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Damage Tolerance Design Procedures for an Automotive Composite*

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ABSTRACT

Among the durability issues of concern in the use of composites in automobile structures is the damaging effects that low-energy impacts (e.g., tool drops and roadway kickups) might have on strength and stiffness. This issue was experimentally investigated, and recommended design evaluation procedures were developed for a candidate automotive structural composite—a structural reaction injection-molded polyurethane reinforced with continuous strand, swirl-mat E-glass fibers. Two test facilities were built to cover the range of impacts of interest—a pendulum device to characterize the effects of relative heavy objects at low velocities and an air gun to characterize the effects of relatively light objects at higher velocities. In all cases, the test specimen was a $9 \times 9 \times 1/8$ -in.-thick plate clamped on an 8-in.-diam circle. Sixty-five impact tests were performed. Included were tests using various impactor sizes and weights, tests at -40°F , and tests on specimens that had been presoaked in water or exposed to battery acid. Damage areas were determined using ultrasonic C-scans, and the resulting areas were found to correlate with the quantity impactor mass to a power times velocity. A design curve was derived from the correlation and validated using dropped brick tests. To evaluate strength and stiffness reductions, the impacted plate specimens were cut into tensile, compressive, and fatigue test specimens that were used to determine reductions as a function of damage area. It was found that for design purposes, the strength reduction could be determined by representing the damage area by a circular hole of equivalent area.

INTRODUCTION

The U.S. Department of Energy, in coordination with the Automotive Composites Consortium (ACC) has a 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 reliability of polymeric composite automotive structures. Design criteria that include damage tolerance design guidance have recently been published for a reference structural composite [1-3]. This paper describes the bases for the damage tolerance design recommendations.

The range of low-energy impacts that might be expected to produce undetected damage extends from the dropping of relatively heavy tools and other objects at low velocities to roadway kickups of rocks having low mass but relatively high velocities. To bound this range, an approach used for airplane composite missile casings was used [4]. Two impact facilities were designed and built—a pendulum device to characterize the effects of relatively heavy objects at low velocities and an air gun to characterize the effects of relatively light objects at higher velocities. The test specimen is the same in both facilities—a $9 \times 9 \times 1/8$ -in.-thick plate clamped on an 8-in.-diam outer circle. The specimens are impacted at the center, normally with a hardened steel hemispherical impactor.

Sixty-five impact tests were performed in the two facilities to provide the experimental basis for the damage tolerance design rules in the criteria. In addition, four tests involving dropped bricks were performed to assess the broader applicability of the results. The 65 tests included ambient air baseline tests, which, in the case of both pendulum and air gun, employed 0.5-in.-diam hemispherical impactors. Other tests were used to examine the effects of impactor size and mass, various fluid environments, and a test temperature of -40°F .

Each impacted specimen was examined ultrasonically to determine the damage area. The resulting areas were then related to impactor mass and velocity.

After testing, the square impact specimens[†] were cut into side-by-side mechanical property test specimens. These specimens were subjected to either tensile, compression, or fatigue tests to determine the degradation in properties at the impact site. This degradation was related back to the damage

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area. Thus, a path was provided for assessing the effects of low-energy impacts in design.

The subsequent section describes the reference composite. The impact tests are next described, and the correlation between damage area and mass and velocity is presented. The effect of impact damage on mechanical properties is then given. Finally the results are used to recommend the design approach given in [1].

REFERENCE COMPOSITE

The reference composite was a structural reaction injection-molded (SRIM) isocyanurate (polyurethane) reinforced with continuous strand, swirl-mat E-glass. The isocyanurate resin was DOW MM364, and the reinforcement was Vetrotex Certainteed Unifilo U750. This candidate structural composite was chosen and supplied by ACC 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). The plaques were slightly anisotropic, with the average ultimate tensile strength in the weaker direction being 21.3 ksi.

Four 9 x 9-in.-square impact specimens were cut from each plaque. As described in the following section, the specimens were clamped on an 8-in.-diam circle for testing.

IMPACT TESTS

The pendulum and a mounted test specimen that has been impacted are shown in the foreground of Fig. 1. The accumulator tank and barrel of the air gun can be seen in the background. The pendulum weight, which is suspended by cables from the ceiling, is a 25.4 lb bar. The hemispherical impactor point seen on the front of the weight is 0.5-in.-diam and was used for baseline testing. Points having 0.25-in.-diam and 4-in.-diam were also used. A miniature dynamic load cell behind the impactor point measures contact force during the impact event.

Figure 1. Pendulum and test specimen arrangement for impact tests.

In the case of the air gun, the baseline impactor, or projectile, is a 0.5-in.-diam cylinder with a hemispherical point and weighing 0.05 lb. Ordinary plant air, with a pressure exceeding 100 psi, is used to charge the accumulator. A quick-acting solenoid valve is used to release the compressed air into the breech of the 65-in.-long barrel. A second 0.875-in.-I.D. barrel allows for use of a larger projectile.

In addition to the load cell at the front of the pendulum weight, both facilities are fitted with laser-based devices for measuring velocity just prior to impact. Two beams of light, separated by a known distance, are used in each case, and the time from when the first beam of light is interrupted until the second beam is interrupted is measured. The projectile, in the case of the air gun, breaks the two beams, while a flag suspended below the pendulum weight is used in the case of the pendulum. Low-power visible lasers are used for the light sources, and infrared sensitive phototransistors are used to sense the laser beams.

Several specimens were instrumented with 0.5-in.-gage-length foil strain gages to measure the time-dependent structural response of the plates. The strain gage output as well as the load cell output from the pendulum tests was recorded and analyzed using an HP workstation-based dynamic data acquisition and processing system. The system uses the Structural Dynamics Research Corporation (SDRC) Test Data Analysis System (TDAS).

The effects of larger and smaller impactor diameters, different impactor masses (in the case of the air-gun projectile), a test temperature of -40°F , and presoaks in water and battery acid were explored and compared to the ambient air baseline. Almost all of the specimens were subsequently cut into 1-in.-wide tensile, compression, or fatigue specimens and the property degradation determined.

Table 1 summarizes the overall test program. In all, 65 impact tests and 414 mechanical property tests were performed. Note that residual tensile, compression, and fatigue

Table 1. List of impact tests and subsequent mechanical property tests

Impact tests	Pendulum	Air gun
Baseline (0.5-in.-diam impactors)	18 (8T, 4C, 3F) ^a	20 (10T, 5C, 3F)
4-in.-diam impactors	2 (T)	2 (T)
0.25-in.-diam impactors	4 (T)	3 (T)
Test temperature, -40°F	2 (T)	4 (T)
Distilled water presoak, 1130 h	2 (T)	2 (T)
Battery acid pre-exposure, 24 h at 150°F	2 (T)	2 (T)
Demineralized water presoak, 1079 h at 180°F	1 (T)	1 (T)

^aT = Tension (315 specimens).

C = Compression (63 specimens).

F = Fatigue (42 specimens, 36 tested).

Note: Numbers in parentheses in the table denote the number of impact specimens devoted to each mechanical property test type. Generally, each impact specimen was cut into seven mechanical property specimens. Not all baseline impact specimens were cut into mechanical property specimens.

properties were obtained from the baseline specimens. Only tensile tests were performed for all of the other impact specimens.

For every impacted specimen, the damage area was measured from an ultrasonic C-scan image of the damage zone. Considering just the baseline results for a moment, it was found that the damage areas correlated reasonably well with the quantity $m^{0.564} \times v$, where mass, m , is in pounds-second squared per foot and velocity, v , is in feet per second. This correlation can be seen in Fig. 2. Both the pendulum and air-gun data result in essentially the same binomial curve fit when correlated on this basis.

Figure 3 shows the results of all the nonbaseline tests listed in Table 1 compared to the baseline correlation. All of the data, with the exception of the 180°F water soak, either lie below the baseline correlation (less damage) or well within the scatter band of the baseline data points. Thus, the baseline correlation can be used for a variety of conditions, covering significant impactor size and mass variations, as well as environments and a temperature of -40°F.

The test results presented in the previous two figures are all for smooth hemispherical steel impactor points. Are they applicable to impacts from more irregular objects? To answer this question, the effects of bricks dropped on a corner were evaluated. The new bricks used weighed, on average, 3.7 lb. Four tests were run in which bricks were dropped from 2-, 4-, or 8-ft heights. The same clamped specimen design was used as in the previous tests. Sound, sharp corners of the bricks were chosen for the impact tests, and the corners were essentially undamaged by the impacts. The bricks were released from the diagonally opposite corner, so the center of gravity was in line with the impact point. Video footage of the drops confirmed that each brick maintained its alignment until impact.

Figure 2. Baseline correlation—damage area vs $m^{0.564} \times v$. Mass is in $\text{lb-s}^2/\text{ft}$ and velocity is in ft/s .

▲	0.5/0.875 in. AG	✱	DW P
⊞	4 in. P	▷	DW AG
⊕	4 in. AG	⊠	BA P
⊗	0.25 in. P	◊	BA AG
▽	0.25 in. AG	◊	180 P
⊠	-40° F P	◊	180 AG
◊	-40° F AG

Figure 3. Comparison of results for other conditions with baseline correlation. P denotes pendulum results; AG denotes air-gun results. DW and BA denote tests of specimens preexposed to distilled water and battery acid, respectively; and 180 denotes tests of specimens presoaked 1079 h in water at 180°F.

The results of the four tests are shown in Fig. 4, where damage area is again plotted vs $m^{0.564} \times v$. The results are in the scatter band of the previously discussed baseline data. These results add credibility to using the baseline correlation as a basis for design.

EFFECT ON TENSILE, COMPRESSIVE, AND FATIGUE PROPERTIES

The 9 x 9-in.-square impact specimens were cut into seven parallel 1-in.-wide mechanical property test specimens. The center specimen was always centered on the impact damage area. Figure 5 shows typical plots of tensile properties, as determined from seven 1-in.-wide tensile specimens cut from each of two impacted plates. In all cases, the outer four specimens did not appear to be affected by the impact. Hence, average results from these four specimens

Figure 4. Comparison of damage areas from brick drops with baseline data.

were used as the reference to which the results from the center specimen were compared.

Figure 6 shows the resulting baseline relative strength values as a function of damage area. Tensile strength was degraded most, fatigue next, and compressive least. All of the fatigue tests were tension-tension ($R = 0.1$) with a maximum tensile stress of 11.3 ksi. The resulting failure points were used to construct fatigue curves parallel to the baseline curve for the material [5]. Strength values at 10^6 cycles were estimated from these curves and used to develop the relative values shown in Fig. 6. Because the fatigue correlations are assumed to be straight lines on log-log plots, the relative strength values apply to any number of cycles.

The relative properties shown in Figs. 6 are pseudoproperties. Clearly, they depend on specimen width.

The following question arose relative to Fig. 6: Can the reduction in properties due to impacts be predicted, or bounded, by representing damage area as a circular hole? To answer this question, a series of finite-element analyses of 1-in.-wide tensile specimens with holes of various sizes was first carried out to determine theoretical stress concentration factors. The factors varied from the well-known 3.0 for an infinitely small hole to 1.0 for a hole approaching 1-in.-diam. For a 0.25-in.-diam hole, the theoretical stress concentration factor (SCF) was 2.4. Tensile and fatigue tests on specimens with 0.25-in.-diam holes indicated an effective SCF of only 1.1. That is, based on the average ligament stress, the average strengths were 90% of those for specimens without holes. Thus, the stress concentration effect is very weak (2.4 vs 1.1 actual).

Returning to the original question of impact damage, Fig. 7 is a plot of relative tensile strength vs impact damage area taken from Fig. 6. Also shown on the figure are two sets

a. Specimen with no detectable damage.

b. Specimen with significant damage.

Figure 5. Typical distributions of tensile properties across air-gun impacted specimens.

of points from the series of analyses on specimens with circular holes. One set assumes no SCF at all; the other assumes that the calculated SCFs are fully effective (failure would occur when the peak stress reaches the UTS). The case of no SCF fits with the impact results very closely. Thus, the strength degradation can be predicted by assuming the impact damage area is a circular hole with no SCF.

RECOMMENDED DESIGN APPROACH

For a free impacting body having a known mass and impact velocity, the design curve in Fig. 8 is recommended for determining the damage area. The design curve is the upper limit of the scatter band of data in Fig. 2. No further reduction factors should be required. Figure 9, which comes from Fig. 6, should be used to estimate strength degradation corresponding to the damage area determined from Fig. 8.

Figure 6. Relative tensile, compressive, and 10^6 cycle fatigue strengths vs damage area.

Figure 7. Circular hole strength reduction predictions compared with impact strength degradation results.

Conventional wisdom regarding impacts on composites states that damage areas should correlate well with the maximum contact force reached during the event, at least for larger masses [6]. This offers an alternative way of estimating damage areas for cases where it is desired to include more of the specifics of the composite structure and of the impact event. Analytical work demonstrated that force could be reasonably and accurately predicted by a thick-shell, dynamic time-response analysis, provided the nonlinear contact response was properly modeled.

The relation between contact force and indentation was determined experimentally using a method discussed by Sun in [6] and depicted in Fig. 10. The test specimen is a simply-supported circular plate of the reference composite. The indenter is a 0.5-in.-diam steel hemisphere, thus matching the baseline impactors. The bracket attached to the rigid

Figure 8. Design curve for determining impact damage area.

Figure 9. Strength degradation as a function of damage area.

indenter holds an LVDT on the bottom of the plate. The LVDT thus measures the indentation, α .

Sun [6] suggests the classical Hertzian contact law

$$F = K\alpha^{2/3}$$

Figure 10. Indentation test setup.

is appropriate. Here F is the contact force and K is a constant. Based on the loading portions of the F vs α curves from four specimens, and considering the peak forces reached in the pendulum impact tests, a value of 17.0 for K was chosen (F is in pounds and α is in inches). The contact law can be used as a nonlinear spring at the point of impact on the composite structure being modeled.

Once the peak force in the impact is predicted, Fig. 11 can be used to estimate damage area. This figure comes from a correlation of predicted force vs damage area for the baseline pendulum and air-gun tests. Note that the curve in Fig. 11 should not be extrapolated beyond the limit shown,

Figure 11. Calculated peak contact force vs damage area.

because the pendulum and air-gun results begin to diverge at larger damage area values.

Once the damage area is estimated from Fig. 11, property degradation can be determined from Fig. 9. Alternatively, the damage area can be introduced into the structural model as an equivalent circular hole.

SUMMARY

- Pendulum and air gun facilities were used to characterize impact damage in 9 x 9 x 1/8-in.-thick plate specimens that were clamped on 8-in.-diam circles. The specimens were impacted in the center.
- A total of 65 tests was performed. In addition to baseline tests performed in ambient air using 0.5-in.-diam hemispherical steel impactor points, tests to assess the effects of impactor size and weight, temperature, and preexposure to water and battery acid were performed.
- Damage areas were determined using ultrasonic C-scans. It was found that the baseline test areas could be correlated with the quantity $m^{0.564}v$, where m is impactor mass in pounds-second squared per foot and v is velocity in feet per second. This baseline curve was found to be an adequate representation for the other conditions examined as well. Thus, the baseline curve was used to derive a recommended design curve, which can be used to conservatively estimate damage area from the impactor mass and velocity.
- The damage area can also be estimated by first calculating the peak contact force using dynamic finite-element-analysis. A curve is given relating force to damage area.
- The applicability of the design curve to other impacting objects was demonstrated in four tests in which bricks were dropped on specimens.
- After impact, most of the impact specimens were cut into tensile, compression, or fatigue test specimens. The specimens were tested to determine the property degradation due to the impact damage. It was found that the degradation was a function of the damage area. Thus, knowing the impactor mass and velocity, the property degradation can be determined.
- It was found that the property degradation can also be bounded by assuming the damage area to be a circular hole of equivalent area. The hole effect can then be assessed in a finite element analysis.

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