SUPER LAP SHEAR JOINT STRUCTURAL TEST-ANALYSIS CORRELATION STUDIES

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Abstract

Computer aided engineering-based design methodologies have been utilized throughout the Automotive Composites Consortium Focal Project 4 to assess the vehicle level structural stiffness and impact performance of the composite underbody design proposals, and to estimate the potential mass reduction for several candidate material scenarios. To increase confidence in the vehicle level model predictions, and to better understand the effect of hybrid composite-to-metal joint performance, several quasi-static structural coupon tests were simulated for the purpose of test-analysis correlation and modeling methodology development. Analysis correlation studies were conducted for the tensile testing of fiberglass fabric Sheet Molding Compound (SMC) composite-to-steel “super lap shear” joint coupons. Super lap shear tensile performance simulations were conducted to account for -40°C, ambient, and +80°C adhesive material properties for both an adhesively bonded and a weld bonded configuration. Although composite delamination was not considered in the model, the results of the study indicated that the predicted peak joint loads fell within the range of test data when accounting for temperature dependent adhesive properties, inplane composite failure, and steel yielding.

Background

The Automotive Composites Consortium Focal Project 4 (ACC FP4) is a joint program between GM, Ford, and Chrysler to develop structural automotive components from composite materials. Part of this project is to develop a structural composite underbody capable of carrying crash loads.

A compression molded multi-layered fiberglass fabric reinforced SMC composite was selected as the material and process system to best meet the performance and cost objectives of the program. The process of weld bonding was selected as the means to join the composite underbody to the steel body-in-white (BIW) structure [1, 2]. A schematic of the selected woven fiberglass fabric material underbody structure application and the composite-to-steel joining concept are illustrated in Figure 1. The effects of fabric draping on structural performance are discussed in a companion paper [3].

The potential benefits of joining the composite underbody to the steel BIW structure via weld bonding were outlined in [1]. Several physical tests have been conducted to date to evaluate the structural performance of steel-to-composite weld bond joints under various loading conditions [4]. The current paper will discuss the modeling methodology used to simulate the tensile response of weld bonded joints subjected to quasi-static loading. The methodology is being developed to evaluate the vehicle level performance of weld bonded joints under a variety of quasi-static, dynamic, and fatigue loading conditions.
Correlation Studies

A 150mm wide “super lap shear” (SLS) joint test specimen was originally designed to evaluate the performance of a steel-to-composite structural joint [1, 5]. The specimen geometry was further refined to its current width of 120mm to improve robustness. SLS specimens were fabricated and subsequently quasi-statically tested at -40°C, “ambient” (~20°C), and 80°C both by the ACC and by the Oak Ridge National Laboratory (ORNL). Tensile force vs. deflection data and photographs of tested samples were provided as a basis for the present test-analysis study [4]. FE analysis studies were conducted to determine a practical joint modeling methodology in an effort to account for joint performance in vehicle level crash and durability models.

Test Specimens

An exploded view schematic and photographs of the two test specimen configurations can be seen in Figure 2. The “adhesively bonded” configuration features a bonded lap joint, while the “weld bonded” configuration features an additional bonded steel doubler plate which effectively clamps the composite panel to the steel substrate via (3) spot welds. The composite substrate is a 7-ply [0/45/90/-45/90/45/0] “quasi-quasi isotropic” (QQI) laminate [6].
**Quasi-Static Tensile Testing**

As shown in Figure 3, the quasi-static tensile testing was conducted in an environmental chamber at three test temperatures: -40°C, ambient (~20°C), and 80°C [4]. In each test, load was measured using a load cell, while the test machine stroke was used to measure displacement*. Note that hydraulic grips were used in the ORNL tests (Figure 3a), while mechanical wedge grips were used in the ACC tests (Figure 3b). The representative load vs. stroke data compared in Figure 3 (c) indicates that the effective SLS specimen stiffness predicted by FE analysis (discussed later in this paper) is greater than the stiffness measured using the ORNL test setup, which in turn is greater than the stiffness measured using the ACC test setup. This apparent difference in stiffness seems reasonable when considering the differences in the various test setups: A perfectly rigid “test setup” is assumed in the FE analysis, while the physical test setups would be expected to exhibit some compliance. Although test setup compliance was not measured, it seemed reasonable to assume that the load frame with hydraulic grips used in the ORNL tests was less compliant than the smaller mechanical wedge grip system used in the ACC tests.

*Note that machine stroke measurements include compliance associated with the load frame and test fixture, and thus may indicate reduced effective specimen stiffness.
Modeling Approach

A key consideration in the FE modeling was to use an approach compatible with the typical 5 to 10mm element size and overall full vehicle modeling approach described previously [7]. The modeling methodology was based on the FE solver LS-DYNA [8] and analytical material properties derived from test coupons [6].

As shown in Figure 4, the composite and steel substrates were modeled using shell elements, the spot welds were modeled using solid beam elements, and the adhesive was modeled using solid elements with the MAT169 adhesive model described in [9]. Given the shell element representation of the substrate materials, the adhesive thickness was modeled from shell mid-plane to shell mid-plane, resulting in non-physical adhesive thickness which was taken into account in the adhesive model parameters. A 5mm nominal element size was used.

Figure 3: (a) ORNL and (b) ACC tensile test setup; (c) representative test data comparison

Figure 4: Super lap shear FE model assumptions
As outlined in [9], both tensile and shear stress-strain data are needed to define the adhesive model. However, only limited proprietary OEM temperature-dependent adhesive tensile data were available to estimate the analytical adhesive tensile parameters. A schematic depicting the nature of the tensile adhesive stress-strain performance is shown in Figure 5 (a). An iterative strategy was used to develop the analytical adhesive shear material properties in order to achieve a satisfactory correlation with the adhesively bonded SLS specimen tensile tests. The resulting level of correlation between the FEA model and the test results is shown in Figure 5 (b). Presently, the effect of temperature is accounted for only in the adhesive properties. Temperature-dependent composite substrate properties may be used in the future when additional test data become available.

Due to the differences in effective stiffness observed in testing discussed in the previous section, the predicted displacements shown in Figure 5 were scaled to closely match the adhesively bonded test data provided by ORNL. A scale factor of 1.5 was used for all -40°C and ambient temperature data, and a scale factor of 2.2 was used for all +80°C. These scale factors were used for test-analysis comparison purposes only.

![Adhesive tensile stress-strain response schematic](image1)

![Representative adhesively bonded SLS tests (ORNL)](image2)

*Figure 5: Adhesive modeling*

**Predicted Response**

Once the temperature-dependent adhesive properties were selected using the methodology discussed above, the predicted results were compared to test results for both the adhesively and weld bonded test configurations.

**Joint Failure**

The predicted joint response is shown in Figure 6 for each joint configuration at ambient temperature. Several images detailing the failure of the adhesively bonded and weld bonded joint configurations are shown in Figure 6 (a) and (b), respectively. The label identifying each image corresponds to a portion of the associated load vs. stroke curve shown in Figure 6 (c). For the adhesively bonded geometry, the joint begins to rotate upon loading from 1-2, and the peel stresses begin to build in the solid adhesive elements at the edge of the joint until the adhesive failure stress is reached and the adhesive elements are deleted from the model.

*The higher scale factor of 2.2 may indicate temperature related stiffness reduction not accounted for in the composite.*
resulting in complete joint separation at 3. For the weld bonded joint, the initial response of the joint is similar to the adhesively bonded joint from 1-2. At 2, the first adhesive elements begin to fail at the edge of the joint, resulting in a slight reduction in load. The entire row of adhesive elements between the composite and steel substrates fails between 3 and 4, resulting in a larger decrease in load. Between 4 and 5, the remaining adhesive elements between the composite and weld doubler fail, and the weld buttons begin to rotate further and bear on the composite substrate inducing inplane failure in the composite elements and subsequent element deletion at displacement levels beyond 5. In addition to inplane composite failure, rotation of the joint leads to yielding of the weld doubler and welds.

Figure 6: Predicted SLS joint failure progression at ambient temperature

Test-Analysis Comparison

The predicted load vs. stroke results for the adhesively bonded and weld bonded joint configurations are compared to the ORNL-provided test data for -40°C, ambient (~20°C), and 80°C in Figure 7 through Figure 9, respectively. In each figure, post-test photos of representative test samples are shown to indicate the general nature of the observed failure modes and also the quantity of test samples that exhibited each observed failure mode. Note also that the predicted displacements were scaled as noted previously to facilitate test-analysis comparisons only.

The -40°C results in Figure 7 (a) indicate that the 3 of 4 adhesively bonded test samples ultimately failed due to a mixed mode adhesive failure / partial composite substrate
delamination, while one sample appeared to fail due to composite substrate delamination alone. Failure was indicated by a sudden reduction in load carrying capacity as was predicted in the analysis. The results in Figure 7 (b) indicate that all 4 weld bonded test samples exhibited an initial load drop, followed by an increase in load until the peak load was reached. Upon reaching the peak load, the test samples exhibited a gradual reduction in load capacity as the weld buttons were pulled through the composite. The predicted response is very similar to the observed responses, giving insight into the progression of failure in the joint. The predicted reduction in load carrying capacity beyond the peak load is more severe than observed in the tests, possibly due to the fact that composite delamination is not considered in the model.

The ambient temperature results in Figure 8 (a) indicate that the 3 of 4 adhesively bonded test samples ultimately failed due to composite substrate delamination, while one sample exhibited composite delamination in the tab section prior to ultimate failure at the grip. The reduction in post peak load carrying capacity was not as abrupt in all cases as was predicted in the analysis, likely due to the observed composite delamination. The results in Figure 8 (b) indicate that all 5 weld bonded test samples exhibited a similar response as the -40°C samples, with the predicted response showing a similar correlation.

The +80°C results in Figure 9 (a) indicate that all 4 adhesively bonded test samples ultimately failed due to adhesive failure with partial composite substrate delamination. Failure in all cases was indicated by a sudden drop in load as was predicted by the analysis. The results in Figure 9 (b) indicate that all 4 weld bonded test samples exhibited a significant reduction in load carrying capacity after the peak load was reached, after which the weld buttons were observed to pull through the composite. The drop in load was more abrupt than observed in the -40°C and ambient temperature tests, which is consistent with the reduced amount of composite delamination observed in the joint. As a result, the predicted post-peak load response is very similar to the observed responses.

The measured and the predicted peak loads for all quasi-statically tested adhesively bonded and weld bonded coupon configurations are compared in Figure 10. The results indicate good agreement between the measured ACC and ORNL peak loads despite the differences in test setup. The predicted results generally fell within the range of measured peak loads which is reasonable given the limited data used to characterize the adhesive model, and also the fact that composite delamination was not accounted for in the composite substrate.
Figure 7: Super lap shear response comparison at -40°C

Figure 8: Super lap shear response comparison at ambient temperature
Summary and Next Steps

The goal of this effort is to develop an adhesive modeling methodology to predict the quasi-static temperature-dependent performance of weld bonded joints within vehicle level crash and durability models. The present modeling methodology accounted for temperature-dependent behavior in the adhesive material model. Limited temperature-dependent adhesive tensile test data was used in conjunction with adhesively bonded super lap shear test data to select the required adhesive model parameters. Several failure modes were observed in physical testing, including adhesive failure, inplane and delamination composite substrate failure, and steel substrate / doubler yielding. Although the observed composite delamination mode was not accounted for in the model, the predicted peak joint loads generally fell within the range of test data. Furthermore, the predicted post peak response was similar to the test responses, with the predicted reduction in load carrying capacity generally more severe than observed in testing.
Additional adhesive testing is recommended to refine the adhesive material model peel and shear properties at the temperatures of interest.

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