J. Performance Evaluation and Durability Prediction of Dissimilar Material Hybrid Joints

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Objective

- Develop new experimental methods and analysis techniques to enable hybrid joining as a viable attachment technology in automotive structures. This will be accomplished by evaluating the mechanical behavior of composite/metal joints assembled using a variety of hybrid joining methods and quantifying the resultant damage mechanisms under environmental exposures, including temperature extremes and automotive fluids, for the ultimate development of practical modeling techniques that offer global predictions for joint durability.

Approach

- Characterize the structural hybrid joint to quasi-static load conditions.
- Characterize response to fatigue, creep, and environmental exposures.
- Conduct predictive analysis.

Accomplishments

- Completed fatigue tests at 85%, 70%, and 40% of ultimate load for Quantum rails.
- Evaluated GENOA for predicting the damage development.

Introduction

Weight can be reduced and fuel efficiency increased in automobiles, without compromising structural integrity or utility, by incorporating innovative designs that strategically utilize modern lightweight materials—such as polymeric composites—in conjunction with traditional structural materials such as aluminum, magnesium, and steel. Despite the advantages associated with such dissimilar or hybrid material systems, there is reluctance to adopt them for primary structural applications. In part, this reluctance can be

attributed to the limited knowledge of joining techniques with such disparate materials where traditional fastening methods such as welding, riveting, screw-type fasteners, and bolted joints may not be appropriate.

One solution to this problem is the use of hybrid joining techniques by which a combination of two or more fastening methods is employed to attach similar or dissimilar materials. One example is a mechanically fastened joint (i.e., bolted or riveted) that is also bonded with adhesive. These types of joints could provide a compromise between a familiar mechanical attachment that has proven reliability, and the reduction of problematic issues such as stress concentrations and crack nucleation sites introduced by using mechanical fasteners with polymeric composites.

The use of hybrid joining could also lead to other potential benefits such as increased joint rigidity, contributing to overall stiffness gains and a reduction of vehicle mass. Additionally, the use of adhesives in conjunction with mechanical fasteners could significantly reduce stress concentrations, which serve as locations for crack starters. Hybrid joining methods can also provide additional joint continuity to allow increased spacing between fasteners or welds.

Although numerous benefits are derived from using hybrid joining techniques and the joining of dissimilar materials is becoming a reality, little or no practical information is available concerning the performance and durability of hybrid joints. Therefore, this project has taken on the task of developing new technologies to quantify joint toughness and predict long-term durability. This will necessitate identifying and developing an understanding of key issues associated with hybrid joint performance, such as creep, fatigue, and effects of environmental exposure.

To initiate this study, it was necessary to choose a candidate hybrid joint representative of those typically encountered in automobiles. Because of their wide applicability in automotive structures, several combinations of hat-section geometries were considered. Hat sections can be incorporated into a variety of generic automotive structural components, such as crush tubes or frame rails, when they are bonded and mechanically fastened to other geometries. For the current study, the Joining Task Force selected a composite hat section bonded and riveted to a steel base, as shown in Figure 1. This selection was made on the basis of general applicability to a variety of automobile structural components. Members of the Joining Task Force identified industry partners for sources for the steel, rivets, composite hat section, and adhesive.

To determine the influences of the adhesive and the rivets on the structural performance of the rail, it was also decided to investigate bonded specimens without rivets and riveted specimens without adhesive.

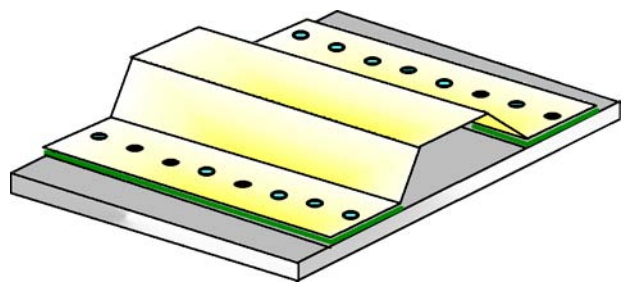

Figure 1. Hybrid joint schematic.

Fatigue Tests of Quantum Rails

Fatigue tests were performed at 85%, 70% and 40% of average ultimate static load at room temperature for both loading configurations—hat in tension and hat in compression. Three replicates of each test at 70% of ultimate load were completed. At least one data point exists for tests at 85% and 40% for all joint-load combinations. Ratio of R = 0.1 and frequency f = 1 Hz were used for tests at 85% and 70% of ultimate load. A higher frequency of 3 Hz was used for tests at 40% of ultimate load to allow for more specimens to be tested.

Several orders of magnitude scatter in number of cycles to failure, which is characteristic of fatigue tests, were observed for the Quantum rails. Inconsistency in the damage mechanisms occurred and can be attributed to previously reported scatter in material properties of Quantum composite. In spite of the scatter and inconsistencies, several trends are clearly distinguishable, and some general observations can be made.

Specimens failing at low cycle count ($N_f < \sim 10^4$) exhibit failure at the top of the hat section for hat in tension (Figure 2) and tearing of flanges for hat in compression (Figure 3). These failure mechanisms are identical to those observed in quasi-static tests.

Figure 2. Failed hat in tension—typical failure at low cycle count.

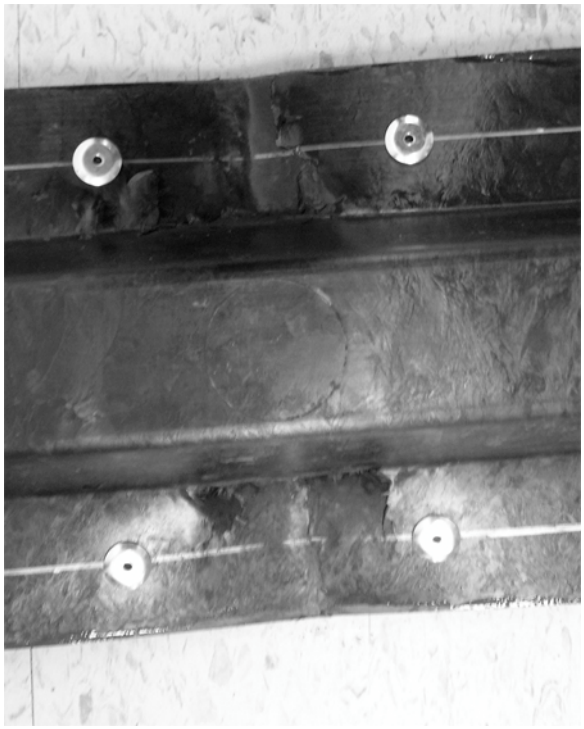

Figure 3. Failed hat in compression—typical failure at low cycle count.

Specimens reaching high cycle counts display entirely different damage, such as metal cracking and rivet failure. Specimens containing adhesive (adhesive with rivets and adhesive only) encounter cracks in the metal substrate initiating in areas of high stress concentration, such as in the vicinity of roller supports and rivet holes (Figure 4). As these cracks grow, usually in the direction perpendicular to the longitudinal axis, the load carried by the composite hat increases. Most specimens failed before the crack or cracks in the metal grew across the entire width of the specimen (Figure 5). Cracks in adhesive were never observed prior to damage or failure of either the composite hat or the metal substrate. Additionally, the adhesive contained the crack growth at the flanges (Figure 6).

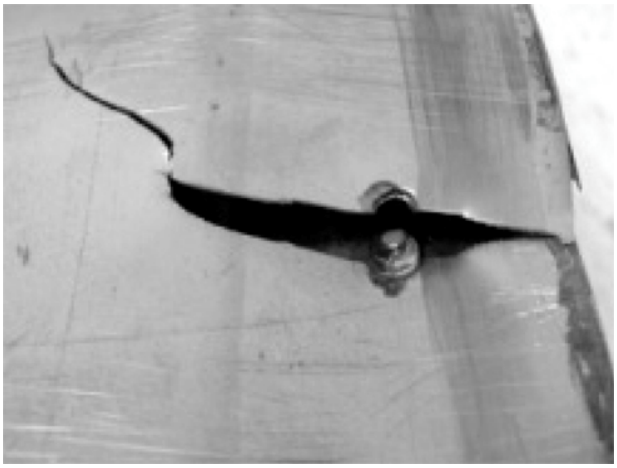

Figure 4. Crack in metal substrate initiated from rivet hole for a specimen with rivets and adhesive.

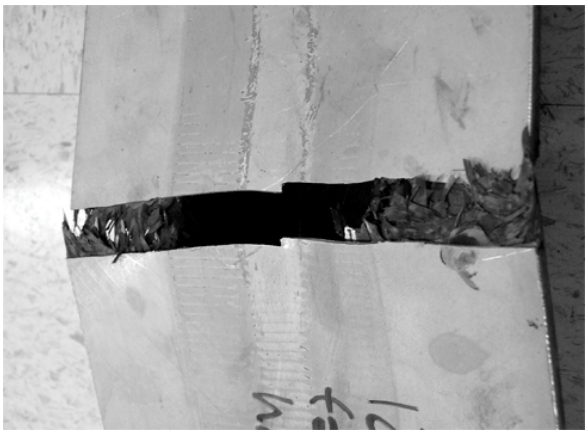

Figure 5. Cracks initiated under roller supports that grew through the substrate before final failure for hat with adhesive only.

Figure 6. Adhesive-containing crack opening—specimen with adhesive only.

Riveted specimens reaching higher cycle counts exhibited broken rivets prior to catastrophic composite failure. In some cases, all rivets ruptured on one side of the specimen, leaving no joint between the composite hat and metal substrate (Figure 7). Metal cracking as well as rivet failure can be detected from load-displacement behavior of the structure as illustrated in Figure 8. Typical S-N data are shown in Figure 9.

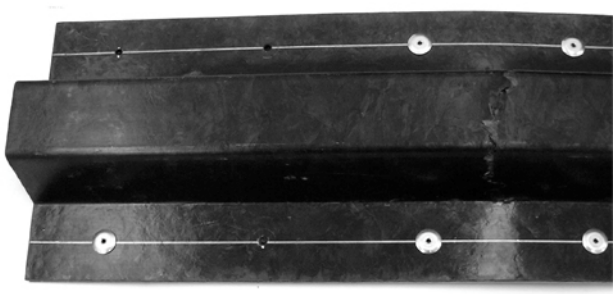

Figure 7. Half of rivets broken; some fell out during the test for specimens with rivets only.

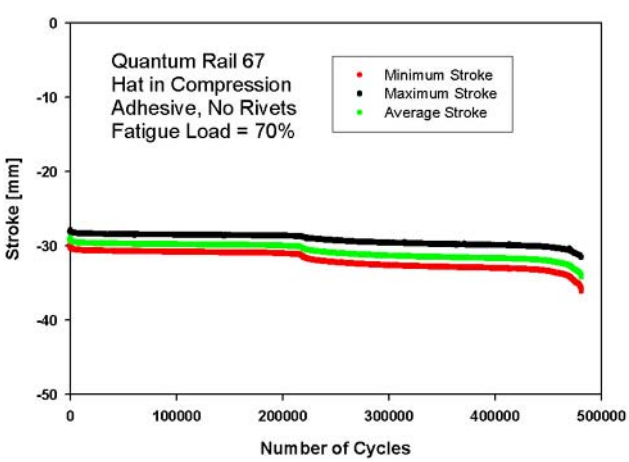

Figure 8. Crack initiation detectable at 2.2×10^5 cycles.

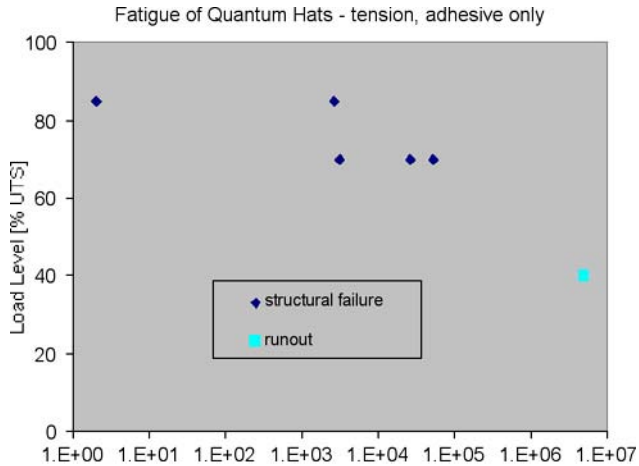

Figure 9. Typical S-N data for hat section.

Results from these fatigue tests as well as previous quasi-static tests indicate that joints containing adhesive outperform riveted joints. No damage in the adhesive joint was observed during the study prior to macroscopic cracking of either the metal substrate or the composite hat section. Under quasi-static conditions, adhesively bonded specimens reached higher ultimate loads and resulted in higher stiffness of the structure. This conclusion is further reinforced by previously reported results and analyses from environmental and creep tests.

Finite-Element Modeling

With the exception of fatigue tests with high cycle count, the hat specimens lost bearing capability due to composite failure. As a result, predictive capabilities for progressive failure of composites are critical for accurate modeling of the hat structure under consideration. A popular commercial finite-element code, ABAQUS by Hibbit & Carlsson Inc., was successfully used to predict load-displacement behavior up to the point of failure or significant damage in the composite hat. Postdamage behavior modeling with this code proved to be challenging.

GENOA code, developed by Alpha Star Corporation specifically for composites, is currently being explored, and initial results indicate that this code may provide more predictive power compared to standard finite-element codes such as ABAQUS, Nastran, and Ansys. GENOA performs stress analysis on the structure level, but instead of assuming an homogenized model for the material behavior, another finite-element analysis is performed on the fiber-matrix level for each node of

the structure model. This multiscale approach results in computationally intensive analysis through which the degradation of material properties on fiber-matrix level can be modeled (Figure 10). GENOA has been used primarily in the aerospace industry where chopped fiber composites are used scarcely if at all. Consequently, capabilities of GENOA in this area have room for improvement. It was decided that results from previously tested continuous fiber composite hat sections with T300 Mat/Urethane 420 IMR composite will be used to evaluate GENOA's capabilities. The following seven steps must be completed before obtaining results for component-level model:

- input fiber and matrix properties,
- select coupon-level experiments to be matched numerically,
- match elastic properties of composite,
- evaluate sensitivity of ultimate properties to material coefficients,
- develop models of selected coupon tests,
- calibrate material coefficients to match experimental coupon-level tests, and
- input calibrated properties into subcomponent level model.

Durability reports by J. M. Corum et al. were extensively used in this iterative material calibration process. To date, this process has been performed with the assumption of linear material behavior up to the point of ultimate failure for tension and compression coupon tests with 0/90 and ±45° fiber orientation. A comparison of experimental and numerical ultimate failure loads for hat sections with adhesive only is presented in Table 1. Predicted failure load for hat in tension matches the experimental value with remarkable accuracy.

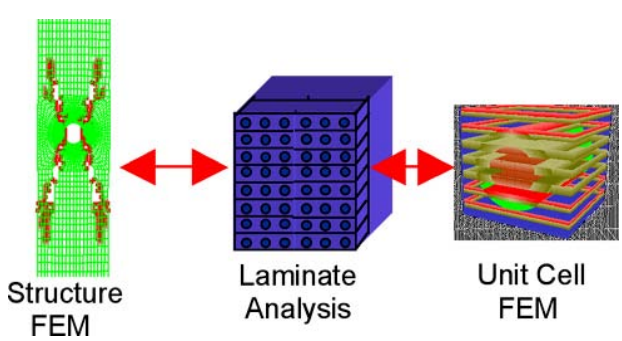

Figure 10. Scales of analysis in GENOA.

Table 1. Comparison of experimental and numerical values for hat section with adhesive only

Test configuration	Ultimate load (lb) experimental	Ultimate load (lb) GENOA
Hat in tension	4335	4340
Hat in compression	7474	4280

Results for hat in compression do not coincide as well. This can likely be attributed to the assumption of linear behavior until the point of catastrophic failure. As such, only sudden catastrophic failure, such as observed for hat in tension, can be modeled accurately. A failed model with dark v-shaped regions, designating damage in the composite, is depicted in Figure 11.

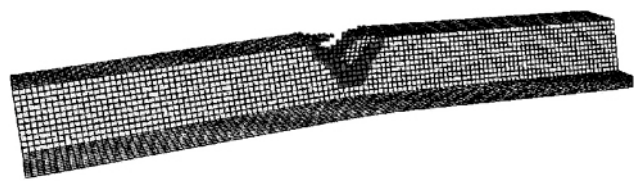

Figure 11. GENOA model of hat in tension after failure.

Nonlinear behavior of composite material used in the hat section must be captured to realistically model the response of the structure. Nonlinearity can be introduced either on the fiber-matrix level or on lamina level. Both approaches are being investigated at the present time. Plastic yielding of resin accounts for the majority of the nonlinear response of the cross-ply composite. Stress-strain response of neat resin is necessary for input on the fiber-matrix level. This information was not available from the resin manufacturer or from the durability reports. An iterative procedure was implemented in custom Python script through which the resin properties can be obtained from the response of the composite in coupon-level tests. This script repeatedly executes GENOA runs, compares the numerical results to experimental results, and adjusts the resin stress-strain curve in GENOA input to match the numerical and experimental data.

A special version of GENOA was provided by Alpha Star Corporation to enable implementation of the approach proposed by Deng, Li, Lin, and Weitsman in "The non-linear response of quasi-isotropic laminates." This paper, published in *Composite Science and Technology*, investigated

T300 Mat/Urethane 420 IMR composite with a quasi-isotropic layout.

Axial Tests

Several specimens were tested in an axial direction to assess setup in the Test Machine for Automotive Crashworthiness (TMAC). The setup is shown in Figure 12. Edges on the impact side of the specimen were filed to 45° to form a crack initiator. The energy absorption properties for all three joining techniques were compared to an aerospace-quality crush tube (Figure 13). The tube was designed specifically as an energy-absorbing member and is made of two identical aerospace-quality, continuous-fiber sections joined via adhesive bonding. The thickness of the composite section is identical for the hat and the tube (approximately 0.125 in.). The hat has 1.3 in.^{2} of composite material in the cross section and 0.3 in.^{2} of steel metal substrate. The cross-sectional area of the composite tube is 2 in.^{2}. Note that the tube in this experiment was approximately 1 in. longer in length than the hat. Energy absorbed by the structures was calculated as the area under the load-displacement curve obtained during the test (Figure 14). The total energy values as well as energy per material volume and energy per composite material crushed are compared in Table 2. It is apparent that the performance of a low-cost structural member approximately matches and possibly exceeds the performance of an aerospace-quality crush tube. The results for hats

Figure 12. Setup of axial test in TMAC.

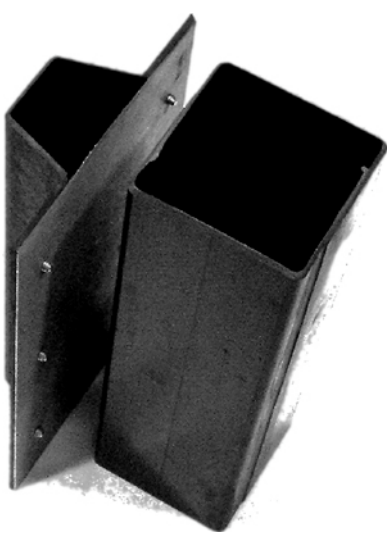

Figure 13. Hat section and crush tube.

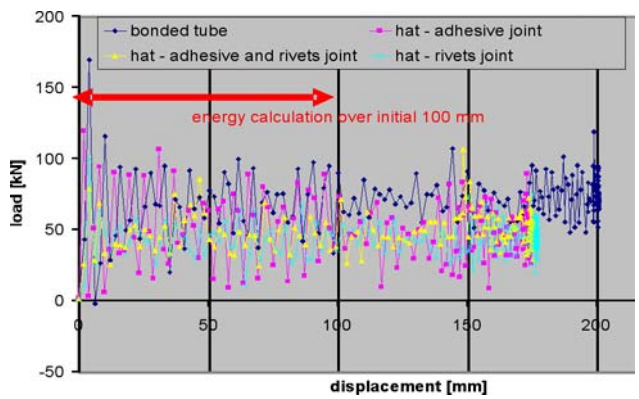

Figure 14. Superimposed test results for hybrid hat sections and bonded tube.

Table 2. Energy absorption of hybrid hat sections and bonded tube

	Total energy over 100 mm (kJ)	Energy per crushed total material volume (MJ/m^3)	Energy per crushed composite volume (MJ/m^3)
Bonded tube	6.7	51.9	51.9
Hat—adhesive	5.3	51.3	63.1
Hat—rivets	4.3	41.7	51.2
Hat—rivets and adhesive	4.7	45.5	56.0

may be statistically similar because the low-cost SMC composite exhibited significant variation in properties and only a single test was performed for each joint combination.

In Figure 15 the difference in metal substrate deformation in the initial phases of impact, which may be attributed to joining method, can be seen. It is uncertain if the joint and the substrate absorb significant levels of energy compared to the energy absorbed by the composite hat section. However, we suspect that the composite hat section is the primary energy-absorbing component of the system. Also note the difference in curvature of metal substrate for adhesively bonded joints in quasi-static (Figure 16) and the rapid 4-m/s tests (Figure 17). This difference in curvature is likely a result of time-dependent behavior of the adhesive, resulting in faster crack propagation at higher velocity. While the visco-elastic behavior of the adhesive is a likely candidate for the difference in curvature consistently observed for bonded specimens, the interaction of the metal substrate may also contribute to the overall time-dependent behavior of the structure.

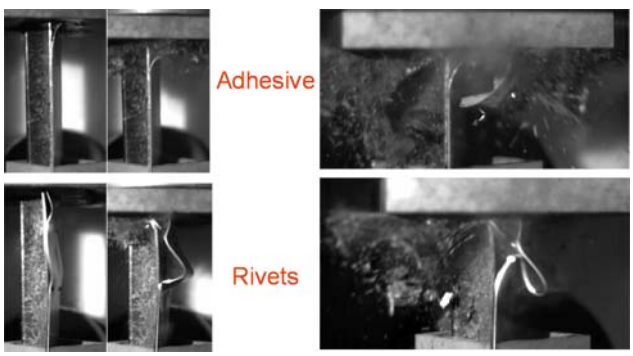

Figure 15. Initial phases of impact for bonded and riveted hat sections.

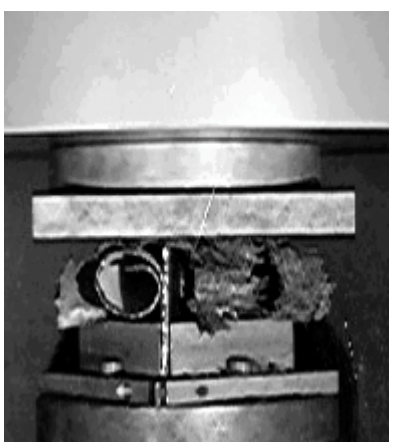

Figure 16. Specimen with adhesive only after quasi-static axial test.

Figure 17. Specimen with adhesive only after intermediate-strain-rate axial test.

Conclusions

Fatigue behavior in bending, energy absorption under axial loading, and finite-element simulation for quasi-static loading were explored for structures with a composite hat section joined to metal substrate by adhesive bonding or riveting or a combination of bonding and riveting.

Failure of specimens reaching low cycle counts in fatigue experiments was caused by damage in the composite hat section, closely resembling damage observed in quasi-static tests. Joint failure was not observed during these tests. Specimens reaching higher cycle counts exhibited cracking in the metal substrate for bonded joints and rivet failure for rivets-only joints. As a result of the damage in metallic parts of the structure, more load was carried by the composite hat section, which often lead to eventual damage of the composite and failure of the structure.

Energy absorption properties of the hat structure and aerospace-grade crush tube were compared. Low-cost hat structures approximately matched the energy absorption per volume of crushed material of the crush tube.

Progressive failure capability of GENOA software was used to model damage in the composite hat section during quasi-static tests with promising results.