93	0.92	3.85	0.68	3.3	0.46
	average	4.98	1.00	3.73	0.60	3.16	0.49

Sd = standard deviation (n-1 basis) with n = 6 for 0/09 orientation data and n = 12 for averages.

3.3 Fatigue Response Figures 15 through 18 contain plots that model the fatigue response of this material as a function of test condition and temperature. The plots contain the static strength of the material at a particular test condition as well as a mathematical relationship for the fatigue response down to some lower stress limit. Data is presented as a percent of the static ultimate tensile strength as established for this plaque for the particular test condition.

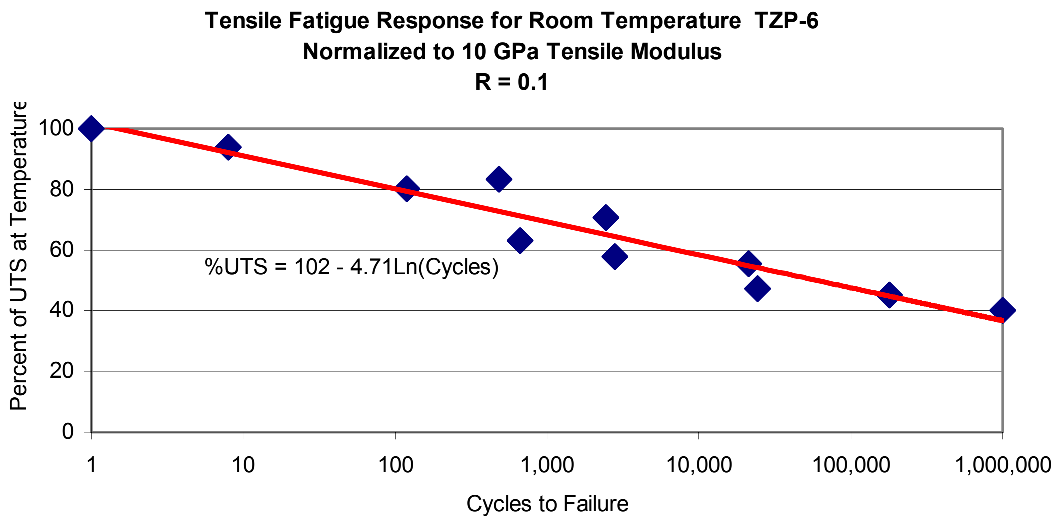

Figure 15. Tensile fatigue response of TZP-6 material at room temperature conditions.

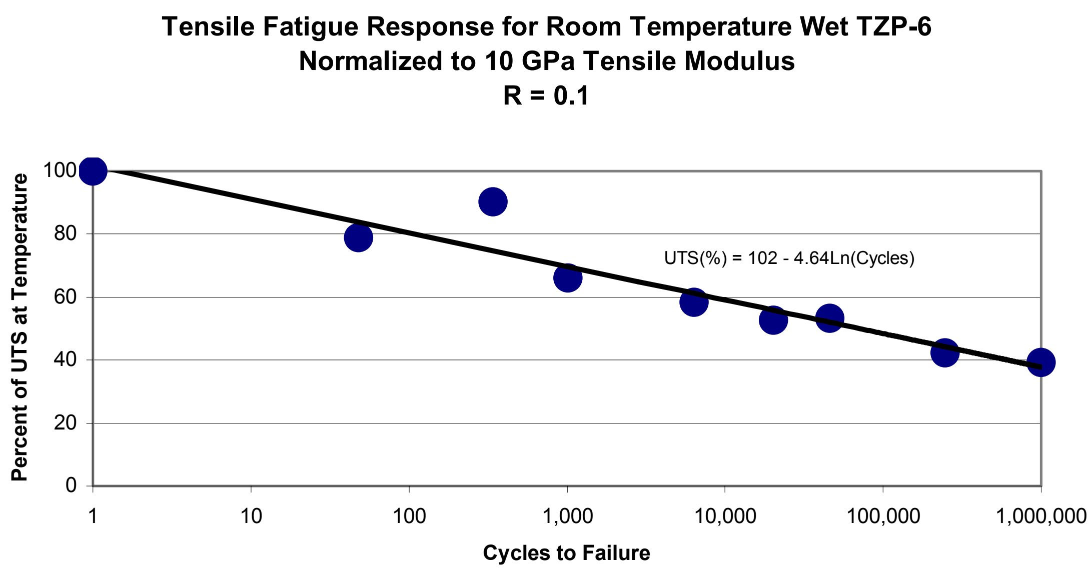

Figure 16. Tensile fatigue response of TZP-6 material at room temperature, moisture saturated conditions.

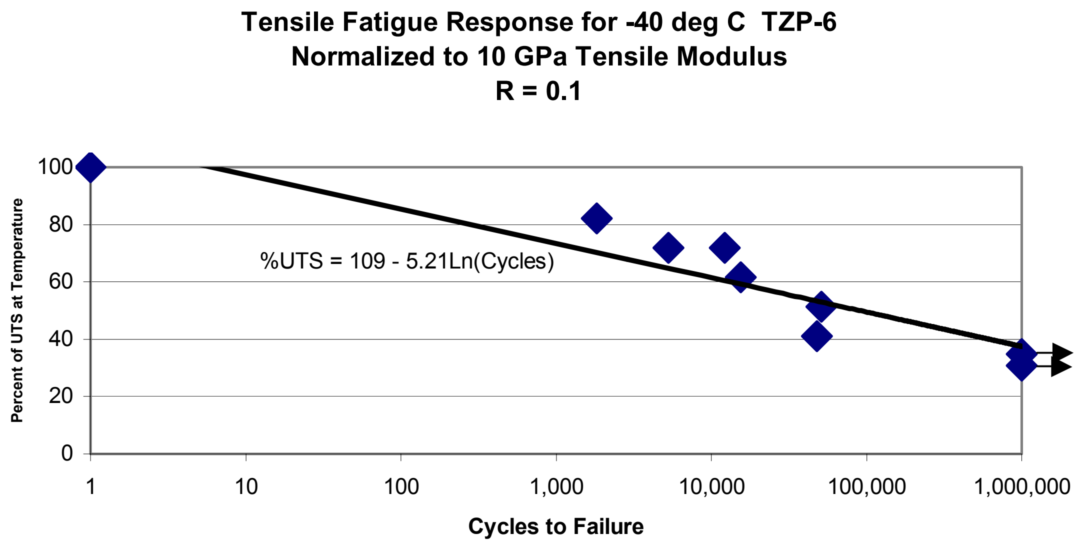

Figure 17. Tensile fatigue response of TZP-6 material at –40ºC test conditions.

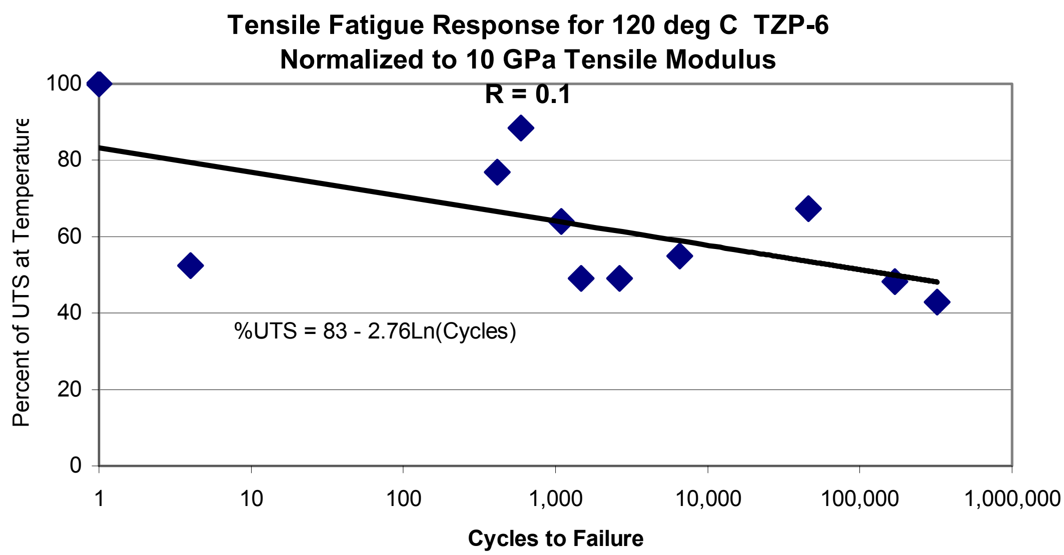

Figure 18. Tensile fatigue response of TZP-6 material at 120ºC test conditions.

3.4 Creep Response The results of the creep behavior of the SRIM urethane material in terms of design constraints are summarized below with some predictions of 10 and 15 year behavior. All the raw creep data can be found in Ref [2]. The creep results are for a variety of test conditions including tensile creep at room temperature dry and wet, 50ºC and 120ºC. Creep response was also measured for compression at room temperature and 120ºC.

The creep response models presented below are based upon multiple replicate specimens tested under identical conditions. The uncertainties associated with these models are determined by the propagation of error technique [3] presented in Ref [2]. Extrapolations to times beyond those listed are possible. But, no guarantee is given as to the linear response of the material beyond the times listed for the loads listed. The data collected indicate the linear portion of the creep response increases with decreasing load. There is insufficient data to quantify this relationship. No long duration (3000 hours) tests were performed at loads below 60% UTS. In general it appears that at or above 1.5% tensile strain the creep specimens are prone to out right failure or at least the initiation of non-linear creep strain that may go on for quite some time until failure occurs. Therefore, extrapolations are limited to 1.5% strain.

3.4.1 Tensile Creep Response at Room Temperature Conditions Figure 19 depicts the creep response model developed for this load condition. The data generated by the current study indicate this material, when loaded above 106 MPa has a linear response only out to about 400 hours at which point it has failed or is in the process of failing. The upper load limit of 106 MPa represents approximately 70 percent of the static ultimate tensile strength reported in Table 3. The following relationship best describes the creep response for this material in the highly loaded case.

$$\varepsilon = A\sigma t^{n} \qquad \text{Eq. (1)}$$

where:

$\varepsilon =$ Linear Creep Response

$A =$ 0.00013

$\sigma \geq$ 100 MPa

$t \leq$ 400 hours

$n =$ 0.018

Uncertainty associated with this model, $U_{\varepsilon} =$ 0.0010 mm/mm

The long-term creep deformation is described below. The nominal creep failure strain is 1.5 percent. Extrapolation of the following creep response out to 1.4 percent strain yields a 15-year load life. The creep deformation linear response is modeled for load levels below 70% UTS. Eq.(1) and the following variables describe the linear creep response.

$A =$ 0.00010

$\sigma \leq$ 100 MPa

$t \leq$ 131,400 hours

$n =$ 0.015

$U_{\varepsilon} =$ 0.0006 mm/mm

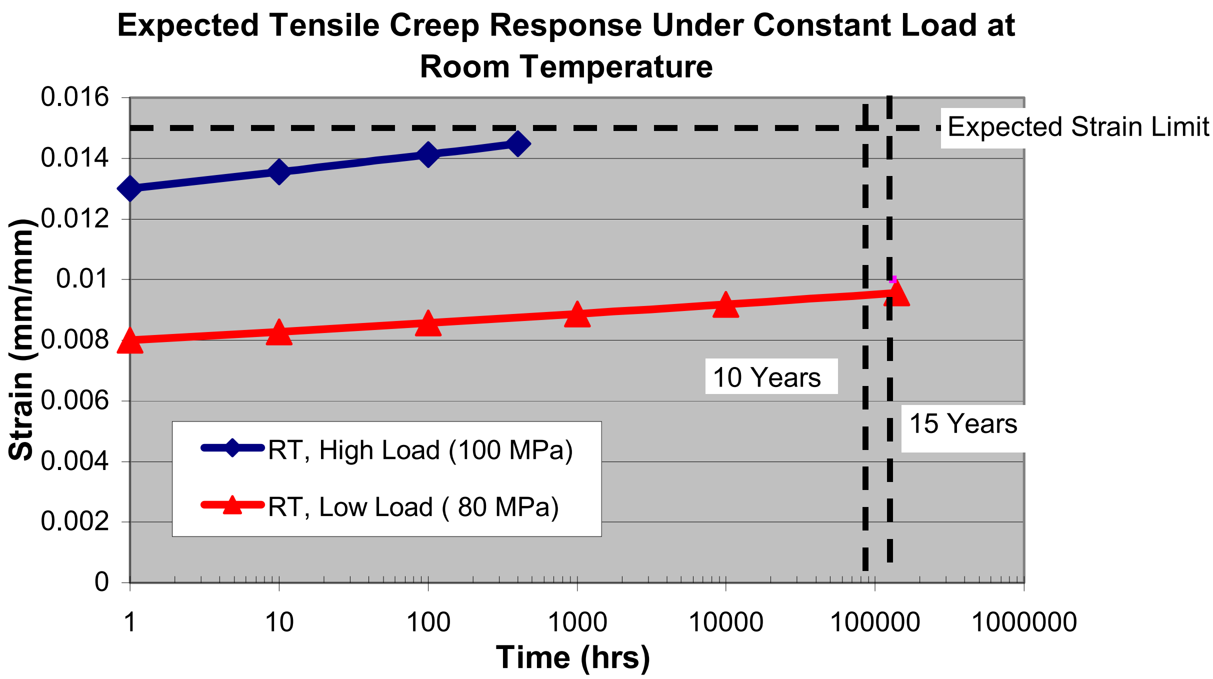

Figure 19. Predicted tensile creep response behavior under room temperature conditions.

3.4.2 Tensile Creep Response at Room Temperature, Moisture Saturated Conditions Figure 20 depicts the creep response model developed for this load condition. The data from the current study show this material has a bilinear response over time. A set of creep rupture data was generated for loads at or above 80 MPa (55% UTS) and a set of creep deformation data was generated at loads below 60 MPa (41% UTS). Using Eq. (1), the following variables model the creep response for the select load and time durations.

Initial response (high loads):

$A =$ 0.000123

$\sigma \geq$ 80 MPa

$t =$ 0 to 100 hours

$n =$ 0.023

$U_\varepsilon =$ 0.0012 mm/mm

Long term response (high loads):

$A =$ 0.000101

$\sigma \geq$ 80 MPa

$t \geq$ 100 hours

$n =$ 0.066

$U_\varepsilon =$ 0.0016 mm/mm

Initial response (low loads):

$$A = 0.000131$$
$$\sigma \leq 60 \text{ MPa}$$
$$t = 0 \text{ to10 hours}$$
$$n = 0.017$$
$$U_{\varepsilon} = 0.0008 \text{ mm/mm}$$

Long term response (low loads):

$$A = 0.000117$$
$$\sigma \leq 60 \text{ MPa}$$
$$t = 10 \text{ to } 131{,}400 \text{ hours}$$
$$n = 0.063$$
$$U_{\varepsilon} = 0.0012 \text{ mm/mm}$$

At 15 years the creep strain is close to the failure strain of 1.5%

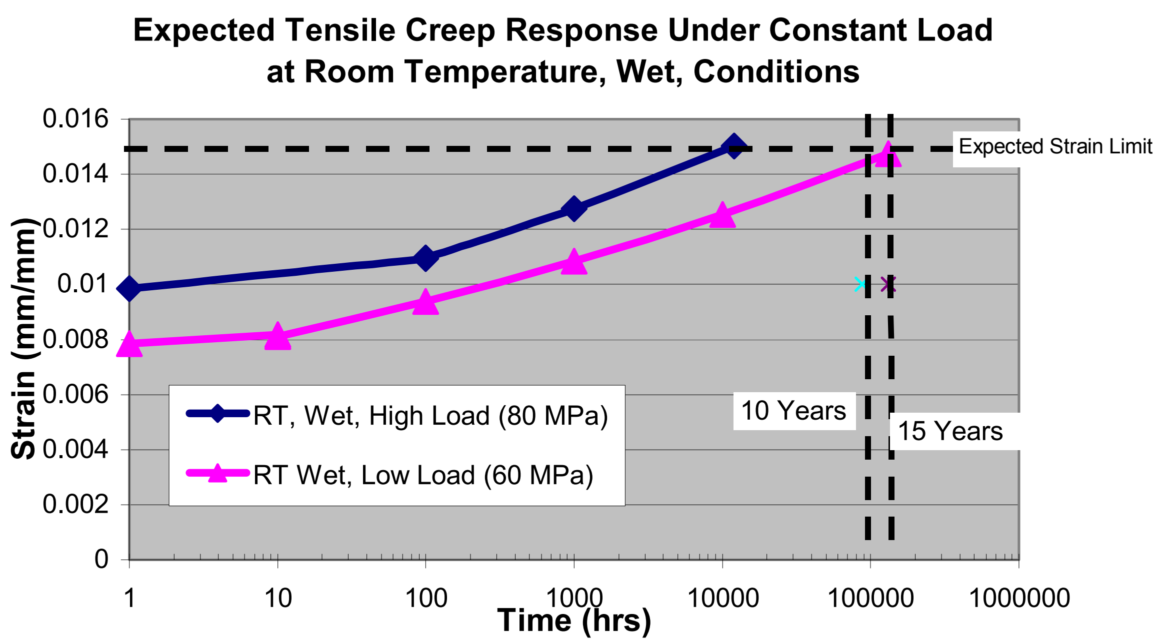

Figure 20. Predicted tensile creep response behavior under room temperature, wet conditions.

3.4.3 Tensile Creep Response at Elevated Temperatures Figure 21 depicts the creep response model developed for this load condition. Data from the study [2] were used to generate the following models for describing the tensile creep response of this material at various temperatures and load levels. For high loads (greater than 110 MPa) the creep response becomes very non-linear after 1000 hours. The creep-deformation responses at lower loads (less than 60 MPa) seem unaffected by the temperature conditions. Use Eq. (1) and the following variables to evaluate the material behavior at temperature.

High loads at 50ºC: $A =$ 0.000134

$\sigma \geq$ 90 MPa

$t \leq$ 1000 hours

$n =$ 0.013

$U_{\varepsilon} =$ 0.0012 mm/mm

High loads at 120ºC: $A =$ 0.000139

$\sigma \geq$ 90 MPa

$t \leq$ 1000 hours

$n =$ 0.033

$U_{\varepsilon} =$ 0.0019 mm/mm

Low loads at either 50ºC or 120ºC: $A =$ 0.000156

$\sigma \leq$ 60 MPa

$t \leq$ 131,400 hours

$n =$ 0.013

$U_{\varepsilon} =$ 0.0012 mm/mm

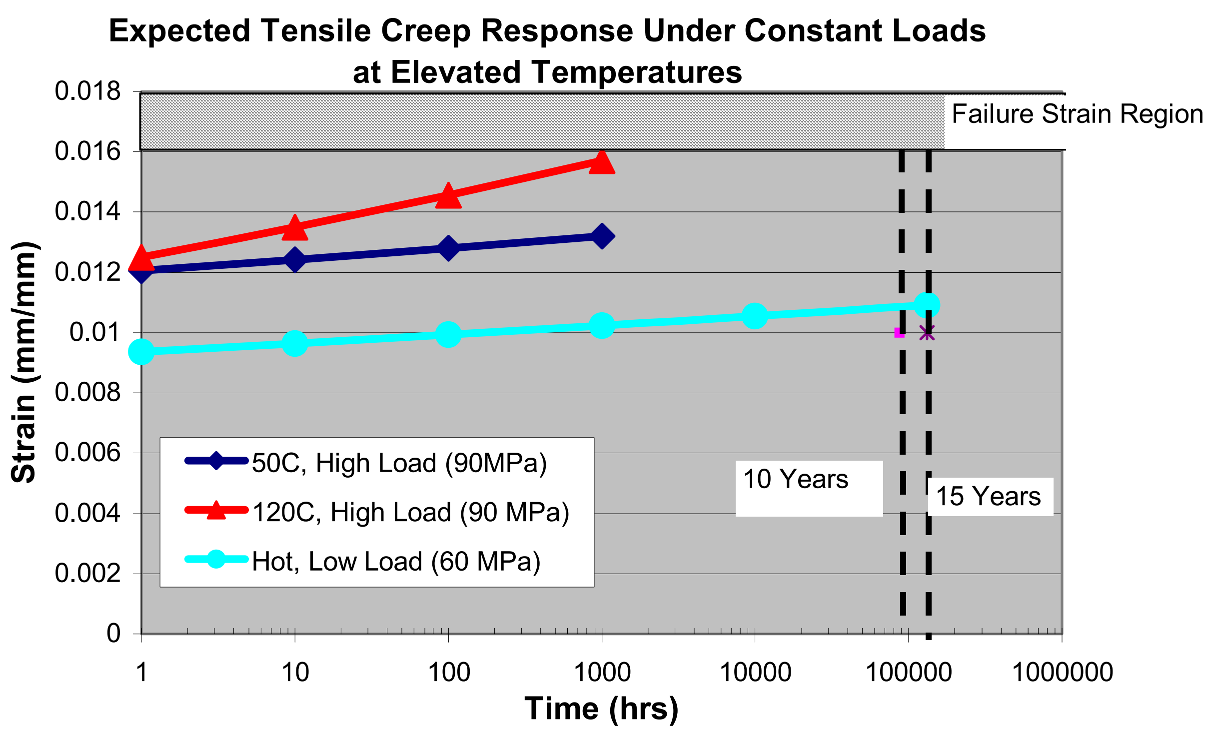

Figure 21. Predicted tensile creep response behavior under elevated temperature conditions.

3.4.4 Compressive Creep Response at Room Temperature Data from the study [2] were used to generate the following models for describing the compressive creep response of this material at room temperature under high loads. The creep response becomes very non-linear after 2000 hours. Use Eq. (1) and the following variables to evaluate the material behavior at temperature.

High loads at Room Temperature: $A =$ 0.000102

$\sigma \geq$ 90 MPa

$t \leq$ 2000 hours

$n =$ 0.017

$U_{\varepsilon} =$ 0.0018 mm/mm

3.4.5 Compressive Creep Response at Elevated Temperatures Data from the study [2] were used to generate the following models for describing the compressive creep response of this material at 120ºC under low loads. The creep response becomes very non-linear after 3000 hours. Use Eq. (1) and the following variables to evaluate the material behavior at temperature.

Low loads at 120ºC: $A =$ 0.000107

$\sigma \leq$ 50 MPa

$t \leq$ 3000 hours

$n =$ 0.046

$U_{\varepsilon} =$ 0.0019 mm/mm

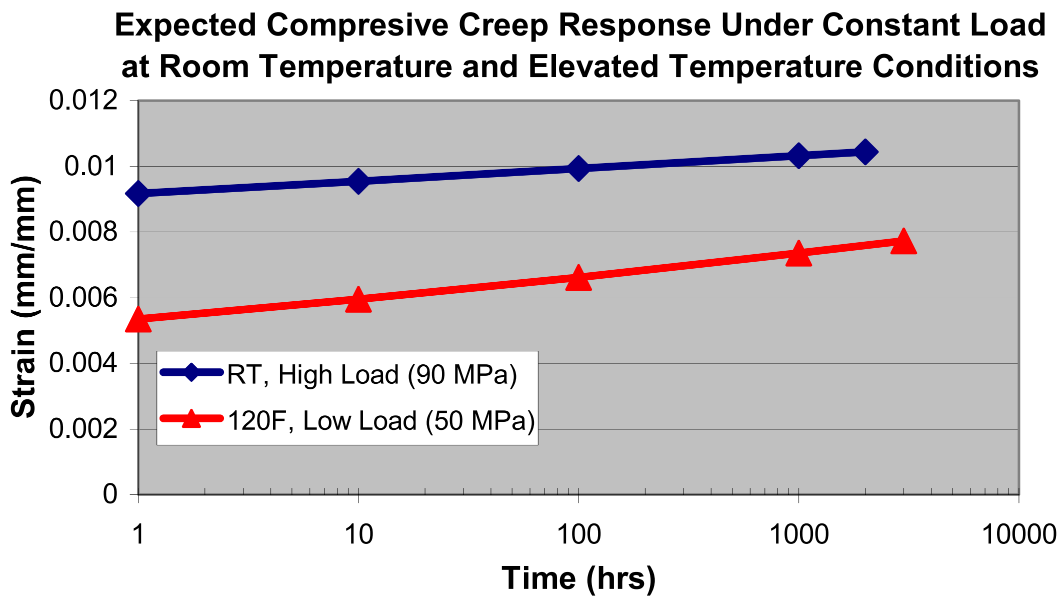

Figure 22. Predicted compressive creep response behavior under room temperature and elevated temperature conditions.

3.5 Damage Tolerance Figures 19 and 20 summarize the results of the tension-after-impact and compression-after-impact testing that was performed. These plots compare the retained tensile or compression strength as a function of the impact energy. The retained strength is the ratio of the strength in an undamaged portion of the plaque relative to the strength of a damaged test specimen. As these figures show, above 8 Joules of impact damage, there is substantial loss in tensile and compressive strength.

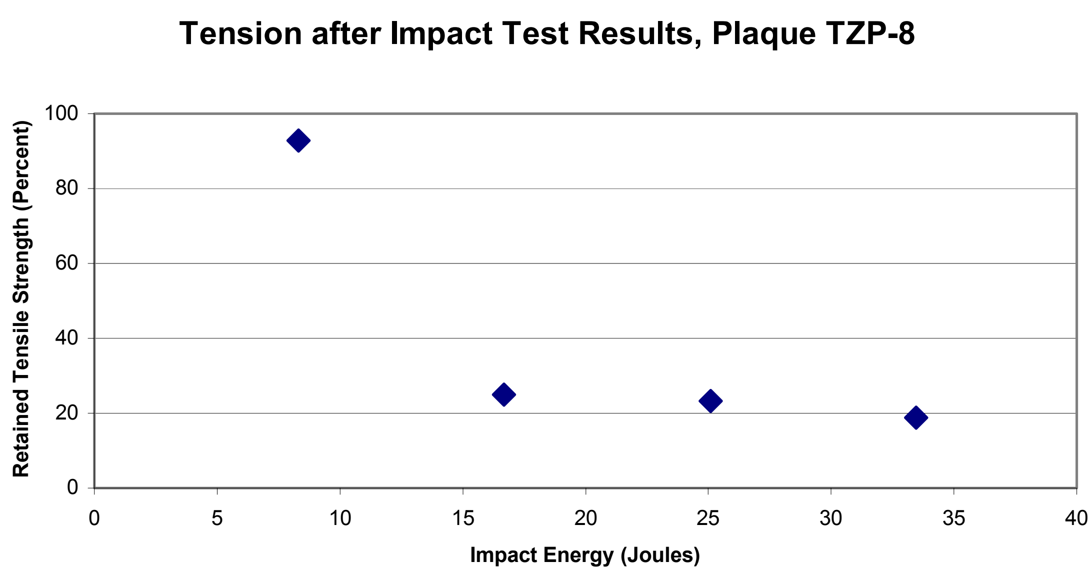

Figure 23. The effect of impact damage on the tensile strength of Plaque TZP-8.

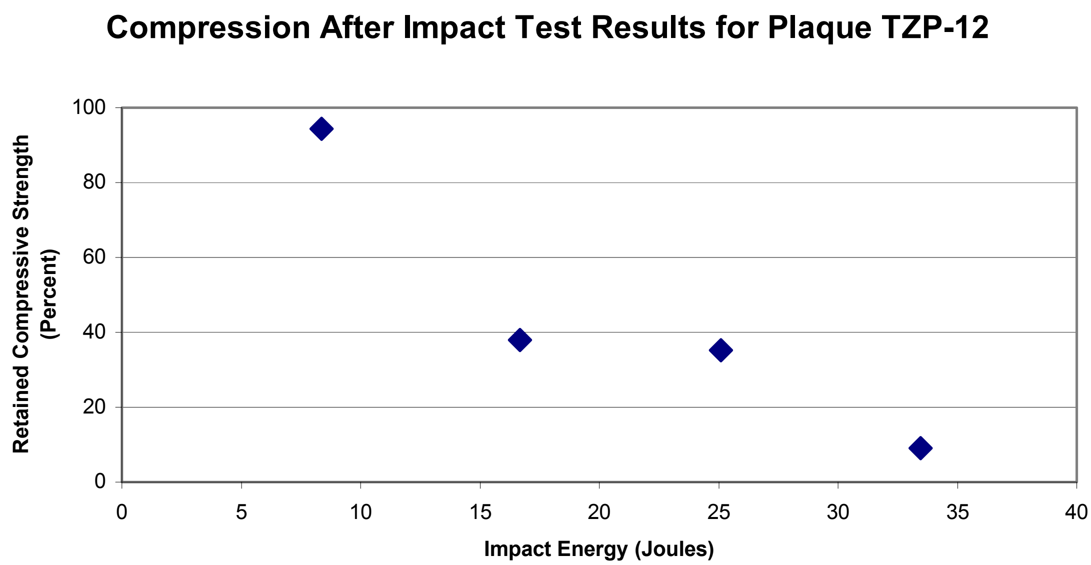

Figure 24. The effect of impact damage on the compressive strength of Plaque TZP-12.

4. DISCUSSION

The test methodology presented has proven to be a practical approach for ascertaining the durability of random glass-fiber-reinforced composites. Detailed evaluations of the test methods are presented in Ref. [2]. The test method section of this paper is intended to place the subsequent test data presentation in the proper context. Having established the origin of the data, the data is then presented in a reduced and summarized form that allows the designer ready access to the test results.

The static data presents a statistically significant body of results that include material uncertainties in terms of standard deviations associated with a particular material property. The plots of the fatigue response provide a convenient model for predicting fatigue behavior while graphically depicting the uncertainties associated with the model. The creep test results are also presented graphically and in terms of numerical models. The models have certain restrictions that are a function of time, temperature and load. Within these restrictions, the data, as summarized by the model, have a low degree of experimental error and material uncertainty. This should provide a reasonable level of confidence when using these models within the established restrictions on time, temperature, and load. The graphical representations illustrate the situation in which 10 and 15 year extrapolations are valid.

5. REFERENCES

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