H. Crash Analysis of Adhesively-Bonded Structures (CAABS)

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Objectives

- Develop a comprehensive experimental and analytical methodology to analyze and design adhesively-bonded automotive composite structures to sustain axial, off-axis, and lateral crash/impact loads.
- Determine the rate sensitivity of bonded tubes to crush-through experiments on the Oak Ridge National Laboratory (ORNL) Test Machine for Automotive Crashworthiness (TMAC. See 8.B).
- Determine influence of critical joint design parameters, for example, bond length, bond thickness, and fillet, on specific energy absorption.

Approach

- Coordinate with the bonded-joint experimental and analytical efforts undertaken in the Automotive Composites Consortium (ACC) project "Composite Crash Energy Management." (See 4.G)
- Select a substrate, adhesive, and representative subcomponent joint geometry for evaluation.
- Characterize substrate material, adhesive material, and coupon-level joints under static and dynamic loads.
- Build and test unbonded and bonded rail components under static and dynamic crush loads.
- Correlate experimental results with analytical results by developing finite-element-based tools with appropriate material models and progressive damage algorithms.
- Enhance the understanding of joint performance by conducting full-field deformation measurements.

Accomplishments

- Completed static and dynamic tests at five different velocities on both unbonded and bonded tubes using TMAC.
- Designed and fabricated test fixtures for conducting dynamic fracture-toughness tests.
- Completed bulk adhesive dynamic fracture-toughness tests at rates above 1 meter/second.

- Completed static and dynamic Mode I, Mode II, and mixed-mode fracture-toughness tests.
- Installed high-rate equipment for conducting coupon-level dynamic tests at crosshead rates up to 18 meters/second.

Future Direction

- Complete Mode III fracture toughness tests at static and dynamic rates.

Introduction

The objective of this project is to develop a comprehensive experimental and analytical methodology to analyze and design adhesively-bonded automotive composite structures to sustain axial, off-axis, and lateral crash loads. This direct-funded project is closely aligned with the experimental and analytical efforts undertaken by the Automotive Composites Consortium (ACC) for adhesively-bonded composite substrates. The focus of this work, however, is restricted to the adhesive-joint issues. The key to the methodology development is the understanding of how critical joint design parameters, for example, bond length, bond thickness and fillet, affect the energy absorption. Recent investigations at ORNL have provided valuable insight toward the understanding of composite joint performance and composite crashworthiness. The next logical step is determining the correlation between measurable adhesive-joint parameters and their influence on the structure to dissipate energy and ultimately predict crashworthiness for a particular composite design.

Experimental tasks include material testing under quasi-static and dynamic loads for substrates, adhesives, and joints; strain-rate sensitivity studies; fracture-toughness testing; and test method development as required. These experimental results will provide the building blocks for model developments—first at the coupon level, then progressing in complexity to component level. Correlation with experimental results will provide the basis for which the analytical developments, including development of constitutive laws, materials models, damage algorithms, and new finite elements will be made. Structural tests are conducted on the new intermediate-rate TMAC at ORNL (see 8.B).

Approach and Results

The technical approach involves both experimental and analytical tasks. There are four main tasks:

Task 1—Materials Selection and Screening,
Task 2—Material Characterization,
Task 3—Component Testing, and
Task 4—Computational Tools Development.

Task 1 was completed and reported on in the FY 2002 annual report. The selected chopped-carbon-fiber prepreg material system was characterized from flat plaques provided by the vendor. Discussions with the vendor led to an overly optimistic view of the suitability of the material for this project. Additionally, delays in receipt of the material from the supplier resulted in consideration of a carbon-fiber sheet molding compound (SMC). Both materials were unsatisfactory due to processing difficultly and material variability. As a result of the variability in the initial material screening tests and difficulty in fabricating tubes with this material, the substrate material was changed to a carbon-fiber braided system. The woven-fabric prepreg comprises T300B carbon fiber with a tow size of 3K and 42% (by weight) epoxy resin.

Task 2 was initiated during FY 2002 and has been a continuing effort through FY 2006. This task focuses on determining the rate dependencies, if any, for mechanical properties of the bulk adhesive, substrate, and coupon-level joints.

Task 3 started in FY 2004 with preliminary tests to determine if the selected composite tube geometry would provide for a stable progressive crush behavior instead of global buckling. The geometry for the tube was 100 mm by 100 mm square with a 3-mm wall thickness and a 300-mm length. A 45-degree bevel was used for the triggering mechanism. These tests showed that a progressive crush failure mechanism was achievable using this geometry. Therefore, the required unbonded and bonded tubes needed for the remainder of the project were procured from Pacific Composites. These tubes were then tested on TMAC at five different velocities during FY 2005 and FY 2006.

Task 4, the development of computational tools, was subcontracted to Virginia Tech under ACC Cooperative Agreement funding.

Bonded and Unbonded Tube Tests

The matrix for the tube testing consisted of crushing at different velocities tubes having different bond widths (BWs) and bond thicknesses (BTs). The test velocities were 5 mm/sec, 50 mm/sec, 100 mm/sec, 500 mm/sec, and 5000 mm/sec. The bond-line thicknesses were either 0.5 mm or 1.0 mm and the bond width or tube overlap was either 25 mm or 50 mm. Figure 1 shows the test results in terms of the specific energy absorbed (SEA) as a function of test velocity. A snapshot of one of the bonded tubes being crushed at 5000 mm/sec is shown in Figure 2. The results in Figure 1 show a significant decrease in SEA as a function of loading rate with the largest reduction seen to occur below the 500 mm/sec rate. Also, the unbonded or complete tubes are seen to have the highest SEA compared to the bonded tubes. The effect of bond width appears to be negligible but there does appear to be a slight effect of bond thickness with the thinner bond having slightly higher SEA's.

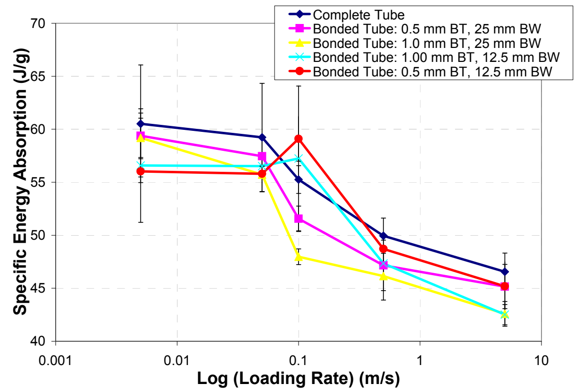

Figure 1. Measured tube SEA as a function of cross-head rate.

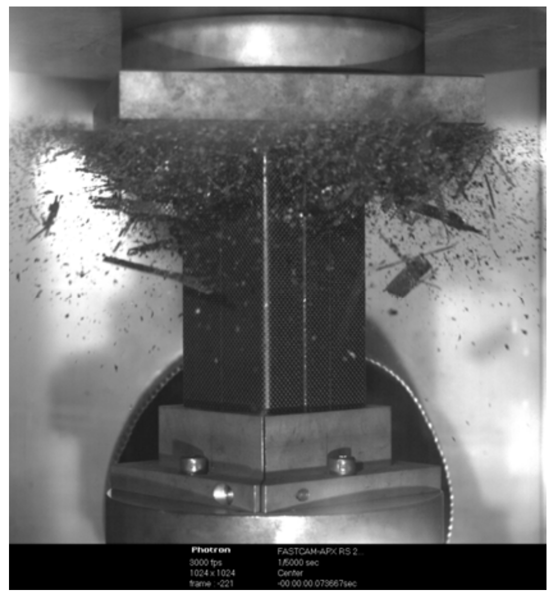

Figure 2. Bonded tube tested at 5000 mm/sec.

Bulk Adhesive Fracture Toughness

A key parameter in the development of computational models under Task 4 was the rate-sensitive fracture toughness of the bulk adhesive. Miniature compact-tension (CT) specimens were machined from hockey-puck-shaped adhesive castings. Quasi-static and dynamic fracture toughness tests were conducted on the bulk adhesive using an 8-mm-thick specimen per the geometry specified in ASTM D5045-99.

Fracture-toughness tests of the bulk adhesive were conducted at room temperature on a conventional closed-loop servo-hydraulic machine at rates ranging from 10^{-6} to 1 m/s. The load frame was equipped with a commercial slack adaptor or lost-motion device. Checkout tests were completed and it was determined that the target velocities could be achieved prior to the load application. However, at rates of 0.5 and 1 m/sec, it was difficult to accurately detect the relatively small loads generated by the test specimen because of contributions from the momentum of the 4 kg commercial slack adapter. Hence, a much smaller and lighter slack adapter was fabricated in-house. Fracture-toughness tests were successfully repeated at various rates from 10^{-6} to

1 m/sec with three specimens tested at each rate. The new setup included a smaller load cell, a shorter and simplified load train between the load cell and specimen, and reduced weight on the specimen because of the lighter adapter.

Even with the new setup, there was some question about the validity of the 1-meter/second test results. This was due to using a strain-gage load cell for measuring force. The new 18-meter/second test machine came on-line which uses a piezoelectric load cell. Therefore, some of the CT tests were repeated using the new test machine. The piezoelectric load cell should eliminate any inertia effects associated with the higher velocity test rates. Additionally, a new lightweight slack adaptor was designed and fabricated to provide a means for the actuation of the high-rate test machine to reach maximum velocity prior to engaging the test specimens. Results obtained from this study provide a much more accurate depiction of the behavior expected under such high rates of strain for the adhesive system in question.

Results show that the average fracture toughness, K_{Ic}, for the bulk adhesive CT specimens range from an average of $2.5 \pm 0.1\ MPa\sqrt{m}$ under quasi-static loading conditions to $1.7 \pm 0.01\ MPa\sqrt{m}$ at an applied loading rate of *1 m/s*. Furthermore, when converted from fracture toughness to strain-energy release rate (SERR), G_{Ic}, the corresponding average values ranged from $2260 \pm 180\ J/m^2$ under quasi-static loading conditions to $1015 \pm 7\ J/m^2$ at an applied loading rate of *1 m/s*. These average values take into account only those tests that were in compliance with the ASTM D5045-99 test standard. A full summary of the CT test results is presented in Table 1 while Figure 3 illustrates the relationship established between the Mode I fracture toughness, K_{Ic}, and the applied loading rate.

It is believed that the characterization of the performance of both the bulk adhesive and bonded composite joint specimens is best completed by looking at a local crack-tip loading rate, $d\sqrt{\mathcal{G}}/dt$, instead of a global loading rate, $\dot{\Delta}$. This conclusion was established based on the difference in stiffness among the bulk adhesive CT and the 11-ply, 20-ply, and 36-ply bonded composite joint specimens, both in the standard Mode I double-cantilever beam (DCB) configuration, as well as the newly-developed driven-wedge (DW) specimen geometry by Virginia Tech. With the newly obtained CT results, a correlation could be established between the bulk adhesive and bonded composite joint specimens as a function of local crack-tip loading rate, as illustrated in Figure 4.

Table 1. Summary of Mode I CT Test Results.

Rate (m/s)	K_{Ic} (Mpa*m$^{1/2}$)	$\mathcal{G}_{Ic}$ (J/m^2)
1.70E-05	2.5	2256
1.70E-04	2.3	1959
0.01	1.8	1191
0.1	1.9	1334
0.3	1.9	1335
1	1.7	1014

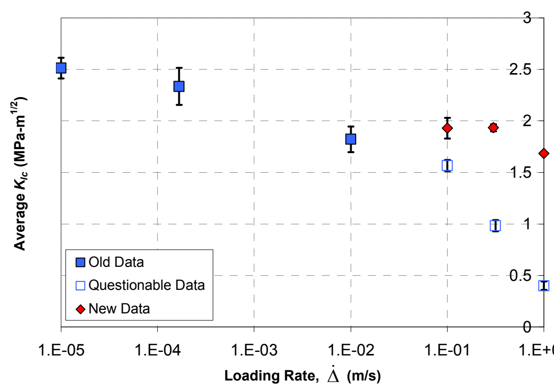

Figure 3. Mode I fracture toughness, K_{Ic}, vs. applied loading rate for bulk adhesive CT specimens.

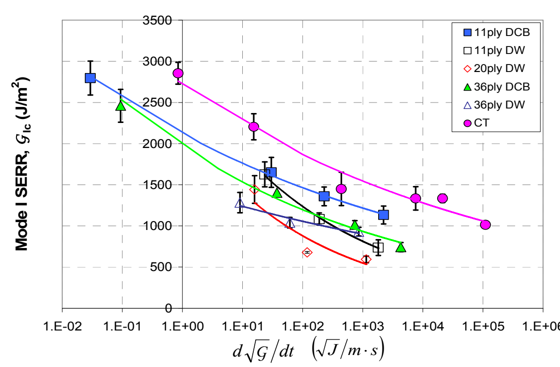

Figure 4. Complete summary of Mode I fracture results correlation.

DMA Results

Virginia Tech completed a dynamical mechanical analysis (DMA) test to verify the value for the glass transition temperature, T_g, for the SIA (Sovereign Specialty Chemicals) adhesive. Additionally, this test was conducted in an attempt to determine whether or not the Time Temperature Superposition Principle (TTSP) was applicable to the material system in question. A single-cantilever bend specimen was utilized for this study, and was subjected to a full frequency sweep from *0.1 – 20 Hz* over a temperature range of *-100 – 160°C*. Specialized rheology software was utilized for constructing a master curve in order to generate shift factor data to be used in the future for determining accurate frequency steps according to TTSP in order to conduct sub-ambient fracture tests relating to previously conducted high-rate experiments.

Results from the DMA test provide conclusive evidence that suggests a glass transition temperature of roughly *130°C*. This was determined from a tan(δ) versus temperature, T, curve, and is illustrated in Figure 5. Additionally, the generated shifted-frequency master curve was used to develop shift factors that can be used to relate temperature to frequency, thus corresponding to applied loading rate. In other words, the generated data can provide information that will allow for the sub-ambient testing of bonded composite joints that will directly correspond with tests conducted under high applied loading rates or at least this is the expected relationship. This will not only provide an accurate characterization of materials, but it will also provide a much easier means for completing such experiments. Figure 6 illustrates the final master curve that was generated with the specialized rheology software.

Conclusion

Material characterization tests were completed on bulk adhesive specimens and carbon-fiber woven-fabric adhesive joint specimens. A key parameter for the modeling efforts being conducted at Virginia Tech was the determination of the rate-sensitive fracture-toughness for the bulk adhesive. This was accomplished for Mode I by conducting compact-tension tests at different loading rates. These tests were conducted on the new 18 meter/second high-rate test machine in addition to tests previously conducted on a conventional servo-hydraulic machine. A new piezoelectric load cell was used in combination with a refined slack adaptor in an attempt to refute test results obtained from previous experiments conducted at high test velocities. These previous results were believed to be suspect due to inertia effects associated with the strain- gage-based load cell utilized in those experiments. Furthermore, additional DMA tests have been conducted on the SIA bulk adhesive in an attempt to determine whether or not the principle of TTSP can be used for future tests in order to virtually eliminate the need for high-rate testing. The results presented in this report illustrated that this concept is entirely possible.

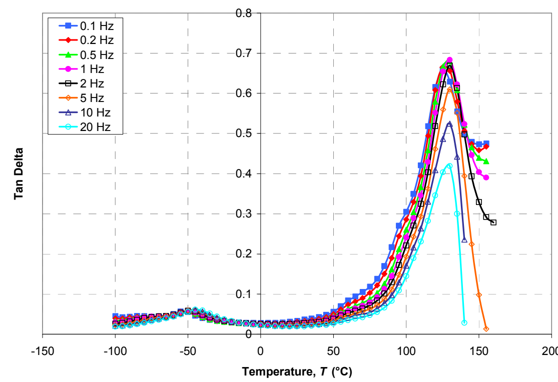

Figure 5. Tan δ vs. temperature curve generated from SIA adhesive DMA test.

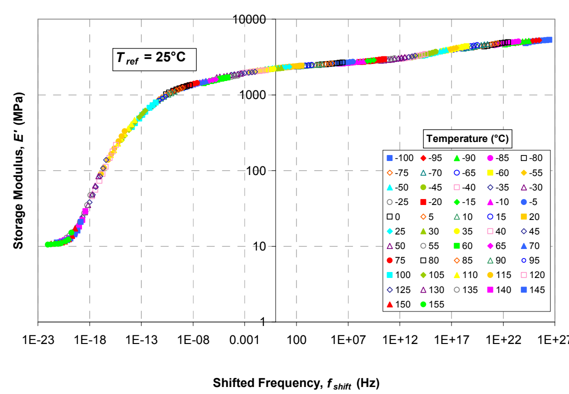

Figure 6. Shifted frequency vs. storage modulus for SIA adhesive DMA specimen.

To validate analytical models and to quantify the effect that an adhesive joint has on specific-energy absorption, a series of progressive crush tests on composite tubes were conducted using TMAC. Tests on bonded and unbonded tubes were completed at loading rates of 5, 50, 100, 500, and 5000 mm/sec. The SEA's were calculated and the results showed a decrease in SEA with loading rate for both the unbonded and bonded tubes. This trend is similar to that seen in previous ACC composite tube crush data, where the majority of the decrease in SEA appears to occur below the 500 mm/sec velocity.

Presentations/Publications/Patents

"The Effect of Rate on the Fracture of an Automotive Adhesive," presented at the 29th Annual Meeting of the Adhesion Society, Jacksonville, Florida, February 19-22, 2006.

"Using a Driven Wedge Technique for Characterizing Fracture Resistance of Adhesives Exhibiting Pronounced Slick-Slip Behavior," presented at the 29th Annual Meeting of the Adhesion Society, Jacksonville, Florida, February 19-22, 2006.

"Crashworthiness of Adhesively Bonded Composite Structures and Their Strain-Rate Sensitivities," presented at the Society for Experimental Mechanics Annual Conference on Experimental and Applied Mechanics, June 4-7, 2006, St. Louis, Missouri.