G. 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

- Conducted replicate fatigue tests at 85%, 70% and 40% of ultimate load for Quantum rails.
- Performed progressive failure analysis with contact and non-linear material behavior using coupled GENOA and ABAQUS codes.

Future Direction

- This project was completed Month 6 FY 2005.

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. 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.

Replicate Fatigue Tests of Quantum Rails

Replicate fatigue tests have been performed at 40% of average ultimate static load at room temperature for both loading configurations—hat-in- tension and hat-in-compression. These tests, carried out at frequency of 3 Hz, require significant test machine time, since most specimens incur damage after more than 10^6 cycles. Most specimens reach run-out limit of 10^7 cycles without catastrophic failure. Three replicate fatigue tests at 40% of ultimate load will be completed when two remaining tests in progress conclude.

To date, replicate tests have confirmed our previously reported observations. Specimens reaching high cycle counts during fatigue tests exhibit failure mechanism different from mechanisms observed in quasi-static tests. Specimens containing adhesive bonds have been consistently outperforming specimens with rivets only as illustrated by Figure 1 and Figure 2. Specimens that encountered catastrophic failure, before reaching run-out limit of 10^7 cycles, have sustained significant damage. Adhesively-bonded specimens developed cracks in the steel substrate, while riveted specimens sustained partial or complete loss of rivets prior to final failure. None of the specimens tested at 40% of ultimate load showed failure modes identical to that of quasi-static test.

Finite Element Modeling

An in-house developed Python code was used to calibrate material properties for input to GENOA. This calibration enables simulation of non-linear behavior of the matrix of the composite, which is important in specimens with ± 45 fiber orientation. Experimental stress-strain curves from coupon tests

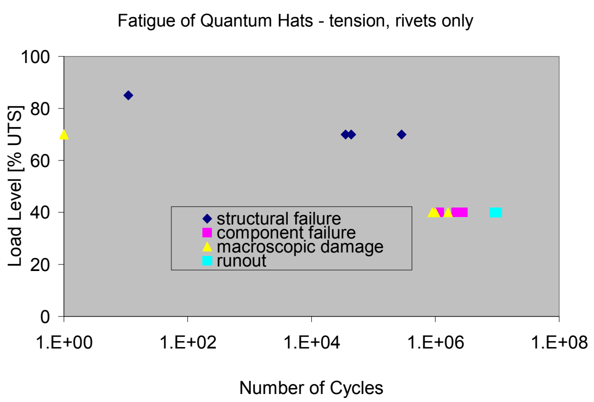

Figure 1. Specimens with rivets only exhibited rivet failure before reaching run-out limit at 40% of ultimate load.

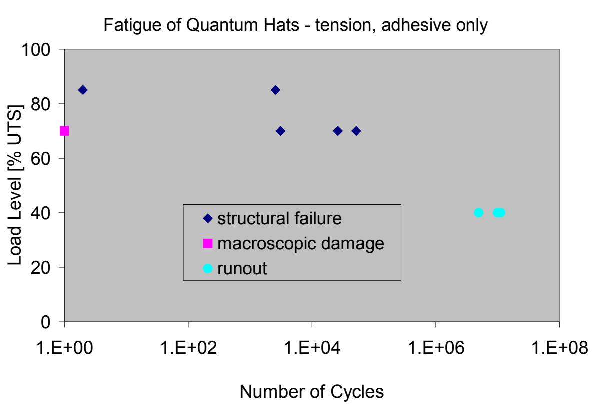

Figure 2. Specimens with adhesive did not exhibit damage before reaching run-out limit.

were matched in equivalent GENOA models. The modified distortion-energy failure criterion was disabled, since it inaccurately predicted premature failure.

Previous GENOA analyses disregarded complex contact conditions that exist in real tests due to unavailability of a contact algorithm in GENOA finite element solver (MHOST). ORNL and Alpha Star collaborated in coupling GENOA and ABAQUS finite element solvers. This development allows analysts to take advantage of multi-scale progressive failure capabilities as well as non-linear and contact capabilities of ABAQUS.

A full model of hat-in-tension presented in Figure 3 was developed. Previously calibrated material properties for ± 45 cross-ply composite were used along with material properties of adhesive and steel. Figures 4-5 show damage. The sequence of push-through damage due to contact and subsequent failure in the hat was observed in experiments. The model with the disabled modified distortion-energy failure criterion over-predicts ultimate load of the structure and does not reflect the unloading part of the load-displacement curve. The model with all damage criteria active under-predicts ultimate load, as expected based on coupon test calibration; however, the unloading part of the load-displacement curve is reflected in the results. This indicates strong sensitivity of the model on parameters affecting modified distortion-energy criterion. Material calibration is presently being re-visited in order to include all failure criteria in the coupon models.

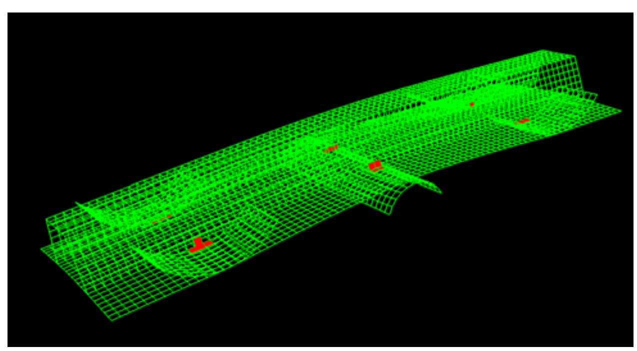

Figure 3. Initial damage due to contact in GENOA model.

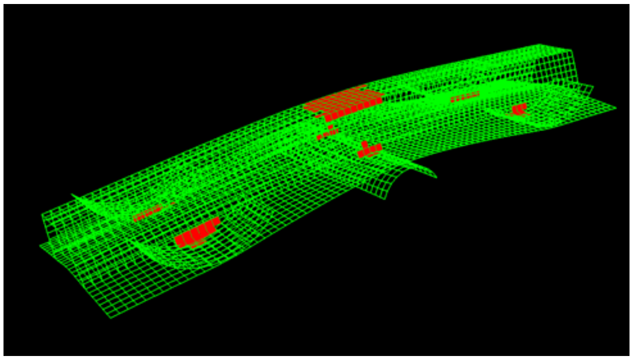

Figure 4. Failure at the top of the hat in GENOA model.

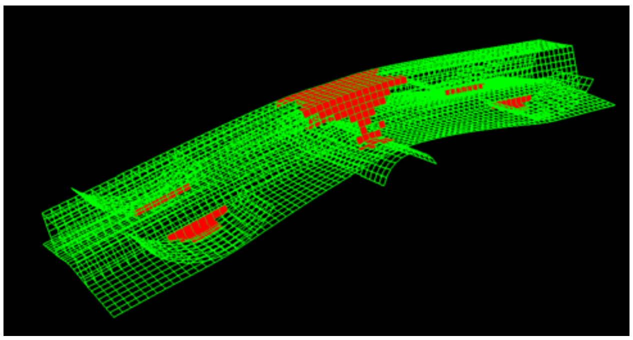

Figure 5. Advanced stage of damage in GENOA model.

Conclusions

Replicate fatigue tests have been conducted and statistical certainty was increased for previous observations. Multi-scale progressive failure analyses with contact and non-linear material behavior have been performed.

Presentations/Publications/Patents

V. Kunc, D. Erdman and L.B. Klett, "Hybrid Joining in Automotive Applications", Presented at the SAMPE 2005 Symposium and Exhibition, Renaissance Long Beach Hotel/Long Beach Convention Center, Long Beach, CA, 1-5 May 2005