STRUCTURAL PERFORMANCE EVALUATION OF COMPOSITE-TO-STEEL WELD BONDED JOINT

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Abstract
The Automotive Composites Consortium (ACC), a collaboration of Chrysler, Ford, General Motors, and the United States Department of Energy is conducting a focal project to demonstrate the use of composite materials in high volume structural applications such as an underbody capable of carrying crash loads. One of the critical challenges is to attach the composite part to the steel structure in a high-volume automotive manufacturing environment and meet the complex requirements for crash.

Weld-bonding, a combination of adhesive bonding and spot welding, was selected as the primary joining method. A novel concept of bonding doubler steel strips to composite enabled the spot welding to the steel structure, ensuring the compatibility with the OEM assembly processes. The structural performance of the joint, including durability, was assessed via analytical and physical testing under quasi-static loading at various temperatures. This paper discusses the results of the experiments designed to generate key modeling parameters for Finite Element Analysis of the joint.

Background
The Automotive Composites Consortium (ACC) is a collaboration of Chrysler, Ford, General Motors, and the United States Department of Energy with a mission to conduct pre-competitive research on structural and semi structural polymer composites to advance high strength, lightweight solutions in automobile technology. In 2007, ACC initiated a focal project IV with an objective to demonstrate the use of composite materials in high volume structural applications such as an underbody capable of carrying crash loads[1]. Figure 1 shows the concept design of the composite underbody.
One of the critical challenges is to attach the composite part to the steel structure in a high-volume automotive manufacturing environment and meet the complex requirements for crash. Adhesive bonding is the most commonly used joining method to integrate the composite parts into vehicle steel structures. Crash toughened structural adhesives which meet the OEM performance requirements in a crash are available commercially. The process of bonding works well for low volume off line production. However, in a typical high volume automotive environment, cycle time and compatibility with body shop processes are also key requirements. Almost all of the body shops today are built for steel structures where welding is the most commonly used joining technique. Therefore, to ensure the compatibility with the OEM assembly processes in high volume production, weld bonding, a combination of spot welding and adhesive bonding, was selected as the primary method of joining the composite underbody to the steel body-in-white (BIW). It combines the advantages of both adhesive bonding and spot welding. Adhesive bonding offers enhanced seam integrity, gap bridging or tolerance functions, galvanic separation, and improved fatigue performance, while spot welds serve as peel stoppers preventing catastrophic failure in the joints [2-4]. OEMs today use this technique in part of the body structures (steel-steel) to reduce mass and improve durability. However, to attach composite to steel, a novel concept of using a steel doubler was proposed [5]. It enabled the use of spot welding to the surrounding steel structure ensuring the compatibility with the existing OEM processes. Schematics shown in Figure 2 illustrate the concept of weld bonding to attach the composite underbody to a steel body-in-white structure. The concept is to bond the steel doubler plates to the floorpan in the joint areas. The composite assembly is then bonded to the surrounding steel structures and then spot welded. The adhesive would be cured in the subsequent bake during ELectrophoretic Priming Operation (ELPO). No additional fixtures are necessary during adhesive cure as spot welds provide the necessary fixturing.
Several modeling techniques are available today to assess the structural performance of the joint in a crash. Numerous studies on analytical and physical testing of the joints have been reported in the literature [2-4, 6-10]. However, all the available data and modeling methodologies are for metallic adherends, predominantly steel. In this study, quasi-static, dynamic and fatigue tests were conducted to generate physical data needed for modeling composite-steel weld bonded joint. Experimental results of quasi-static testing and fatigue testing are discussed in this paper while the analytical modeling and the correlation with the physical testing are reported in detail in a separate paper [11].

**Experimental**

**Materials and Fabrication of Test Specimen**

120mm wide super lap shear (SLS) joint test specimen was designed to assess the structural performance of the joint, including durability. Figure 3 shows the schematic of the weld bonded test specimen. Composite (3.3mm thick 7-ply quasi-quasi isotropic laminate; 63% glass by weight[12]) and steel (1.52mm DP 590 unless otherwise specified) coupons were cut to the specified dimensions using Mazak 5 axis 1500W laser equipment. Three weld buttons were stamped at once in a 120mm wide doubler
strip (1.2mm HSLA 350 unless otherwise specified). All composite and steel coupons and doublers were wiped with a dry cloth to remove dirt. 1-part crash toughened epoxy adhesive was applied in the joint area on composite and on the doubler strip. Coupons and doubler strip were then placed in a custom-made fixture in a specific order to create the joint as shown in Figure 3. The assembly was then clamped together and the doubler strip was spot welded through the holes in the composite to steel coupon using Matuschek DC mid frequency welder (180KVA). The specimens were baked at 180°C for 60 min to cure the adhesive. Tabs (2mm DP600) were then bonded to composite and steel coupons using 1-part structural epoxy adhesive. As shown in Figure 4, samples with three other types of joint configurations were also prepared using the procedure described above with necessary modifications.

Figure 3. Schematic of composite-steel super-lap shear weld bonded specimen
Figure 4. Various types of joint configurations tested in this study

Test Methods

Quasi-Static Tests

Three specimens of each type of joint configuration were quasi-statically tested with a MTS Sintech 30/G using a lap-shear test method as shown in Figure 5. Specimens were placed in the load frame in 50.8mm mechanical wedge grips and pulled in tension to failure. All sample sets were tested at room temperature, and several samples were tested at -40°C and 80°C. For at temperature testing, specimens were equilibrated to the test temperature for at least 15-20 minutes prior to testing. Load vs. cross-head displacement data was recorded.

Figure 5. Weld bonded specimen installed in ACC MTS servohydraulic test machine and environmental chamber
Fatigue Tests

Tension-tension fatigue tests were conducted with “super lap shear” test specimens shown in Figure 3. Adhesive only and weld bonded joint configurations were evaluated. S-N plots (maximum fatigue load vs cycles to failure) were generated at three test temperatures (-40°C, ambient, and 80°C). Limited testing was also conducted with both joint groups at 50°C. Figure 6 shows a weld bonded specimen installed in the ORNL MTS servohydraulic test machine and environmental chamber used during the course of this investigation. All fatigue tests were conducted in load control test mode with a stress ratio of $R = 0.1$ and a frequency of 3 Hz. Machine control software written by ORNL was used to record test machine displacement amplitude versus cycle during fatigue testing. Quasi-static tensile tests were conducted in the same test machine in order to determine the average baseline strength for the joint specimens with temperature. The quasi-static tensile tests were conducted at cross head speeds of 0.025 mm/s and the peak tensile loads for each group are included on the S-N plots (defined as one cycle-to-failure). The maximum fatigue loads were specified at lower levels than the average break load for the joint specimen configuration and were selected to encompass a range of loads at (typically) 2.2-4.4 kN (500-1,000 lb) increments in order to provide cycles-to-failure data that was at least greater than 100 cycles (on the high load end of the S-N plot) and greater than 1,000,000 cycles (on the low load end). Fatigue tests lasting greater than 1,000,000 cycles without detectable specimen damage or failure (defined as “run-out” condition) were terminated.

Figure 6. Weld bonded specimen installed in ORNL MTS servohydraulic test machine and environmental chamber

Results and Discussion

Quasi-Static Tests

120mm wide super-lap shear (SLS) coupons, shown in Figure 3, were subjected to quasi-static tension at different temperatures. Four types of joint configurations; adhesive only, weld only and weld + adhesive with one and two layers of adhesive
(shown in Figure 4) were tested at three temperatures (-40°C, ambient, and 80°C). Figure 7 shows the load-displacement plots at each test temperature, while Figure 8 shows the average peak loads at each test condition. Figure 9 shows the representative pictures of the different failure modes observed.

Figure 7. Load vs displacement charts for various types of composite-steel SLS specimens tested under quasi-static tensile loads at different temperatures.
Figure 8. Average peak loads for various types of composite-steel SLS specimens tested under quasi-static tensile loads at different temperatures

![Graph showing average peak loads for various types of composite-steel SLS specimens tested under quasi-static tensile loads at different temperatures.]

Figure 9. Representative pictures of various failure modes after the quasi-static tensile testing of various types of SLS specimens. a. Weld pulled through composite; b. Broken welds; c. Cohesive adhesive failure; d. Failure and delamination of composite in and near the joint; e. Composite failure in tab section and delamination near composite grip

![Images illustrating the various failure modes after quasi-static tensile testing of SLS specimens.]

As seen, the peak loads for weld only specimens were in the range of 11 kN to 17 kN. In all specimens, weld nuggets were intact and the buttons were pulled through composite resulting in shear-out of the composite substrate (Figure 9-a). This is not surprising considering that only composite surrounding three spot welds bear the applied load in absence of the adhesive layer between composite and steel. Since the weld nuggets were intact, the peak load numbers are influenced by the inplane composite strength. The peak loads for adhesive only specimens were in the range of 30kN to 42kN. The initial failure mode appeared to be the adhesive peel and/or the composite delamination.
at the edge of a joint (Figure 9-c-d). Separation of adherends appeared immediately after the initial failure, displaying the brittle nature of the adhesive failure. In some cases, failure occurred due to the delamination of composite in the tab section resulting in the composite failure in the grip area (Figure 9-e). For weld bonded samples with adhesive on both sides, the peak loads were in the range of 35kN to 40kN. The initial failure mode was similar to the adhesive only samples; however, the presence of welds delayed the separation after the initial failure. Maximum displacement for these samples was about 1.5 to 2 times greater than the adhesive only samples. The results confirm the role of weld spots as an adhesive peel stopper. For weld-bonded samples with only one layer of adhesive, the average peak load was in the range of 27kN – 37kN, slightly lower than the samples with two layers of adhesives. It should be noted that the spread in the peak loads was wider for these specimens. After the initial failure in the adhesive layer between composite and steel, all specimens failed via weld nuggets pulling through composite as in weld only samples (Figure 9-a). Since there was no adhesive layer between doubler and composite to share the applied load, it is not surprising that in-plane composite failure occurred at lower loads compared to specimens with two layers of adhesive.

Figure 7 also shows the affect of temperature on the performance of the joint. Adhesive only samples showed a slight decrease at hot and cold temperatures (31kN at -40°C and 34kN at 80°C vs. 40kN at 23°C). Weld bonded samples with only one layer of adhesive also showed inferior performance at -40°C and 80°C with more than 20% reduction in the average peak loads compared to peak load at 23°C. Weld bonded samples with two layers of adhesive, however, did not show any significant reduction in peak load at -40°C and showed only a slight decrease at 80°C (35kN vs. 40kN at 23°C).

**Effects of Doubler Thickness**

Specimens made of various combinations of steel adherend (1.5mm DP590 and 1.2mm HSLA 350) and doubler (0.7mm and 1.2mm HSLA 350) were evaluated at three temperatures (-40°C, 23°C, and 80°C). Figure 10 shows different combinations of steel adherends and doublers tested and corresponding average peak load data.
As expected, the average peak load decreased with the decrease in doubler thickness. The average peak load for specimens made with the 0.7 mm doubler (\_0.7D) was \(\sim 15\%\) lower than the average peak load for specimens made with the 1.2 mm doubler (\_1.2D). As seen in the previous studies, the initial failure mode appeared to be the adhesive peel and/or the composite delamination at the edge of a joint or the tabs. Additionally, specimens with the 0.7 mm doubler exhibited weld failures (Figure 9-b). Temperature did not show any significant effect on the average peak loads of weld bonded specimens, with the exception of specimens made with the 1.5 mm steel adherend and 1.2 mm doubler (1.5S\_1.2D). These specimens showed a slight decrease in the peak load at 80°C (35kN vs. 40kN at 23°C). Overall, the results indicate the potential for weight reduction by using thinner doubler strip than the proposed 1.2mm HSLA 350mm steel since the drop in the peak load was not very dramatic even with 0.7mm steel.

**Quasi-Static Strength Comparison**

The ACC and baseline average ORNL quasi-static SLS tensile strength data are compared to predicted peak load values in Figure 11 for the adhesive only and weld + adhesive test configurations for all three test temperatures. The details of the finite element analysis (FEA) methodology and test-analysis correlation are discussed in [11]. The results in Figure 11 indicate that baseline average ORNL peak loads at -40°C and ambient were comparable to the average peak loads from the tests done by ACC (discussed in earlier section). At 80°C, average ORNL peak loads were slightly lower than average ACC peak loads, however, it should be noted that the spread in the data was relatively high making the difference statistically insignificant. The results further indicate good agreement between the predicted FEA results measured peak loads. The predicted results generally fell within the range of measured peak loads which is
reasonable given the limited data used to characterize the analytical adhesive material model, and also the fact that composite delamination was not accounted for in the composite substrate [11].

Figure 11. Average peak loads for SLS specimens tested under quasi-static tensile loads at different temperatures and comparison to FEA results

Fatigue Tests

SLS test specimens with two types of joint configurations (adhesive only and weld bonded) were subjected to tension-tension fatigue tests. The tests were conducted at three test temperatures (-40°C, ambient, and 80°C). Limited testing was conducted at 50°C.

Figure 12 shows the selected fatigue displacement amplitude vs. cycle count plots for a weld bonded and adhesively bonded only specimen that were both tested at -40°C and at maximum fatigue loads of 21.1kN and 22.2kN respectively. The results show that the weld bonded specimen incurred some detectable damage (denoted by the sharp increase in displacement amplitude) after about 45,000 cycles but remained sufficiently intact to continue testing until 59,400 cycles. Failure of the adhesively bonded only specimen is more abrupt and with significantly fewer additional cycles recorded after initial damage is detected.

Observations from these fatigue tests indicate that both the weld bonded and adhesively bonded joint specimens exhibit visible bending in the joint due to the eccentricity of the applied loads.
Figure 13 are S-N data plots of fatigue test results for weld bonded and adhesively bonded only joint specimens. As seen, the joint life expectancy for both configurations was about 12-13kN at ambient, 13.5-15.5kN at -40°C and 3-4.5kN at 80°C (30%-35%, 40%-45% and 10%-15% of the ultimate peak loads at ambient, -40°C, and 80°C respectively). Close proximity of the glass transition temperature of adhesive to the test temperature explains the reduction in fatigue performance at 80°C. The data suggests that the overall fatigue performance of the weld bonded joint configuration is noticeably improved than that of the adhesively bonded only specimens, particularly at the higher fatigue loads, although the limited number of data points make statistical comparisons difficult. A virtue of the weld bonded joint design is that the failures are less catastrophic, i.e. the specimen remains more-or-less intact for longer periods even after its load bearing capability has been reduced. This is also true of the weld bonded specimens tested for quasi-static tensile properties. This feature is attributed to the spot welds which continue to hold the specimen together even after the composite adherend and/or adhesive has failed.

Under ambient, -40°C and 50°C test conditions, failures of both the weld bonded and adhesively bonded only joint specimens were typically observed within the composite adherend, and resembled an interlaminar composite shear failure between the composite plies. At 80°C, fatigue life for both joint types was reduced and debonding from either the steel or the composite adherends was observed.
Figure 13. Tension-tension fatigue results for weld bonded and adhesive only specimens tested at ambient temperature, 50°C, 80°C and -40°C

Photographs of typical fatigue failures for weld bonded and adhesively bonded only specimens with test temperature are provided respectively in Figures 14 and 15. The data and photos suggest that the strength of the adhesive is significantly reduced at the 80°C test temperature, altering the primary failure mechanisms for these specimens.
a) Ambient temperature
24.5 kN maximum fatigue load
Cycles to failure – 560

b) 50°C
22.2 kN maximum fatigue load
Cycles to failure – 3,989

c) 80°C
4.4 kN maximum fatigue load
Cycles to failure – 137,734

d) -40°C
15.6 kN maximum fatigue load;
Cycles to failure – 995,424

Figure 14. Fatigue failure results for adhesively bonded only specimens
a) Ambient temperature  
20.0 kN maximum fatigue load; Cycles to failure – 52,012

b) 80°C  
13.3kN maximum fatigue load; Cycles to failure – 5,644

c) -40°C  
28.9 kN maximum fatigue load; Cycles to failure – 3,876

**Figure 15.** Fatigue failure results for weld bonded

**Summary and Next Steps**

Custom designed super lap shear specimens were tested under quasi-static tensile load at different temperatures to generate the physical test data needed to determine the key modeling parameters. Fatigue tests were also conducted to assess the durability of the joint. Methodologies for analytical models are being developed using this data to predict the quasi-static temperature-dependent performance of weld bonded joints within vehicle level crash and durability models.
The physical test results confirmed the role of spot welds as peel stopper. The performance of the weld bonded joint subjected to quasi-static tensile loading was found to be robust within the tested temperature range. Several failure modes were observed depending on the test temperature. The initial failure mode appeared to be the adhesive peel and/or the composite adherend delamination at the edge of the joint/tabs. Adherends were separated immediately for adhesive only specimens while spot welds delayed the separation in weld bonded specimens. The results also indicated that thinner doubler could be used in the joint enabling additional weight reduction in a underbody assembly.

The overall fatigue performance of the weld bonded joint configuration was noticeably improved relative to the adhesively bonded only specimens, particularly at higher load levels. At 80°C, fatigue life for both joint types was reduced significantly.

In the next phase, SLS specimens with different joint configurations will be tested under torsional loads and dynamic tensile loads. Data obtained from these tests will be used to develop FEA models to assess the joint performance under various loading conditions within overall vehicle level crash models. Sub-component level testing will also be conducted to validate the methodologies developed.

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