F. Durability of Carbon-Fiber Composites

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Objective

- To develop experimentally-based, durability-driven design guidelines to ensure the long-term (15-year) integrity of representative carbon-fiber-based composite systems that can be used to produce large structural automotive components. Durability issues being considered include the potentially degrading effects of cyclic and sustained loadings, exposure to automotive fluids, temperature extremes, and low-energy impacts from such events as tool drops and kickups of roadway debris on structural strength, stiffness, and dimensional stability.

Approach

- Characterize and model the durability behavior of a progression of three representative carbon-fiber composites, each with the same thermoset urethane matrix but having a different reinforcement preform: (1) continuous fiber, ±45° crossply; (2) continuous fiber, quasi-isotropic; and (3) random chopped fiber.
- Replicate on-road conditions in laboratory tests of each composite to generate durability data and models.
- Subsequently shift focus to suitable thermoplastic composites, for which durability issues are generally more significant.
- Develop and publish durability-based design criteria for each composite.

Accomplishments

- Completed durability assessment of a quasi-isotropic carbon-fiber-reinforced thermoplastic material.
- Completed program review with ACC representatives.
- Completed and published durability-driven design criteria document on carbon-fiber-reinforced PPS material suitable for automotive structural applications

Future Direction

- Investigation developing durability-driven design criteria documents for thermoset and thermoplastic fiber-reinforced composite materials has been completed.

Introduction

Before composite structures will be widely used in automotive applications, their long-term durability must be assured. The Durability of Carbon-Fiber Composites project at ORNL was established to develop the means for providing that assurance. Specifically, the project is developing and documenting experimentally-based, durability-driven design criteria and damage-tolerance assessment procedures for representative carbon-fiber composite systems to assure the long-term (15-year) integrity of composite automotive structures. Durability issues being considered include the potentially degrading effects of cyclic and sustained loads, exposures to automotive fluids, temperature extremes, and incidental impacts from such things as tool drops and kick-ups of roadway debris. Research to determine the effect that these environmental stressors and loadings have on structural strength, stiffness, and dimensional stability is being conducted. The project is carried out in close coordination with the ACC.

The approach to investigating durability initially was to address a progression of thermoset composites, each of which had the same urethane matrix:

- reference $[\pm45]_{3S}$ crossply composite,
- $[0/90/\pm45]_S$ quasi-isotropic composite, and
- randomly-oriented chopped-carbon-fiber composite.

Characterization of the first two continuous-fiber composites has been completed, and design criteria documents published. In mid-FY 2002, the focus turned to chopped-carbon-fiber composites. Characterization of the randomly-oriented chopped-carbon-fiber composite was completed in FY 2003 and the durability-based design criteria report published. In FY 2003 investigation of carbon-fiber-reinforced thermoplastic materials for structural automotive applications was initiated.

All experimental activities investigating the initial thermoplastic material have been completed and the final report providing durability-based design criteria has been completed and published.[1] Contained in the following sections is a description of the quasi-isotropic carbon-fiber-reinforced thermoplastic material (T material) and a summary of results obtained for this material including a comparison to a previously-investigated quasi-isotropic thermoset carbon-fiber composite (Q material).[2]

Material Description

The T material consisted of a polyphenylene sulfide (PPS) thermoplastic matrix reinforced with 16 plies of carbon-fiber unidirectional tape, $[0°/90°/+45°/-45°]_{2S}$. The carbon fiber was Hexcel AS-4C and was present in a fiber volume of 53% (60%, by weight). Nominal plaque thickness of the T material was 2.9 mm.

The Q material had a 40% volume fraction and a Baydur 420 IMR urethane matrix. Carbon-fiber reinforcement for the Q material was a $[0/90/\pm45]_S$ layup of continuous, 6K tow, aerospace-grade fibers. Nominal plaque thickness of the Q material was 2 mm.

Elastic and Creep Properties for Design Analysis

In-plane elastic constants for the quasi-isotropic thermoplastic composite (T material) are listed in Table 1, where they are compared with the quasi-isotropic thermoset composite (Q material) values. The T material stiffness is about 13% larger than the Q material value at room temperature, and it is slightly less affected by an increase in temperature to 120°C than is the Q material. Prior thermal cycling had a small effect on the T material. After 25 thermal cycles between -40° and 120°C the

Table 1. Elastic constants.

Temperature (°C)	**Elastic modulus, E (GPa)**	**Poisson's ratio, ν**
Quasi-isotropic thermoplastic composite (T material)		
23	36.5	0.29
120	35.7	0.30
Quasi-isotropic thermoset composite (Q material)		
23	32.4	0.31
120	29.8	0.34

tensile strength increased 9.2%, compressive strength decreased 8.4%, and shear strength increased 6.6%. With respect to the Q material, the tensile strength decreased 6.6%, the compressive strength increased 19.7%, and shear strength decreased 3.4%. The loss in shear stiffness was more significant for the Q material (25.1%) than for the T material (4.2%).

A few prior mechanical loadings within the allowable stress range degraded the modulus of elasticity slightly for both materials. For the T material there was no loss of stiffness during the first load cycle, but the stiffness decreased slightly with succeeding load cycles reaching a maximum of about 4% during the last load cycle. Both the T and Q materials exhibited no degradation in ultimate tensile strength during the final load cycle to failure. However, larger numbers of cyclic loads, within the design-allowable cycle numbers, can lead to a gradual stiffness loss. There was no indication that the limit of 10% loss of stiffness over the design-allowable life (reflection of damage accumulation under cyclic loading) would be exceeded in either quasi-isotropic composite.

The bounding effect of fluids on elastic modulus was the same for both the thermoplastic and thermoset quasi-isotropic composites — a reduction of 4%.

Time-dependent tensile creep strains at room-temperature were significantly less in the T material than they were in the Q material. This is illustrated in Table 2 by the time-dependent creep strains predicted to result from the application of a 60 MPa stress for 5000 h.*

Time-dependent creep strain for this condition is about 14 times larger at room temperature in the Q material than in the T material. At 120°C, the factor jumps to 37.9 using the information in Table 2.

* The 60-MPa stress level is below the allowable stress levels, even at 120°C.

Table 2. Time-dependent tensile creep strains due to a stress of 60 MPa applied for 5000 h at room temperature.

Composite	Creep strain (%)	Temperature multiplication factor at 120°C
T material	0.000981	1.7
Q material	0.014684	4.3[a]

[a]The actual stress-dependent factor is 2.9 for 60 MPa, but a single bounding factor of 4.3 was used in Ref. 2.

At room temperature, compressive creep is the same as tensile creep for both the quasi-isotropic composites. At 120°C, compressive creep is about six times the predicted tensile creep for the T material. For the Q material, the factor ranges from 8 to 18 for the stresses examined. In either case, compressive loadings at 120°C should be carefully considered in design.

A single creep-strain multiplication factor of 2.2 is recommended to account for fluid effects in the T material. The corresponding factor for the Q material was 1.7.

Allowable Stresses for Static Loadings

The basic time-dependent allowable-stress quantity used for the T material was the same as that used for the Q material except that the design factor on creep rupture strength was changed from 0.8 to 0.67.

$$S_t \leq \begin{cases} S_0 \\ 0.67\,\sigma_r \text{ (T material)}; 0.8\,\sigma_r \text{ (Q material)} \end{cases}$$

Here, S_t is the time-dependent allowable stress applicable to tensile stress components, S_0 is the short-time (time-independent) allowable stress, σ_r is the average creep-rupture strength, and S_r is the minimum creep-rupture strength corresponding to time t. Representative values of S_t are tabulated in Table 3 for both the T and Q materials. The room-temperature S_0 value for the T material is 169% of the value for the Q material. This percentage increases to 200% at 120°C, so the short-time strength of the T material is degraded less by temperature than is that of the Q material. At 5000 hours, the corresponding percentages are 160% and 200%, so temperature has about the same affect on both materials.

Table. 3. Tensile S_t values in air (MPa).

Temperature (°C)	**Time**		
	0 h	**5000 h**	**15 years**
Quasi-isotropic composite (T Material)			
23	327	311	302
120	314	284	279[a]
Quasi-isotropic composite (Q Material)			
23	194	194	194
120	157	142	130[a]
[a] Unrealistic condition.			

Prior mechanical loads, thermal cycles, and fluid exposure each degrade the allowable stress, S_0. Bounding relations for the T material are summarized and compared with the corresponding reductions for the Q material in Table 4.

Table 4. Bounding strength reductions.

Effect	**Strength reductions (%)**	
	Quasi-isotropic composite (T Material)	**Quasi-isotropic composite (Q Material)**
Prior loads	4	15
Prior thermal cycles	3	7
Fluid exposure	35	0

For tensile biaxial stress states, the maximum principal-stress theory is recommended for design with both composites. The principal-stress theory is also recommended for compressive and other nontensile biaxial stress states for the Q material. However, the maximum shear strength criterion is recommended for the T material for compressive and other nontensile biaxial stress states. For these latter stress states, the stress is limited to the quantity S_t*, which is based on short-time compressive strength and compressive creep-rupture results. Representative S_t* values for the T material are tabulated and compared with Q material values in Table 5.

The T material allowables in Table 5 are reduced 26% by fluid exposure at room temperature, and 35% at 120˚C. These are much larger than the values used for the Q material.

Table 5. S_t* (MPa) allowable stresses applicable to nontensile biaxial stress states.

Temperature (°C)	**Time**		
	0 h	**5000 h**	**15 years**
Quasi-isotropic composite (T Material)			
23	175	134	125
120	93	52	46[a]
Quasi-isotropic composite (Q Material)			
23	130	130	130
120	76	17	10[a]
[a] realistic condition.			

Allowable Stresses for Cyclic Loadings

Two room-temperature design fatigue curves were developed for the T material. The first curve is directly applicable to all cycles having a positive mean stress. The second curve is applicable to all cycles having a zero or negative mean stress. The governing stress parameter is $S = \sqrt{S_{max} \times S_a}$, where S_{max} is the maximum stress reached in the cycle, or in the case of a compressive cycle, the absolute value of the minimum stress, $|S_{min}|$, and S_a is the alternating-stress component. To account for the effect of temperature and fluid effects, stress-reduction factors are provided.

Table 6 compares representative allowable maximum cyclic stresses for tensile cycling for the T material with the corresponding stresses for the Q material. At room temperature, the allowable cyclic tensile stress at 10^8 cycles for the T material is 22% greater than that for the Q material. The percentage is 106% at 120°C.

Table 6. Allowable maximum cyclic stresses for tensile cycling (R = 0).

Temperature (°C)	Maximum stress (MPa)	
	10^2 cycles	10^8 cycles
Quasi-isotropic composite (T material)		
23	379	192
120	292	163
Quasi-isotropic composite (Q material)		
23	267	157
120	259	79

Bounding fluid effects multiplication factors for the two materials are tabulated in Table 7. The T material factors are somewhat lower than are those for the Q material.

Table 7. Bounding fluid multiplication factors for allowable cyclic stresses.

Composite	10^2 cycles	10^8 cycles
T material	0.85	0.77
Q material	0.92	0.98

Simplified Summary of Allowable Stresses

As a way of further simplifying and summarizing the allowable design stresses for static and cyclic loadings, Table 8 gives the key allowable stress values for various conditions as percentages of the average room-temperature ultimate tensile strength (UTS) value —551 MPa for the T material and 336 MPa for the Q material. The table shows that while the two sets of values are fairly similar, temperature and time had a greater relative effect on the Q material than they did on the T material.

A strain limit of 0.3 to 0.4% has often been used, at least for glass-fiber composites for design of composite automotive structures.[*] The strain limit is intended to cover all effects. For the T material, strain limits of 0.3 and 0.4% correspond to elastic stresses of 19% and 26% of the average room-temperature UTS, respectively (the corresponding values for the Q material are 29 and 39%, respectively). Comparison of the 19% and 26% stress levels for the T material with the allowable values in Table 8 shows that the 0.3% strain limit covers all the listed conditions, while the 0.4% limit covers all conditions except 10^8 cycles at 120°C with fluid effects. For the Q material, the strain limits would cover all the realistic conditions except for high-cycle fatigue at 120°C.

[*] In the aerospace industry, fixed wing and rotocraft composite structures have been successfully designed to operate at strains up to 0.4%.[2]

Table 8. Key allowable tensile stresses, expressed as a percentage of average room-temperature UTS[a].

Stress allowable	Without fluid effects		With fluid effects[b]	
	23°C	120°C	23°C	120°C
Quasi-isotropic composite (T material)				
S_0 (0 h)	59	57	54	52
S_t				
5000 h	56	52	52	48
15 years	55	51[c]	52	48[c]
S_{max} (R = 0)				
10^2 cycles	69	53	59	45
10^8 cycles	35	30	27	23
Quasi-isotropic composite (Q material)				
S_0 (0 h)	58	47	54	44
S_t				
5000 h	58	42	54	40
15 years	58	39[c]	54	36[c]
S_{max} (R = 0)				
10^2 cycles	79	77	73	71
10^8 cycles	47	24	46	23

[a] T material UTS_{avg} = 551 MPa; Q material UTS_{avg} = 336 MPa.
[b] Prior loads and prior thermal cycling reductions are not included in these values.
[c] Unrealistic condition.

Damage Tolerance Evaluation

For specific low-energy impacts such as roadway kickups, tool drops, and load drops in a pickup box, experimentally-derived correlations are given for (1) estimating the damage area from the mass and velocity of the impacting object and (2) determining, from the estimated damage area, the resulting degradation in strength. While these correlations are clearly tied to the specific sizes and geometries of the impacted plate specimens and of the specimens used for mechanical property evaluations, it is thought that they do provide useful information. This is particularly true when comparing the relative response of two different composites.

Table 9 gives the predicted impact damage areas that were obtained from design curves that had been developed for four representative combinations of impactor mass and velocity for the quasi-isotropic thermoplastic composite (T material), the quasi-isotropic thermoset composite (Q material), and the ±45° crossply laminate.[3] The latter continuous-fiber thermoset composite is added to the comparison because it has roughly the same thickness (3.2 mm) as the T material, whereas the Q material was thinner (2 mm vs. 2.9 mm). With one exception, the damage areas for the T composite are larger than those for the other two composites. As observed from the impact tests, the T material had a greater propensity to delaminate than did the previous composites.

Table 9. Damage areas in mm^2 from design curve.

Mass (kg)	**Velocity (m/s)**	**Quasi-isotropic Comp. (T Mat'l)**	**Quasi-isotropic Comp. (Q Mat'l)**	**±45° Cross-ply**
11.52	0.8	178	168	72
11.52	1.3	350	891	338
0.0227	22.4	321	168	84
0.0227	36.4	911	891	396

The T material is somewhat more damage tolerant than the Q material. For both composites, 76.2-mm-wide mechanical property specimens containing the impact damage area were cut from impacted plate specimens. The T material specimens were used for both tension and compression tests. Only compression tests were performed for the Q material. Typical strength-reduction ratios from the lower-bound curves that had been developed are tabulated in Table 10.

Table 10. Estimated strength-reduction ratios caused by impact damage.

Damage area (mm^2)	**Strength-reduction ratio**	
	T material	**Q material**
100	0.71	0.60
500	0.51	0.45

Conclusions

Recommended durability-based design properties and criteria for a quasi-isotropic carbon-fiber reinforced thermoplastic composite for possible automotive structural applications have been developed. The composite consisted of a polyphenylene sulfide (PPS) thermoplastic-matrix (Fortron's PPS – Ticona 0214B1 powder) reinforced with 16 plies of carbon-fiber unidirectional tape $[0°/90°/+45°/-45°]_{2S}$. The carbon fiber was Hexcel AS-4C and was present in a fiber volume of 53% (60%, by weight). The study was guided by (1) the need to establish criteria that could be readily integrated into the existing automotive structural design process and (2) by the fact that it was not feasible to experimentally examine all possible combinations of conditions. Thus, simplifications, assumptions, and extrapolations were necessary, as is often the case when definitive design guidance must be provided. The criteria were based upon four categories of data: (1) short-time tensile, compressive, shear, and uniaxial and biaxial flexure; (2) cyclic fatigue; (3) time-dependent creep and creep rupture; and (4) prior load effects. In all categories, except for the fourth, the effects of temperature and of two bounding fluids - distilled water and a 70% methanol/30% distilled water windshield washer fluid - were established. From these tests, properties and correlations for elastic and creep design analyses were generated, a biaxial-strength criterion was chosen, time-dependent allowable stresses for static loadings were developed, and limits for cyclic loadings were established. The resulting criteria are summarized in Table 8 for key conditions. The allowable stresses in the table are expressed as a percentage of the average room-temperature UTS of 551 MPa. These allowables vary from 59% of the UTS for short-time loadings at room temperature in air, to 35% for 10^8 cycles at room temperature in air, to 23% for 10^8 cycles at 120°C with fluid effects.

It was not possible to examine all possible combinations of conditions in establishing the allowables reflected in Table 8, and while it is believed that the allowables would lead to an adequate design, some areas should be further examined. In particular, it is suggested that the effects of compression and biaxial stresses in creep and the effects of biaxial and mean stresses in fatigue may require further attention. How do the criteria presented here compare with past design practice for glass-fiber composite automotive structures? A commonly used "rule-of-thumb" has been a strain limit of about 0.3%. For the quasi-isotropic carbon-fiber-reinforced thermoplastic composite, this strain limit corresponds to an elastically-calculated stress of 19% of the average room-temperature UTS. Comparison of this value with the allowables in Table 8 shows that the 0.3% strain limit covers all listed conditions.

References and Publications

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2. J.M. Corum et al., *Durability-Based Design Criteria for a Quasi-Isotropic Carbon-Fiber Automotive Composite*, ORNL/TM-2002/39, Oak Ridge National Laboratory, Oak Ridge, Tenn., March 2002.

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