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# Durability-Based Design Criteria for an Automotive Structural Composite*

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## ABSTRACT

Before composite structures can be widely used in automotive applications, their long-term durability must be assured. The Durability of Lightweight Composite Structures Project at Oak Ridge National Laboratory was established by the U.S. Department of Energy to help provide that assurance. The project is closely coordinated with the Automotive Composites Consortium. The experimentally-based, durability-driven design criteria described in this paper are the result of the initial project thrust. The criteria address a single reference composite, which is an SRIM (Structural Reaction Injection Molded) polyurethane, reinforced with continuous strand, swirl-mat E-glass fibers. The durability issues addressed include the effects of cyclic and sustained loadings, temperature, automotive fluid environments, and low-energy impacts (e.g., tool drops and roadway kickups) on strength, stiffness, and deformation. The criteria provide design analysis guidance, a multiaxial strength criterion, time-independent and time-dependent allowable stresses, rules for cyclic loading, and damage tolerance design guidance. Environmental degradation factors and the degrading effects of prior loadings are included. Efforts are currently underway to validate the criteria by application to a second random-glass-fiber composite. Carbon-fiber composites are also being addressed.

## INTRODUCTION

This paper summarizes a recently-published durability-based design criteria document developed for application to composite automotive structures [1,2]. The criteria are the initial product of a U.S. Department of Energy Advanced Automotive Materials Project at Oak Ridge National Laboratory entitled Durability of Lightweight Composite Structures for Automotive Applications. The overall goal of the project is to develop experimentally-based, durability-driven design guidelines to assure the long-term (15-year) reliability of polymeric composite automotive structures. Durability issues addressed include the potentially degrading effects that both cyclic and sustained loadings, exposure to automotive fluids, temperature extremes, and low-energy impacts from such things as tool drops and roadway kickups can have on structural strength, stiffness, and dimensional stability. The project is closely coordinated with the Automotive Composites Consortium (ACC), an R and D partnership between Chrysler, Ford, and General Motors.

The project approach has been to focus initially on a single reference composite and to replicate the following on-road conditions in laboratory specimens: short-time static loads; sustained loads; cyclic loads; effects of fluids, temperature, vibrations, and loading history; and low-energy impacts. The resulting test data and models, which are described in [2-7], provided the bases for the criteria summarized here and given more completely in [1]. Currently, the criteria framework is being validated by application to a second glass-fiber composite. Also, testing with the goal of extending the criteria framework to carbon-fiber composites is underway. The ultimate objective is to reduce the required durability-based testing to the point that suppliers and their test labs can readily generate the information to adapt the criteria to new composites.

The reference material is a structural reaction injection-molded (SRIM) isocyanurate (polyurethane) reinforced with continuous strand, swirl-mat E-glass. The isocyanurate resin is DOW MM364, and the reinforcement is Vertrotex Certainteed Unifilo U750. This initial reference material 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). Figure 1 is a picture of a reinforcement layer and a finished plaque.

The following section briefly describes the loadings and environments considered in developing the design criteria. Subsequent sections summarize the five main areas of the criteria: properties for design analyses, the chosen multiaxial strength criterion, allowable stresses for static loadings, design limits for cyclic loadings, and damage tolerance design procedures. The final section is a summary, which contains a further simplification of the criteria.

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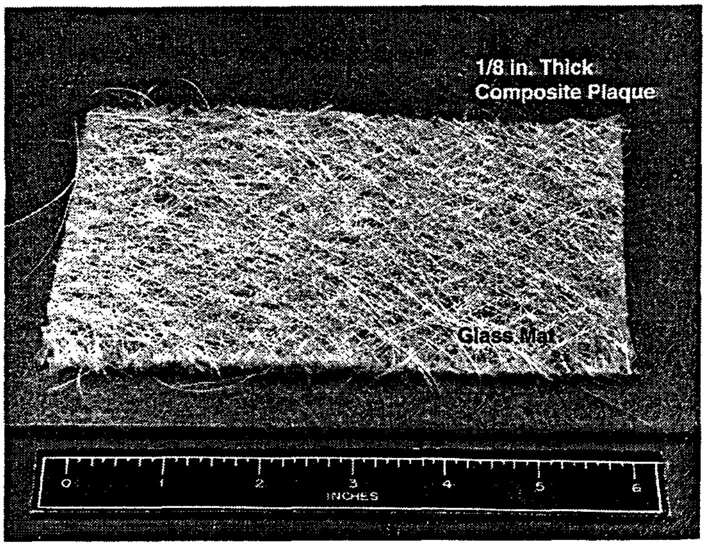


**Figure 1. Reference composite plaque with layer of swirl-mat reinforcement.**

## LOADINGS AND ENVIRONMENTS

From a durability standpoint, it is assumed here that an automobile with a composite structure must last for 15 years (131,000 h) and 150,000 miles. It is further assumed that during the 15 years, the vehicle will actually be operated between 3000 and 5000 h.

The design temperature range is assumed to vary from a minimum of -40°F to a maximum of 250°F, with the higher temperatures occurring only during operation.

In addition to functional stiffness and deformation requirements, structures must support and resist a variety of live and dead loads. During operation, for example, live loads might include a combination of pothole impact, hard turn, and maximum acceleration. Dead loads during the 15-year life would include those from the weight of the vehicle or, more importantly, sustained loads in the bed of a light truck.

Structures will also be subjected to common vehicle fluids and operating atmospheres, and design limits must take the resulting property degradation into account. Fluids and atmospheres considered here include distilled water and saltwater, high-humidity air [>90% relative humidity (RH)], windshield washer fluid, engine coolant, motor oil, brake fluid, gasoline, and battery acid. In addition, motor vibrations were considered because they can degrade long-term creep properties.

Finally, composite automotive structures must be designed to resist damage from routine low-energy impacts, such as roadway kickups, tool drops, and, in the case of a pickup box, dropped bricks and cattle hooves.

## STIFFNESS AND DEFORMATION PROPERTIES FOR DESIGN ANALYSES

It is assumed that design analyses will primarily be elastic finite-element plate and shell analyses providing, in addition to deformations, normal membrane and bending stresses plus shear in the relatively thin molded sections. Thus, elastic constants are required for analysis. Also, a means for at least approximately accounting for time-dependent creep is required. The required properties for the reference composite are presented in this section.

The properties of the continuous-strand mat reinforcement used in the reference composite are intended to be nominally isotropic in the plane of the mat. Manufacturing variables, however, resulted in fewer fibers oriented in the direction of the roll (0° direction) than transverse to it (90° direction). To maintain this anisotropy in the reference composite plaques, the five mat layers were oriented so that their weaker 0° directions coincided. As a result, all of the properties—stiffness, strength, fatigue, and creep—vary from the 0° to 90° direction. The 0° elastic modulus is, on average, 18% less than the 90° value.

For simplicity, the composite is treated as isotropic in the plane of the plaque. Further, the weaker 0° values are assumed to apply.

For an anisotropic material that is isotropic in one plane, there are five independent elastic constants—two associated with the plane of the isotropy and three associated with the direction normal to that plane. In this case, the in-plane constants are taken as the modulus of elasticity, E, and Poisson's ratio, $\nu$. The other three constants are associated with the direction normal to the plane of the plaque and are an $E'$, $G'$, and $\nu'$ value, where $G'$ is a shear modulus.

At room temperature, the in-plane values are taken to be $E = 1.37$ Msi, and $\nu = 0.31$ [3]. These result in a calculated in-plane G value of 0.52 Msi. As long as the stresses in the transverse direction (normal to the plane of the composite) are ignored, as they are in thin plate and shell analyses, only the in-plane properties are required. Some ramifications of this simplification are discussed in [1].

While Poisson's ratio is assumed to be constant with changing temperature, the tensile modulus of elasticity, E, was found to vary linearly according to the multiplication factors tabulated in Table 1 [3].

**Table 1. Multiplication factors to account for effect of temperature on stiffness (and ultimate tensile strength)**

| Temperature (F°) | Factor |
|---|---|
| -40 | 1.21 |
| 70 | 1.00 |
| 135 | 0.88 |
| 190 | 0.77 |
| 250 | 0.65 |

Data on a similar swirl-mat composite with the same matrix as the reference composite indicate that tensile and compressive stiffness values are essentially equal over the temperature range of interest. This is not true of strength; compression values drop much faster with increasing temperature than do tensile values. This observation dictates that a part adjacent to a major heat source not be in compression or, if it is, that it be provided with a heat shield or other form of heat protection [8].

Reference [3] presents data on the effects of moisture and other fluids on stiffness. A stiffness loss of 17% is recommended to bound environmental effects. This value corresponds to the loss that would occur in specimens soaked in water for one year. It is thought that this adequately covers moisture effects, even under design loads. It should also adequately cover the effects of other fluids, including the extreme case of battery acid for soak times up to 6 months. Of course, less conservative values for specific fluids can be used.

Prior loadings can produce internal microstructural damage that is manifest as a reduction in stiffness. Test data from the reference composite are summarized below.

- A *single* tensile loading to 0.67 UTS, which is the specified design allowable, produces a stiffness reduction on subsequent loading of 6.9%.
- Fatigue cycling to 5% of cyclic life, which is the specified design limit (design margin of 20 on cycles to failure), produces a stiffness loss of 10% or less.
- Prior creep does not reduce subsequent stiffness.

On the basis of these findings, it is recommended that a maximum 10% stiffness reduction be used to account for prior loadings.

In the case of long-term sustained loadings—either those associated with the 3000- to 5000-h operating life of an automobile or the 15-year overall life—creep deformations may become important and need to be accounted for in design analyses. This can be done at one of three levels of sophistication:

1. using a creep equation in an inelastic analysis,
1. using a time-dependent "pseudo-elastic modulus" in an elastic analysis, or
1. using an appropriate constitutive model derived for the material that can predict the effects of changing load levels as well as recovery strains upon unloading [7].

Creep curves for the reference composite in various temperatures and environments are presented in [4]. It is shown there that the time-dependent creep response (loading strain subtracted out) at room temperature in air at 50% relative humidity is reasonably well represented by the following creep equation

$$\varepsilon^c = (0.00507\,\sigma)t^{0.196}\,, \qquad (1)$$

where

$\varepsilon^c$ = creep strain (%),

$\sigma$ = applied stress (ksi), and

$t$ = time (h).

This relation is linear in stress and holds reasonably well up to a stress of 14 ksi.

The effect of temperature on creep is to multiply the creep strain predicted by Eq. (1) by a simple factor, values of which are tabulated in Table 2.

**Table 2. Multiplication factors to account for effect of temperature on creep**

| Temperature (°F) | Factor |
|---|---|
| -40 | 0.65 |
| 75 | 1.00 |
| 135 | 1.24 |
| 190 | 1.52 |
| 250 | 1.88 |

Isochronous stress-strain curves, which show the total strain at a given time corresponding to a constant applied stress, are often used to approximately predict creep effects. Although not rigorous, an isochronous curve for a given time can often be used to predict creep deformations reasonably well. Isochronous curves, for this purpose, are given in Fig. 2. An equation is also provided. Because strains are linear with stress at the lower stress levels, the isochronous curves exhibit a "pseudo-elastic" region. The slopes of these linear regions can be viewed as time-dependent moduli and used in elastic analyses to approximately predict creep effects. Values of these time-dependent moduli, $E_t$, are tabulated in the inset of Fig. 2.

Reference [4] develops multipliers on creep strain that, in a manner similar to the temperature multipliers, can be used to estimate the enhanced creep because of submersion in various automotive fluids. In all cases, the factors were derived from tests in which specimens were preconditioned for 100 h and then tested in the fluid of interest. The factors are given in Table 3.

**Table 3. Creep-strain multipliers for immersion in various automotive environments**

| Environment | Multiplier on creep strain |
|---|---|
| Distilled water | 1.60 |
| Motor oil | 1.05 |
| Brake fluid | 1.30 |
| Windshield wash | 1.50 |
| Saltwater | 1.50 |
| >90% RH | 1.55 |
| Battery acid | 1.65 |

A factor of 1.6 adequately covers all cases except battery acid and is recommended for bounding design use. Use of this factor with the creep equation is limited to stresses of 8 ksi and below.

The inverse of the 1.6 creep strain multiplier (0.63) can be used conservatively as a multiplier on the time-dependent moduli tabulated in Fig. 2. Likewise, the inverse of the temperature factor given in Table 2 can be conservatively used for $E_t$.

Another automotive environmental effect that has been explored is motor vibration superimposed on steady creep loads. Although these superimposed vibrations shorten creep-rupture life [4], they have not been found to affect creep deformation. Thus, no multiplying factor is needed for motor vibrations.

## MULTIAXIAL STRENGTH CRITERION-EQUILALENT STRESS

The allowable design limits recommended here are stress based. For design, it is convenient to have a single equivalent quantity representing the multiaxial stress state at a point in the structure and time in the loading history. The equivalent stress used here is the stress intensity, S.

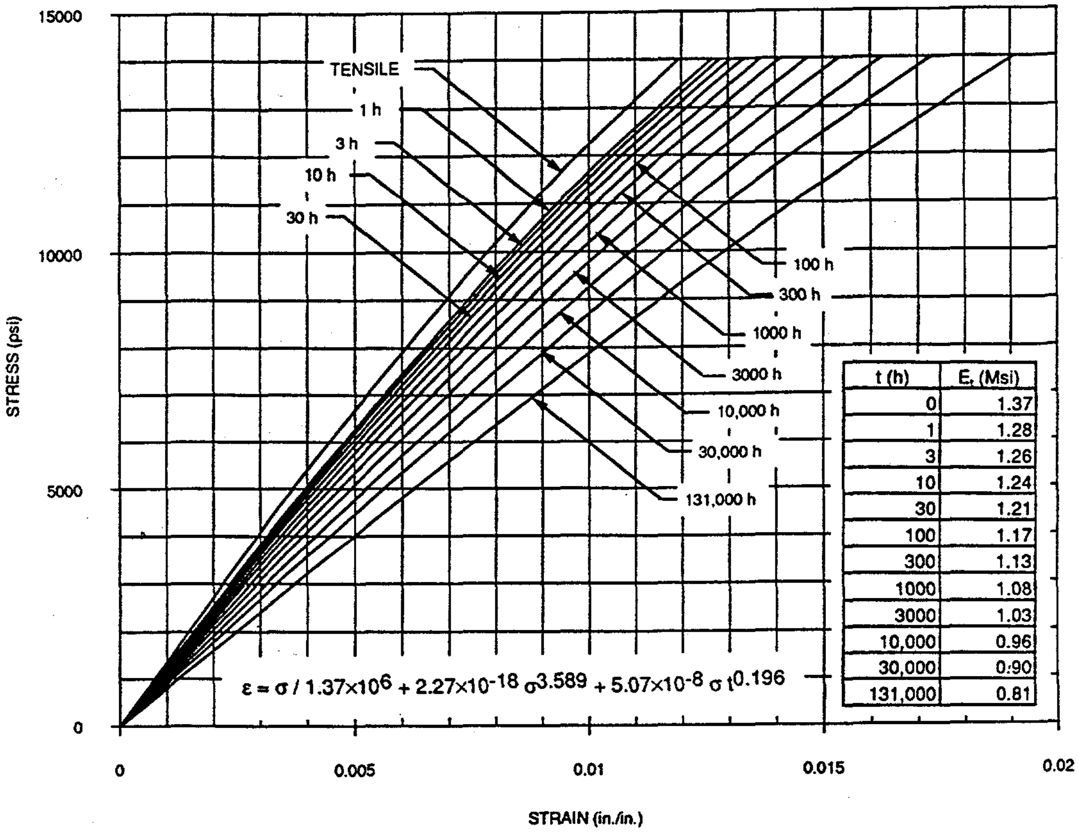


**Figure 2. Isochronous creep stress-strain curves.**

The equivalent intensity of combined stresses, or stress intensity, is defined as twice the maximum shear stress and is equivalent to the difference between the algebraically largest principal stress and the algebraically smallest principal stress at a given point. Tensile stresses are considered positive, and compressive stresses are considered negative.

The stress intensity is based on the maximum shear stress theory of failure, which, for the reference composite, has been shown to conservatively describe multiaxial failure conditions. Figure 3 shows average failure points in tension, compression, and in-plane shear for the reference composite. The failure points labeled "biaxial tension" in Fig. 3 come from bending tests of simply-supported circular disks subjected to a ring loading that produces an equibiaxial stress state. Also shown in Fig. 3 is the maximum shear stress criterion passing through the average uniaxial tensile strength in the weaker 0° direction. The criterion conservatively predicts all the other failure points. Thus, limiting the calculated stress intensity to an allowable uniaxial tensile stress (derived from the weaker 0° direction) ensures that compressive and shear stresses also do not exceed their respective limits.

The area labeled "design space" in Fig. 3 is based on an allowable stress that is two-thirds of the statistically minimum UTS. This design margin is discussed in the following section.

The maximum shear stress criterion is assumed to conservatively apply to fatigue and creep rupture as well. Thus, the stress intensity, previously defined, is used for evaluating sustained and cyclic loadings as well as short-time

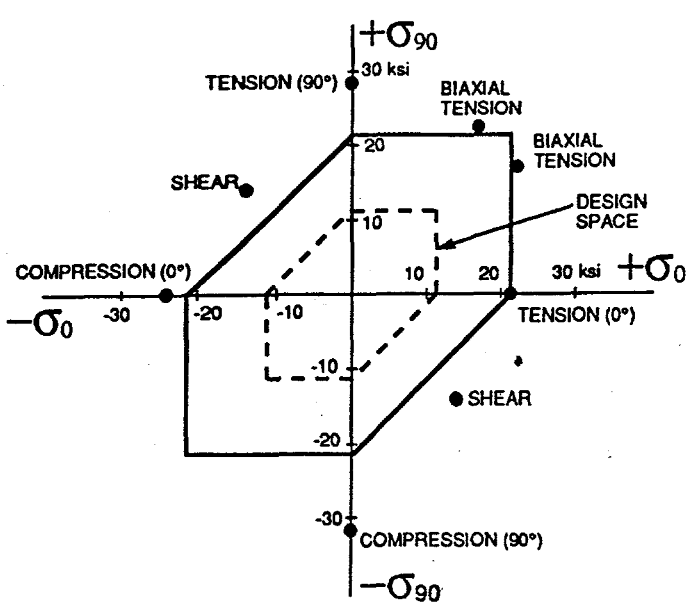


**Figure 3. Comparison of maximum shear stress criterion with average failure points.**

loads. Compressive fatigue tests show a strength higher than for tension at room temperature. Likewise, compressive creep-rupture strength at room temperature is equal to tensile strength. No shear or combined stress-state fatigue or creep-rupture data exist, however.

## DESIGN ALLOWABLES FOR STATIC LOADINGS

Since the swirl-mat composite is treated as a homogeneous material, isotropic in the plane of the mat, some of the relatively simple concepts used in metal design criteria for shell-type structures can be used. For static loadings, the general approach and nomenclature for time-dependent allowable stresses used in the ASME Boiler and Pressure Vessel Code for elevated temperature nuclear components has been adopted [9].

The basic short-time allowable stress intensity used here is two-thirds of the minimum ultimate tensile strength (UTS) in the weaker 0° direction. This minimum room-temperature strength for the reference composite is based on statistical treatment of 185 0° UTS values, such that the survival probability is 90% at a confidence level of 95%. This is the "B-basis stress" used in MIL-HDBK-17 [10]. The resulting room-temperature values are

$$UTS_{avg} = 21.3 \text{ ksi, and}$$

$$UTS_{min} = 17.4 \text{ ksi.}$$

The basic time-dependent allowable stress intensity, $S_o$ thus become $S_o = 2/3\, UTS_{min} = 11.6$ ksi. Values for other temperatures are obtained by using the multipliers previously given for both stiffness and strength in Table 1.

For environmental effects, the same 17% reduction recommended for bounding stiffness holds for strength. For the effects of prior loads, only cyclic loadings reduce subsequent strength. That reduction is limited to just 1.5% with the design factor of 20 that is used on cycles to failure.

For sustained loadings, creep-rupture stress is the basis for allowable stresses. The following design margin is used:

$$0.8\, S_r\,,$$

where $S_r$ is the minimum creep-rupture strength.

For the reference composite, minimum tensile creep-rupture values were determined as described in [4]. Compressive creep-rupture strengths are equal to tensile strength values at room temperature. No elevated-temperature, in-air compressive creep-rupture results are available. However, at elevated temperatures in water, the compressive strength values are less [4], and this would be expected to be the case in air as well.

A time-dependent allowable stress intensity, $S_t$, is defined as

$$S_t \le \begin{cases} S_o \\ 0.8\, S_r \end{cases} . \qquad (2)$$

Values of $S_t$ without environmental effects are tabulated in Table 4. Values are truncated at 5000 h when they are associated only with vehicle operating conditions.

**Table 4. Allowable stress intensity values, $S_t$ (ksi) without environmental effects**

| Temperature | Time | | | | | | |
|---|---|---|---|---|---|---|---|
| (°F) | 0 h[a] | 10 h | 1000 h | 3000 h | 5000 h | 1 yr | 15 yr |
| -40 | 14.1 | 11.9 | 11.1 | 10.9 | 10.8 | 10.7 | 10.3 |
| 20 | 12.7 | 11.9 | 11.1 | 10.9 | 10.8 | 10.7 | 10.3 |
| 70 | 11.6 | 11.6 | 11.1 | 10.9 | 10.8 | 10.7 | 10.3 |
| 135 | 10.2 | 10.2 | 10.2 | 10.2 | 10.1 | 10.0 | 9.6 |
| 190 | 9.0 | 9.0 | 9.0 | 8.8 | 8.7 | | |
| 250 | 7.6 | 6.8 | 6.0 | 5.9 | 5.8 | | |

[a]$S_o$ values

Reduction factors accounting for the effects of environment and prior loading on $S_o$ values were given above. Environment also reduces the $S_r$ values as shown in Table 5 [4]. Use of the values for tensile creep rupture in 135°F distilled water, with 0.51 used for 1 year and 15 years, bounds everything but battery acid and three hot water cases. Prior cyclic loads, again with the design factor of 20 that is used on cycles to failure, reduce subsequent $S_r$ values by a maximum of 3%. When the bounding environmental and prior loading reduction factors are applied to $S_o$ and $S_r$, the $S_t$ values tabulated in Table 6 result.

The $S_t$ values establish limits on *allowable in-plane membrane* stress intensities, P. To explore the limits needed for *membrane plus out-of-plane bending* stress intensities, P + Q, bending tests on the two types of specimens in Fig. 4 were performed. From these tests, the following limits were established:

$$P + Q \le 1.5\, S_t \qquad (3)$$

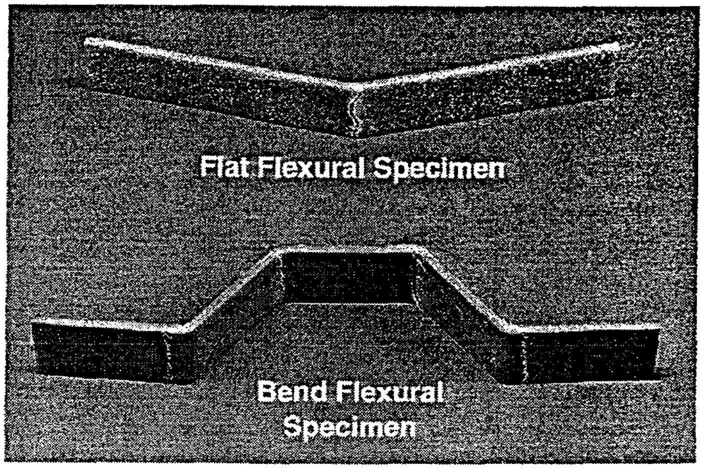


**Figure 4. Bend specimens used for tests to assess basic stress limits.**

**Table 5. Temperature and environmental effects on creep-rupture strength (Factors for conditions associated with operation are truncated at 5000 h)**

| Environment[a] | Time | | | | | |
|---|---|---|---|---|---|---|
| | 10 h | 1000 h | 3000 h | 5000 h | 1 year | 15 years |
| Room-temperature air/50% RH (T and C) | 1 | 1 | 1 | 1 | 1 | 1 |
| 20°F air | 1 | 1 | 1 | 1 | 1 | 1 |
| 135°F air | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| 190°F air | 0.91 | 0.91 | 0.91 | 0.91 | | |
| 250°F air | 0.66 | 0.65 | 0.65 | 0.64 | | |
| Room-temperature air/<10% RH | 1 | 1 | 1 | 1 | 1 | 1 |
| Room-temperature air/>90% RH | 0.86 | 0.68 | 0.65 | 0.63 | 0.61 | 0.53 |
| Room-temperature distilled water (T and C), saltwater, windshield wash, engine coolant | 0.62 | 0.54 | 0.52 | 0.51 | | |
| 135°F distilled water (T) | 0.61 | 0.53 | 0.52 | 0.51 | | |
| 135°F distilled water (C) | 0.53 | 0.41 | 0.38 | 0.37 | | |
| 190°F distilled water (T) | 0.31 | 0.19 | 0.17 | 0.16 | | |
| 190°F distilled water (C) | 0.12 | 0.05 | 0.05 | 0.04 | | |
| Motor vibration | 1 | 0.92 | 0.9 | 0.89 | | |
| Brake fluid | 0.87 | 0.77 | 0.75 | 0.74 | 0.73 | 0.68 |
| Motor oil | 0.98 | 0.93 | 0.92 | 0.91 | 0.91 | 0.88 |
| Battery acid | 0.35 | 0.19 | 0.17 | 0.16 | | |

[a]T = tension, and C = compression.

**Table 6. Allowable stress intensity values, $S_t$ (ksi), with bounding environmental and prior load effects**

| Temperature (°F) | 0 h | 10 h | 1000 h | 3000 h | 5000 h | 1 yr | 15 yr |
|---|---|---|---|---|---|---|---|
| -40 | 11.5 | 7.0 | 5.7 | 5.3 | 5.3 | 5.3 | 5.0 |
| 20 | 10.4 | 7.0 | 5.7 | 5.3 | 5.3 | 5.3 | 5.0 |
| 70 | 9.5 | 7.0 | 5.7 | 5.3 | 5.3 | 5.3 | 5.0 |
| 135 | 8.3 | 7.0 | 5.3 | 5.0 | 4.9 | 4.9 | 4.8 |
| 190 | 7.4 | 6.1 | 4.6 | 4.4 | 4.3 | | |
| 250 | 6.2 | 4.3 | 3.1 | 2.9 | 2.9 | | |

away from geometric discontinuities, and

$$P + Q \leq 0.8\, S_t \qquad (4)$$

at geometric discontinuities. The lower limit at discontinuities (corners and bends) is due to the delaminations that can occur at lower loads at these locations.

For changing stress levels, the time-fraction summation method is recommended to assess cumulative damage. The sum of the use fractions associated with the primary plus bending stresses for all increments of loading shall not exceed a value of 1.0.

$$\sum_i \left(\frac{t}{T_d}\right)_i \leq 1.0 \qquad (5)$$

Here, $t_i$ is the specified duration of a given load increment i, and $T_{d_i}$ is the design allowable time for the stress intensity associated with that load increment.

## DESIGN LIMITS FOR CYCLIC LOADINGS

Design fatigue curves are shown in Fig. 5. These curves are derived from average fatigue curves, as described in [5], by placing a margin of 20 on cycles to failure. This margin is believed to adequately cover data scatter, and it limits stiffness degradation during cycling to 10% or less, on average [5]. The curves are applicable to temperatures over the range from –40 to 250°F. It is necessary only to multiply the ordinate, which is given as a percent of UTS, by the appropriate average UTS at the temperature of interest. Recall that the average room-temperature value is 21.3 ksi. At other temperatures, the UTS can be obtained by multiplying the room-temperature value by the appropriate factor from Table 1.

The design curve labeled R = 0 in Fig. 5 is actually based on tensile fatigue test data obtained at an R ratio (minimum stress in the cycle divided by maximum stress) of 0.1 [5]. It can be used directly to evaluate design cycles that have stresses alternating between zero and a maximum value.

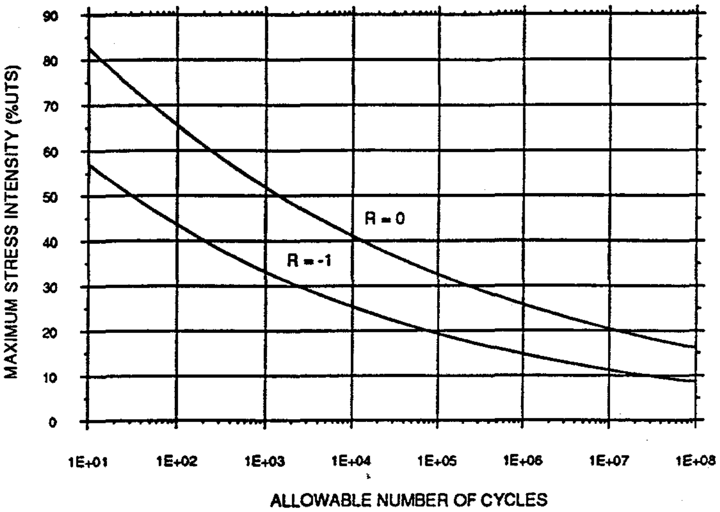


**Figure 5. Design fatigue curves for tensile cycling (R = 0) and reversed cycling (R = -1).**

The R = −1 curve in Fig. 5 is derived from completely reversed cyclic tests (zero mean stress). It can be used directly for design cycles that are completely reversed. It also can be used to evaluate other cycles with a fixed mean stress using the Goodman relation described in [5]. The recommended relation is

$$\sigma_a=\sigma_o\left(1-\frac{\sigma_m}{\sigma_r}\right), \tag{6}$$

where use is made of the creep-rupture strength, $\sigma_r$, corresponding to the cyclic loading time rather than the short-time ultimate tensile strength. The relation gives the allowable stress amplitude, $\sigma_a$, in a cycle with a mean stress, $\sigma_m$, in terms of the stress amplitude, $\sigma_o$, in a completely reversed, zero mean stress (R = -1) cycle producing the same cyclic design life. Thus, the R = -1 curve in Fig. 5 gives $\sigma_o$. The recommended $\sigma_r$ value should correspond to the maximum vehicle operating time of 5000 h.

Table 7 gives environmental fatigue stress-reduction factors. These factors were obtained, as described in [5], from tests at R = 0.1. Specimens were presoaked in the indicated fluids for 100 h (with one exception) and then tested in the same fluid. These factors should be used to reduce the allowable design stress levels in Fig. 5. A single factor of 0.7 for environmental effects covers everything except battery acid and the long-term hot water exposure and thus can be conservatively used.

For varying stress amplitudes, Miner's rule should be used to account for cumulative fatigue damage [5]. For a design to be acceptable, the fatigue damage should satisfy the following relation:

$$\sum_i\left(\frac{n}{N_d}\right)_i \leq 1.0\,, \tag{7}$$

where $n_i$ is the number of specified cycles for cycle type i and $N_{d_i}$ is the number of design-allowable cycles for cycle i determined from one of the design fatigue curves (Fig. 5) corresponding to the maximum temperature of the cycle.

**Table 7. Fatigue stress-reduction factors for various automotive fluid environments**

| Fluid | Cycles | | | |
|---|---|---|---|---|
| | $1\times10^2$ | $1\times10^4$ | $1\times10^6$ | $1\times10^8$ |
| 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 |

## DAMAGE TOLERANCE DESIGN

A two-part design assessment approach is recommended:

1. Assume the presence of a 0.25-in.-diam circular hole in the worst possible location of the structure. Analytically assess the structure with the hole. A calculated local stress concentration factor (SCF) greater than 1.1 need not be considered (based on tests of specimens with holes). However, the effects of the lost area must be taken into account. This evaluation will ensure that the structure can tolerate minor impacts and structural flaws at least up to a size of 0.25 in., no matter where they are located.
1. For specified low-energy impacts such as roadway kickups, tool drops, and load drops in a pickup truck box, the procedures described below may be used to assess damage tolerance for damage areas larger than that corresponding to a 0.25-in.-diam hole.

For a given object of mass, m, impacting the structure with a velocity, v, in the most highly stressed location, away from structural discontinuities, determine the impact damage area from the "design" curve in Fig. 6. The design curve is the upper bound of test data generated from air-gun and pendulum impact tests on clamped 8-in.-diam by 1/8-in.-thick circular plates of the reference material. Development of this design curve and its applicability to real events, such as bricks dropped in a pickup box, are discussed in [6]. The curve has been experimentally shown to cover a variety of variables, such as impactor size and mass variations, different environments (prior specimen soaks in water at various conditions and severe exposure to battery acid), and impacts at a temperature of −40°F.

An alternative procedure for determining damage area involving dynamic structural analysis is given in [6]. That procedure allows the characteristics of the impacting

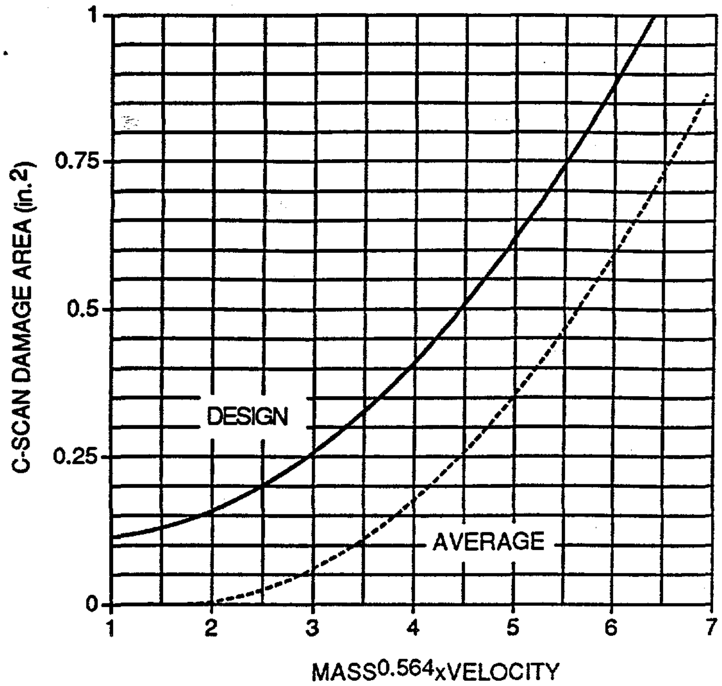


**Figure 6. Design curve for determining impact damage area. Mass is in lb – s²/ft and velocity is in ft/s.**

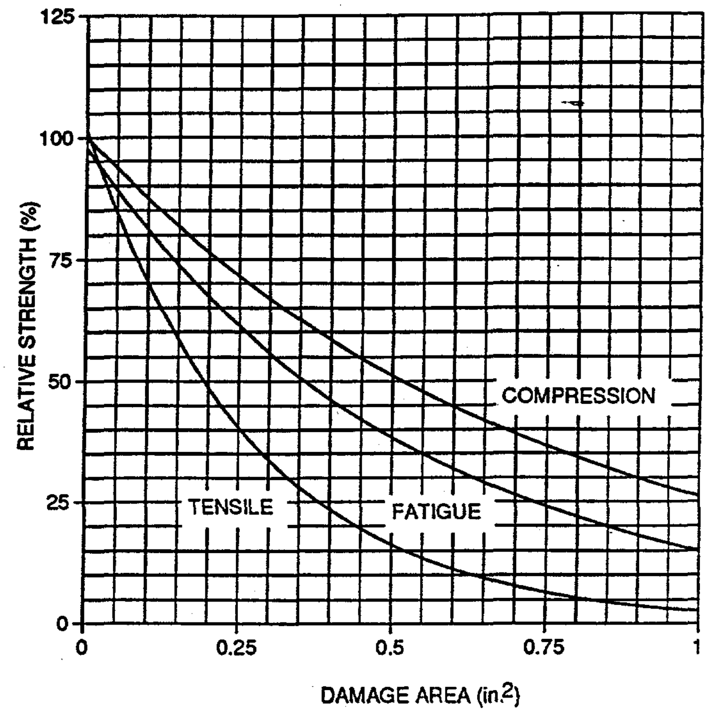


**Figure 7. Strength degradation vs damage area.**

body and of the impacted structure to be taken into account.

The damage area, once estimated, can either be factored into the structural evaluation as an equivalent circular hole, or the degradation in strength can be estimated as specified in the following paragraph. If the equivalent circular hole approach is used, a local SCF greater than 1.1 can be ignored (local stresses at the edge of the hole greater than 1.1× the average stress in that area). Stiffness degradation can best be estimated, conservatively, by the equivalent circular hole method.

For a given predicted damage area, the degradation in tensile, fatigue, and compressive strengths can be estimated using Fig. 7. These curves were derived from test data obtained from 1-in.-wide specimens cut from impacted plates. They show the strength of specimens containing the damage area relative to the strength in undamaged regions. The largest effect is in tension. The tensile curve in Fig. 7 is essentially the same as would be predicted by representing the damage area as a circular hole and basing predicted failure on the average remaining ligament stress in the 1-in.-wide specimen. Clearly, in fatigue and compression the damaged area does contribute to strength. Use of an equivalent hole to estimate fatigue and compressive strength degradation would be conservative. In any event, in interpreting and using the results presented in Fig. 7, the fact that they are from tests of 1-in.-wide specimens should be considered.

## SUMMARY/ADDITIONAL SIMPLIFICATION

The design criteria summarized in this paper for composite automotive structures are in five sections.

1. *Properties for Design Analyses.* It is recommended that the reference composite be considered as isotropic in the plane of the thin molded sheet. Elastic constants are provided over the expected design temperature range of –40 to 250°F. A 17% stiffness reduction is recommended to bound fluid environment effects, and an additional 10% reduction is recommended to cover prior loading effects. To allow prediction of long-term creep deformation, a creep equation with temperature and environmental effects factors is provided. Isochronous creep curves for use in simplified "elastic" analyses are also given.

2. *Multiaxial Strength Criterion..* A stress intensity quantity, defined as twice the maximum shear stress, is recommended for representing multiaxial stress states. The quantity is based on the maximum shear stress theory of failure, which conservatively predicts all average in-plane failure data points.

3. *Design Allowable for Static Loading.* The basic allowable stress quantity is $S_t$, which is defined as the smaller of $S_o$ or 0.8 $S_r$. The quantity $S_o$ is defined as 2/3 of the minimum tensile strength, and $S_r$ is the minimum creep-rupture strength. Thus, $S_t$ depends on temperature and time under load. Tables of $S_t$ values are given—one without environmental and prior loading effects, and one with bounding effects. Calculated membrane stress intensities are limited to $S_t$. Membrane plus out-of-plane bending stress intensities are limited to 1.5 $S_t$ away from bends and other geometric discontinuities and to 0.8 $S_t$, at geometric discontinuities. The linear time-fraction rule is recommended for evaluating changing loads.

4. *Design Limits for Cyclic Loadings.* Two design fatigue curves are given, one for tension fatigue (R = 0) and one for fully-reversed fatigue (R = -1). A Goodman-type relation is suggested for mean stress loadings other than R = 0. The design curves are derived from average curves by placing a margin of 20 on cycles to failure. This factor assures that the loss in stiffness due to cyclic loads does not exceed 10%. A single reduction factor of 0.7 on cyclic stress for environmental effects is recommended as a bound. For varying stress amplitudes, Miner's rule should be used to account for fatigue damage.

5. *Damage Tolerance Design..* A two-step approach is recommended. First, the composite structure should be evaluated with a 0.25-in.-D circular hole assumed to exist in the worst possible location. A calculated local stress concentration greater than 1.1 need not be considered. Second, for specific low-energy impacts a design curve is provided that allows determination of a damage area for a given impactor mass and velocity. This curve covers a variety of variables, including environment and impactor size and mass variations. Curves are given for estimating the resulting degradation in tensile, compressive, and fatigue strength for a given damage area. Alternatively, the damage can be represented in an analysis by a circular hole of equivalent area.

Table 8 is a simplified summary of the criteria in the form of allowable stresses for various conditions. It incorporates the bounding reduction factors suggested earlier for environmental and prior loading effects. Thus the factors might be lower than necessary in a given situation.

A commonly used rule-of-thumb for design of automotive composite structures has been a strain limit of approximately 0.3%. For the reference composite, this corresponds to an elastically-calculated stress of 19% of the room temperature UTS. Comparing this value with those in Table 8 shows that it conservatively covers all conditions except some of those related to fatigue. Thus the current, more rigorously developed, criteria add credence to the rule-of-thumb used in the past, and identify where it can be made more liberal and where it needs to be more conservative.

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**Table 8. Summary of simplified allowable stresses (given as a percentage of the average room-temperature UTS of 21.3 ksi).**

| Stress Allowable | Room Temperature | | 250°F | |
|---|---|---|---|---|
| | w/o environment and prior load effects | w environment and prior load effects | w/o environment and prior load effects | w environment and prior load effects |
| $S_o$ | 54 | 45 | 36 | 29 |
| $S_t$ | | | | |
| 5000 h | 51 | 42 | 27 | 22 |
| 15 yr | 48 | 39 | — | — |
| $S_{max}$ (R = 0) | | | | |
| $10^6$ cycles | 26 | 18 | 17 | 12 |
| $10^8$ cycles | 16 | 11 | 10 | 7 |

[a] $UTS_{avg}$ = 21.3 ksi

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