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Fatigue Behavior and Recommended Design Rules for an Automotive Composite*

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ABSTRACT

Fatigue curves (stress vs cycles to failure) were generated under a variety of conditions (temperatures, fluid environments, mean stresses, block loadings) for a candidate automotive structural composite. The results were used to (1) develop observations regarding basic fatigue behavioral characteristics and (2) establish fatigue design rules. The composite was a structural reaction injection-molded polyurethane reinforced with continuous strand, swirl-mat E-glass fibers. Tensile fatigue tests on specimens from a single plaque at -40°F, room temperature, and 250°F provided the basic behavioral characteristics. It was found that when stress was normalized by the at-temperature ultimate tensile strength, the fatigue curves at the three temperatures collapsed into a single master curve. An assessment of the individual stress-strain loops throughout each test showed a progressive loss in stiffness and an increase in permanent strain, both of which are indicative of increasing damage. Fatigue tests on specimens from several plaques were used to develop a design fatigue curve, which was established by using a reduction factor of 20 on average cycles to failure. This factor assures that the stiffness loss during the design life is no greater than 10 percent. Fatigue reduction factors were established to account for various fluids. Reversed stress fatigue tests allowed a mean stress rule to be validated, and block loading tests were used to demonstrate the adequacy of Miner's rule for cumulative fatigue damage.

INTRODUCTION

The Oak Ridge National Laboratory, as a part of a U.S. Department of Energy sponsored project entitled Durability of Lightweight Composite Structures for Automotive Applications, has recently developed a recommended set of experimentally-based, durability-driven

design criteria for a reference automotive structural polymeric composite [1-3]. The effort, which was carried out in close coordination with the Automotive Composites Consortium (ACC), was intended to provide the framework for establishing criteria for additional composites, both glass- and carbon-fiber reinforced, as they become available.

In addition to guidelines on the properties and models to be used in design analyses, the criteria provide time- and temperature-dependent allowable stresses for static loadings, design limits for cyclic loadings, and damage tolerance design procedures for addressing the effects of low-energy impacts from such things as tool drops and roadway kickups. The effects of exposure to various automotive fluids, temperature extremes, and prior loadings are included in the criteria.

The purpose of this paper is to describe the results of the fatigue testing and resulting data analysis that led to the recommended fatigue design rules in the criteria. The tests included tension-tension fatigue, reversed (tension-compression) fatigue, and compression-compression fatigue. The tension-tension tests were used to characterize temperature effects, automotive fluid effects, and block loading (cumulative damage). In addition, a special series of tests on specimens from a single plaque was carried out at various temperature in which stress, strain, and stiffness were monitored throughout each test. These data were used to evaluate damage accumulation with cycles and to choose the fatigue design margin used in the criteria.

All of the tests were on specimens from the reference composite, which was a structural reaction injection-molded (SRIM) isocyanurate (polyurethane) reinforced with continuous strand, swirl-mat E-glass. The isocyanurate resin was DOW MM 364, and the reinforcement was Vetrotex Certainteed Unifilo U750. This particular composite was chosen by ACC and supplied in the form of 25 x 25 x 1/8-in-thick plaques. Five layers of mat were used in each plaque, resulting in a fiber content of about 25% by volume (40-50% by weight).

After briefly describing the experimental arrangements, the basic fatigue behavior will be presented (the special tests on specimens from a single plaque). Development of design curves will then be discussed. Next, a summary of environmental effects and recommended

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reduction factors for design will be presented. Mean stress effects and a recommended method for handling them in design are then discussed, followed finally, by a description of the block loading test results and the choice of Miner's rule to account for cycles of varying load amplitudes.

EXPERIMENTAL ARRANGEMENTS

The tension-tension fatigue tests were all performed with an R ratio (minimum stress divided by maximum stress) of 0.1. A sine waveform was used, and the frequency was determined for each stress range to result in a constant average loading rate. The resulting frequencies varied from approximately 1 Hz at the highest maximum stress [80% of the ultimate tensile strength (UTS)] to 6 Hz at the lowest (20% UTS).

Three specimen configurations were used for the tensile fatigue tests. All had overall dimensions of 1 x 8 x 1/8-in.-thick.

- Straight sided with 2-in.-long end tabs
- Hourglass shaped, with a minimum center width of 0.8 in. and an hourglass radius of 7 in. on each side (generally tested without end tabs)
- Dogbone shaped, having the same 7 in. radius as the hourglass but reducing the width to a uniform 0.8 in. over a central length of 1.6 in. (tested without tabs)

All of the special tests in which strains were monitored used dogbone specimens.

All of the tension fatigue tests were performed on special-purpose test stands with servo-hydraulic control and mechanical wedge grips. MTS extensometers were used to measure strains, and the capability existed to record cyclic stress-strain data throughout cycling and to monitor stiffness (modulus of elasticity) degradation in real time. For elevated temperatures, either air was passed through rubber chambers surrounding the specimens, or quartz lights were used. For tests at -40°F, vapor from liquid nitrogen, with on/off control, was passed through the chambers surrounding the specimens. For testing in fluids, neoprene bellows, sealed to the specimens at top and bottom, were used. The bellows were filled with fluid from the bottom and vented from the top.

The reversed fatigue and compression fatigue tests used a different specimen design, and the tests were performed in an MTS test machine with hydraulic grips. All of the tests were in ambient air. The specimens, which had overall dimensions of 1 x 5.9 x 1/8-in.-thick, had a central hourglass configuration, with a minimum width of 0.8 in. and an hourglass radius of 4.5 in. on each side. To avoid buckling, the specimens were mounted so that only the central 1.4 in. of the length was outside of the grips.

BASIC FATIGUE BEHAVIOR

All of the tests reported in this section were performed on specimens from a single plaque in order to minimize data scatter. Furthermore, all of the specimens were

from the slightly weaker 0° direction of the plaque*. The following nominal UTS values for the plaque were determined.

Temperature (°F)	UTS (ksi)
-40	31.2
73	26.0
250	17.7

Twenty-five fatigue tests on specimens from the plaque were performed—thirteen at room temperature and six each at -40 and 250°F.

Figure 1(a) shows the fatigue failure data, with power law curve fits, on an S-N plot. Figure 1(b) shows the same test results, but with maximum stress given as a percentage of the at-temperature UTS. The latter figure shows that normalizing by the UTS brings the -40°F and room-temperature results together, but the 250°F curve is slightly high. Our conclusion is that all the curves in Fig. 1(b) would likely coincide if a sufficiently large statistical (UTS) sampling were available. Figure 1(b) indicates that the 10^8 cycle "endurance limit" is about 20% of the short-time static strength. This is consistent with observations made for continuous-strand mat (CSM)/polyester laminates for both tensile and flexural fatigue[4].

Figure 2 shows the first and near-last stress-strain loops for a representative test at room temperature. Results for -40 and 250°F look qualitatively the same. These loops reflect the accumulation of cyclic damage in two ways: (1) a permanent strain increment in each cycle and (2) a cyclic softening (stiffness reduction). The incremental permanent strain drops off rapidly in the first few cycles of a test. Likewise, the stiffness drops most rapidly in the early cycles. Overall, it appears that the decrease in stiffness accounts for about half of the increase in the maximum strain observed in the near-last loop of Fig. 2.

As will be seen, plots of maximum strain vs cycles give the best overall view of damage accumulation. However, plots of stiffness vs life fraction, n/N_f , are also informative. These are shown in Fig. 3 for room temperature tests. It can be seen that with the exception of the two tests at 79.5% UTS, the curves are grouped together fairly well. It is believed that the 79.5% UTS specimens were so damaged on the first load-up that the cyclic mechanisms are somewhat masked. The curves in Fig. 3 are fit very well by power laws up to a life fraction of at least 0.5. Fitting a power law to the values to 0.5 and then extrapolating to a life fraction of 1.0 gives an average predicted end-of-life stiffness reduction of 16.5% (ignoring the two higher results at 79.5% UTS). Rapid damage development near the end of life increases the reduction above that of the power law prediction in most cases.

Curves for the other temperatures are very similar. For -40°F, the average end-of-life stiffness reduction predicted by the power laws is 17.2%. For 250°F, the value is just 8.1%.

* 0° here refers to the roll direction of the swirl mat reinforcement.

a. Maximum stress in ksi.

b. Maximum stress as percentage of UTS.

Figure 1. Fatigue S-N curves. All specimens from a single plaque.

Figure 2. Stress-strain loops for typical room-temperature test ($\sigma_{\max} = 44\%$ UTS).

Figure 3. Stiffness reduction vs life fraction at room temperature. Note that the top two curves correspond to a high cyclic stress of 79.5% UTS.

The maximum peak strains in each cycle are plotted as a function of cycles in Fig. 4 for room-temperature tests. Again, curves for the other temperatures are qualitatively very similar to the room-temperature results. The points represent arbitrary cycle numbers chosen for plotting from the large amount of data. The initial portions of the curves are linear. From microscopic observations of fatigue specimens at various numbers of cycles, it appears that this linear portion involves mostly matrix cracking [2]. Later, where the curves turn up, fiber debonding becomes prevalent.

The initial straight portion of each curve was fit with a logarithmic curve (a straight line on the semilog scale) as shown. The slopes of these lines are linear with maximum cyclic stress, and they extrapolate to a slope of zero at a maximum stress level of 16.3% UTS, as shown in Fig. 5 (again, the two high stress tests at 79.5% UTS are out of line and were not used). Figure 5 suggests that the true endurance limit is 16.3% UTS.

Design margins for fatigue ought to reflect some consideration of damage mechanisms. Stiffness reduction, for example, mirrors damage development to some extent. A limit of 10% stiffness reduction is sometimes used for design. Another possibility is to limit allowable cycles to prevent the onset of the rapid damage that was shown in Fig. 4. These two possibilities are plotted on an S-N diagram in Fig. 6 for room temperature. The 10% reduction points were calculated for each test by the power laws previously described. The increased damage development points are from Fig. 4. Also shown in Fig. 6 are various design margins on average failure that are commonly used in metal fatigue—reduction factors of

Figure 4. Maximum strain vs cycles at room temperature.

Figure 5. Slope of initial straight lines in Fig. 4 vs maximum stress.

10 or 20 on cycles and a reduction factor of 2 on stress. A factor of 20 on cycles would limit the stiffness reduction to 10%. However, even a factor of 2 on stress would not limit the onset of rapid damage at the higher cycles. Higher margins would be prohibitive; thus, some of the latter damage must be tolerated at the higher numbers of cycles. Similar plots for -40 and 250°F yield exactly the same conclusions.

Figure 6. Possible design margins relative to room temperature data.

DESIGN CURVES

A total of 58 tension-tension fatigue tests on 0° specimens from 12 plaques has been performed at room temperature in ambient air. The specimens were either uniform, hourglass, or dogbone in shape. Likewise, 20 fatigue tests on 90° uniform specimens from 5 plaques have been performed. All of these tests had a minimum to maximum stress ratio, R , of 0.1. All of the data are plotted in Fig. 7, where maximum cyclic stress is expressed as a percentage of UTS. The UTS values used were the averages for all plaques tested (30 for the 0° direction and 25 for the 90° direction): $UTS_{0^\circ} = 21.3$ ksi, and $UTS_{90^\circ} = 28.4$ ksi. It is concluded from Fig. 7 that a single fatigue curve can adequately represent both 0° and 90° results when stress is normalized to the appropriate UTS value. The recommended design curves are based on 0° data, since the lower 0° UTS is adopted in the design criteria.

As explained in the previous section, a reduction factor of 20 on cycles would, on average, limit stiffness reduction to 10% during cycling. A larger factor of 2 on stress would limit rapid damage development (involving fibers) at lower cycles but not at higher cycles. It is recommended that the 20× on cycles be adopted. This factor covers data scatter with more than 10× left over for other uncertainties.

The resulting design curve is shown in Fig. 8 labeled $R = 0$.^{*} Again, it is intended that this in-air curve apply for any strength or temperature, provided the proper UTS is used to obtain the stress. The second curve, labeled $R = -1$, will be discussed later relative to mean stress effects.

ENVIRONMENTAL EFFECTS

Room-temperature fatigue curves were generated for seven different automotive fluids: brake fluid, motor oil,

^{*} Note that the $R = 0$ design curve is based on the $R = 0.1$ data. It is believed that any difference between an $R = 0.1$ and an $R = 0$ curve would be small and easily absorbed by the 20× margin.

Figure 7. Normalized S-N curve showing near-colinearity of 0° and 90° fatigue data. The lower curve fit represents the 90° fatigue data.

Figure 8. Recommended fatigue design curves. These curves are applicable to both the 0° and 90° directions and to temperatures over the range from -40 to 250°F when the normalized stress is multiplied by the appropriate UTS.

engine coolant, saltwater, distilled water, windshield washer fluid, and battery acid. In all cases, specimens were immersed for 100 h in the respective fluid and then tested in the fluid.

Because moisture is so important, fatigue curves were developed for three additional moisture conditions:

- specimens presoaked for 1080 h in 180°F demineralized water and then tested at room temperature in distilled water (condition designed to provide an extreme case of moisture degradation),
- pre-exposed 100 h and tested in > 90% RH, and
- pre-exposed 100 h and tested in < 10% RH.

The 180°F exposure had a very significant degrading effect on fatigue. Wet and dry air had little, if any, effect.

In each case, the environmental curve was compared with the corresponding ambient air curve (for the same specimen configuration), as illustrated in Fig. 9 for distilled water. The hourglass specimen curve for distilled water was compared with the hourglass specimen curve for air (using power law curve fits) to develop reduction factors at various numbers of design cycles. The resulting factors for distilled water, as well as factors similarly obtained for the other conditions, are shown in Table 1. These factors should be used to reduce the cyclic design stress obtained from Fig. 8.

Table 1. Fatigue stress reduction factors for various automotive fluid environments

Fluid	Cycles			
	1×10^2	1×10^4	1×10^6	1×10^8
Air	1.00	1.00	1.00	1.00
Brake fluid	1.00	1.00	0.99	0.94
Motor oil	1.00	0.98	0.91	0.84
Engine coolant	1.00	1.00	0.87	0.71
Saltwater	1.00	0.95	0.86	0.78
Distilled water	0.95	0.90	0.85	0.81
Windshield wash	1.00	0.97	0.84	0.73
180°F water, 1080 h	0.64	0.69	0.74	0.80
Battery acid	1.00	0.73	0.50	0.34

In considering the factors in Table 1, it should be realized that there is an infinite variety of exposure conditions to which automotive structures could be subjected. The factors in the table were, with the exception of the 180°F water exposure, obtained on specimens submerged for 100 h prior to testing and then tested in the fluid (receiving more than 60 h additional exposure at 10^6 cycles). These are believed to represent reasonably extreme bounding conditions for design. Note that the projected factors for distilled water and for 180°F, 1080 h water at 10^6 cycles are essentially the same, indicating that the specimens are nearly saturated and responding equally at that point. This adds some confidence to the factors.

Figure 9. Distilled water fatigue data and power law fits to data and to corresponding ambient air data.

TREATMENT OF MEAN STRESSES

The fatigue data and curves discussed to this point were all tensile fatigue with $R = 0.1$ (assumed to be applicable to $R = 0$ as well). These tests probably represent the most common automotive loading condition, so the results are often directly applicable. More generally, however, a cyclic stress of amplitude σ_a is imposed on a mean stress, σ_m . A procedure is needed to handle these situations, because mean stress can have a significant effect.

Owen and Smith [cited in 4] have investigated mean stress effects in a composite with similar behavioral characteristics to the present CSM/isocyanurate composite. Normally, a master diagram showing the relationship between stress amplitude (cyclic stress range divided by two) and mean stress for various cyclic lives is considered to be the most desirable form of fatigue data. When insufficient test results are available for a master diagram to be produced, as is our case, something akin to the Goodman relation must be used. Three possibilities were assessed by Owen and Smith:

1. Goodman relation:

$$\sigma_a = \sigma_o \left(1 - \frac{\sigma_m}{\sigma_{ult.}} \right),$$

2. Goodman with creep-rupture strength:

$$\sigma_a = \sigma_o \left(1 - \frac{\sigma_m}{\sigma_r} \right), \text{ and}$$

3. modified Goodman with creep-rupture strength:

$$\sigma_a = \sigma_o \left(\frac{1 - \frac{\sigma_m}{\sigma_r}}{1 + \frac{\sigma_m}{\sigma_r}} \right).$$

All of these relations give the stress amplitude, σ_a , in a test with a mean stress, σ_m , in terms of the stress amplitude, σ_o , in a completely reversed, zero mean stress ($R = -1$) test having the same cyclic life. The second relation is attributed to Boller [cited in 4]; Owen and Smith proposed the third relation to add conservatism. These latter two use the creep-rupture strength, σ_r , corresponding to the test time rather than the short-time ultimate strength.

To assess these relations, a limited amount of mean stress fatigue data was generated on the CSM/isocyanurate. Figure 10 shows data and an experimental curve for zero mean stress compared to the $R = 0$ (0.1) data and curve. The $R = 0$ tests had a mean stress equal to one-half the maximum; the amplitude was also one-half the maximum. In the $R = -1$ case, the maximum stress and the amplitude, σ_o , are the same.

Figure 10. Comparison of $R = 0$ and $R = -1$ (zero mean stress) fatigue data. The dashed lines are predictions for $R=0$ based on the $R = -1$ curve using the following Goodman relations.

1. Top Curve: Goodman with UTS
2. Middle Curve: Goodman with σ_r corresponding to 3000 h
3. Lower curve: modified Goodman with σ_r corresponding to 3000 h

With the $R = -1$ curve giving σ_o , σ_a for the $R = 0$ case was predicted using the relations given previously. The dashed lines depict the resulting predictions. The top dashed curve is from the usual Goodman relation, using the UTS. The middle curve is from the Goodman relation with σ_r corresponding not to the test time, but to 3000 h, the assumed operating life of an automobile and, hence, the maximum time a structure would be subjected to fatigue cycles. The bottommost conservative curve is from the modified Goodman relation, with σ_r again corresponding to 3000 h.

The second relation, Goodman with σ_r used in place of the UTS, is recommended for design use. It is conservative relative to the $R = 0$ failure curve but not excessively so at the higher cycles. The $R = -1$ design curve in Fig. 8 corresponds to the curve in Fig. 10 with a design margin of 20 on cycles to failure. In cases involving a fixed nonzero mean stress, the $R = -1$ curve, which gives the allowable σ_o , should be used to determine the allowable stress amplitude, σ_a , corresponding to the mean stress σ_m . The σ_r value should be the 5000-h creep-rupture strength for design.

The preceding discussion is for tensile mean stresses. Data have been generated for compression-compression fatigue ($R = 0.1$). The results are shown in Fig. 11 compared with the $R = 0.1$ tension-tension and the $R = -1$ fully reversed curves presented earlier. Clearly, compressive cycling is less damaging than tensile cycling for the reference composite.

* 5000 h is a more conservative operating time and is thus used in the final criteria [1].

Figure 11. Compression-compression ($R = 0.1$) fatigue data compared to tension-tension and fully reversed fatigue data.

Thus, the design curves in Fig. 8 can be used for compression cycling by using the absolute values of the stresses.

TREATMENT OF CYCLES OF VARYING AMPLITUDE

A small matrix of block loading tests was carried out on 0° specimens from a single plaque. All tests involved just two stress levels—30% and 60% of the plaque UTS of 23.4 ksi. Three duplicate tests were planned at each of the following maximum stress conditions:

- 30% UTS
 - 60% UTS
 - 30/60% UTS
 - 60/30% UTS
- } Baseline to determine N_f at each stress

The number of cycles, n_1 , at the initial load were chosen to result in a predicted stiffness reduction of 10%. The logic for this choice was that even though the cycle fraction at a reduction of 10% is very low, a major amount of damage may have occurred by this point. Results of the tests are tabulated in Table 2.

For metals, Miner's rule, $\sum(n/N_f) = 1$, is commonly used. Here, as in past experimental studies [4], it is difficult to draw firm conclusions regarding the applicability of Miner's rule because of the small size of the data set and the inherent scatter. Based on the numbers in Table 2, the average cycle fraction summations for the two block loading series are 30/60: $0.019 + 0.803 = 0.822$ and 60/30: $0.015 + 0.578 = 0.593$. These numbers are not far out of line with the findings for metals, where cycle fraction summations are quoted as varying from 0.5 for high-low loadings to 5.0 for low-high loadings. The design margin of 20 on cycles can absorb these variations from a value of 1.0.

Table 2. Results of block loading tests

Test condition (% UTS)	n_1	n_2^a	Average n_2^a
30	0	13,951,961	9,190,026
		4,264,592	
		9,353,524	
60	0	2,712	2,528
		2,086	
		2,787	
30/60	172,540	3,752	2,029
	172,540	849	
	172,540	1,487	
60/30	37	4,782,169	5,307,658
	37	5,320,480	
	37	5,820,324	

$^a n_2$ = cycles to failure at second stress.

SUMMARY

This paper describes the fatigue tests and results that were used to establish a recommended fatigue evaluation procedure for a candidate swirl-mat/isocyanurate automotive structural composite. The following key observations and recommendations are made.

- The effect of temperature on fatigue strength is the same as on static strength; when maximum cyclic stress is divided by the static, at-temperature, UTS, a single fatigue curve can represent all temperatures.
- The fatigue life at 10^8 cycles (the maximum cycle number usually considered in automotive structural design) is approximately 20% of the UTS.
- Not counting tests at very high stress levels, the degradation in stiffness as a function of cyclic life fraction is relatively independent of stress and, in the first half of life, can be represented by power laws. The average end-of-life stiffness reduction from the power law fits is 16.5% at room temperature, 17.2% at -40°F , and 8.1% at 250°F .
- The peak cyclic strain, when plotted as a function of cycles, is believed to reflect the accumulation of damage. Damage initially accumulates linearly with log cycles but then begins to accumulate more rapidly part way through the cyclic life. The lower the stress, the earlier in life is the onset of rapid damage development (on a cycle fraction basis).
- Assuming that zero initial slope of the maximum strain curves would mean that damage never develops, a room-temperature endurance limit of 16.3% UTS is indicated.
- A design margin of 20 on cycles will limit stiffness reduction to 10% during cycling and was used to establish recommended fatigue design curves.

- Two design fatigue curves are given: one for tensile (or compressive) fatigue ($R = 0$) and one for completely reversed fatigue ($R = -1$).
- For cycles with a fixed mean stress, a Goodman relation that employs a 5000-h creep-rupture strength is recommended for design purposes.
- A table of fatigue stress reduction factors is given to cover the degrading effects of various automotive fluid environments.
- Miner's rule is recommended for assessing cycles of varying amplitudes.

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