E. Attachment Techniques for Heavy Truck Composite Chassis Members

Principal Investigator: Lynn B. Klett
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-6053
(865) 241-8112; fax: (865) 574-8257; e-mail: klettlb@ornl.gov

Principal Investigator: Darrell R. Herling
Pacific Northwest National Laboratory
P.O. Box 999, Richland, WA 99352-0999
(509) 375-6905; fax: (509) 375-4448; e-mail: darrell.herling@pnl.gov

Chief Scientist: James J. Eberhardt
(202) 586-9837; fax: (202) 587-2476; e-mail: James.Eberhardt@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

---

Contractors: Oak Ridge National Laboratory, Pacific Northwest National Laboratory
Contract Nos.: DE-AC05-00OR22725, DE-AC06-76RL01830

Objectives

- Overcome the technical issues associated with joining composite materials in heavy vehicles by developing technically robust and economically attractive joining techniques.
- Develop and validate one or more joint designs for a composite structural member attached to a metal member that satisfies the truck chassis structural requirements both economically and reliably.
- Solicit input from truck original equipment manufacturers (OEMs) and suppliers on the technical hurdles and needs associated with joining structural composite members in heavy vehicles. Use this information to guide the joint design and development activities.
- Publish information on the design, modeling, and testing methodologies that are developed to support the incorporation of composite materials into other chassis components.

Approach

- Collaborate with the National Composites Center (NCC) and its OEM partners to identify and address technical needs related to the manufacturing, joining, and implementation of a composite chassis component.
- Design attachment components and configurations in close coordination with the composite structural component development.
- Use modeling techniques to predict the performance of various joint designs, taking into account damage mechanisms and fatigue/life requirements.
- Characterize various composite materials and mechanical joint configurations through mechanical testing, considering variables such as hole size, hole fabrication method, bolt pre-load, inserts, combined loading, vibration, fatigue, and durability.
- Validate joint design for the composite structural member through shaker and track testing.

Accomplishments

- Conducted tension-tension, compression-compression and variable stress level fatigue testing of candidate 3-D glass reinforced composites.
- Ran static and fatigue tests on 3-D glass and hybrid reinforced composite/steel joints in lap shear (Mode I) and cross tension (Mode II).
- Tested adhesively bonded joints for comparison with bolted joints with Mode I and Mode II static and fatigue loading.
- Conducted bolt bearing tests to investigate the effects of variations in torque level which may result from creep of a composite material in a bolted joint.
- Conducted double lap shear static and fatigue tests to investigate changes in bolt pre-load resulting from through thickness creep of the composite and damage progression.
- Conducted finite element analysis (FEA) modeling, taking advantage of the progressive failure analysis available in GENOA, to evaluate the damage at bolt holes in composite material.
- Conducted FEA to evaluate the current steel to steel component and joint and compared alternative lightweighting designs.

Future Direction

- Continue bolt bearing and fatigue tests to investigate design modifications, molded-in holes, 3D reinforcement levels and acceptable hole clearance levels to minimize damage in the composite and improve the fatigue life of a composite-to-steel joint.
- Evaluate the impact of using adhesive bonding in combination with bolting, as well as the effects of environmental exposure and testing rate for the composite/steel Mode I and Mode II fatigue specimens.
- Continue FEA modeling with input from the composite and joint tests to further optimize and predict the performance of the composite/steel joint.
- Continue to work closely with the industrial team to develop the composite component and composite-to-steel joint design solutions to meet the demanding requirements of the heavy vehicle chassis environment.

Introduction

In May 2003, researchers at Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) began collaboration on a 4-year research effort focused on developing technically robust and economically attractive joining techniques to overcome technical issues associated with joining lightweight materials in heavy vehicles. This work is being performed concurrently with an industry program led by the NCC to develop and commercialize composite chassis components, which will require resolution of the joining challenges. The industry project serves as a "focal project" that provides real load and service data to this project and will potentially field-test and implement the technology developed in this project. The initial focus of research is development and validation of one or more joint designs for a composite structural member attached to a metal member that satisfy truck chassis structural requirements both economically and reliably. Broadening the effort to include other structural joints, including composite-to-composite joints, is anticipated. Durability shaker testing of the first prototype composite component and joint is planned for the first half of 2006.

Composite Material Testing

Tensile and Compressive Fatigue Comparison

Both the component independent baseline Extren® pultruded fiberglass material and a 3D reinforced vinyl ester material supplied by the NCC were tested in compressive and tensile fatigue. The fatigue tests were run with R = 0.1 at 70%, 50% and 30% of ultimate stress at a frequency of 5 Hz. Shorter length specimens were used for the compressive fatigue to prevent buckling. The results, shown in

Figure 1, indicate that the 3D reinforced composite performed better in compression-compression fatigue at lower stress levels compared to tension-tension fatigue. For the pultruded fiberglass, the performance is similar for both compressive and tensile fatigue with a few outliers. Note that the fatigue curves have been normalized to % of ultimate stress to account for the differences in the strengths of the two materials.

Variable Amplitude Fatigue

Components in a truck chassis undergo complex random variable amplitude fatigue loading during their service lifetime. Previous studies reported in the literature indicate that standard methods employed for variable amplitude fatigue life prediction can overestimate the actual experimentally measured life for fiber reinforced composite materials. The inaccuracy is due in part to the different failure mechanisms and property degradation when compared to metals.

One of the most commonly used damage laws is the Palmgren-Miner linear relationship which assumes that fatigue cycles at a specific load level always result in the same damage regardless of the loading history. The overall damage accumulation is determined as a ratio of the loading cycles to the failure cycles at each stress level.

In an attempt to characterize the variable amplitude fatigue behavior of the 3D reinforced glass/vinyl ester composite material, fatigue tests with block loading cycles at 2 different stress levels were conducted. Although there was a significant amount of scatter in the fatigue data, the deviation from the Palmgren-Miner's prediction was pronounced. Additionally, it seems that a low stress level applied prior to the high stress level is more damaging than when the high stress level is applied first.

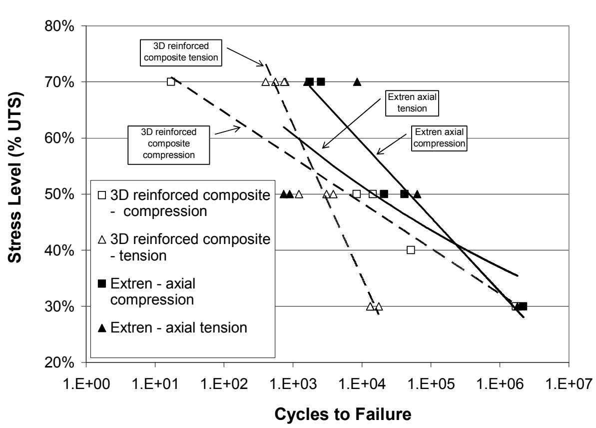

Figure 1. Comparison of tensile and compressive fatigue behavior for 3D reinforced vinyl ester composite and Extren® pultruded fiberglass.

The research team has been working closely with AlphaSTAR Corporation to integrate a damage model into GENOA that will take into account the deviation from the Palmgren-Miner prediction. The progressive failure analysis in GENOA may assist in developing an understanding of the damage development and evolution which may result in the different behavior based on loading sequence. The ultimate goal would be to have a predictive tool that could be used for a more realistic random amplitude fatigue spectrum.

3D Glass Reinforced Epoxy Resin

In order to improve the temperature limit of the composite material, the NCC has provided 3D reinforced epoxy specimens that were tested in tension and fatigue. These specimens were fabricated with the same 3D glass reinforcement that was used for the prior 3D glass/vinyl ester composite discussed in the 2004 annual report. The glass/epoxy specimens had similar average tensile strength and modulus values (402 MPa and 23.7 GPa) as well as comparable fatigue performance. This indicated that the tensile and fatigue properties are dominated by the reinforcing fibers and are not dramatically affected by changing the matrix material.

Loss of Bolt Pre-Load for Bolted Composite/Steel Joints

An important component of a composite/steel bolted joint design is the bolt preload at assembly, which is selected to achieve the desired clamp load for proper function of the joint throughout the service life of the assembly. A minimum clamping force is required to overcome vibration-induced loosening, joint separation, slippage, fatigue, leakage and other similar failures. The maximum clamp force should be below a threshold value that would cause bolt yielding, joint crushing, stress cracking, premature fatigue failure, or other related service failures.

The low through-thickness properties typical of most composite architectures suggest that bolted composite assemblies will experience a loss of preload over time due to the relaxation or creep of the softer composite material.

As discussed in the last reporting period, a testing methodology has been developed to study the effects of bolt pre-load with composite to steel joints.

Washer Load Cell vs. Bolt Load Cell

Indirect measurements of bolt pre-load have been made with several types of washer load cells and a strain gaged bolt. To compare the different load cells, the bolt pre-load was monitored for a steel to steel bolted specimen with both a washer load cell and the bolt load cell. After torquing, the pre-load did not change significantly with time for the washer load cell, which would be expected for steel plates. However, the bolt load cell indicated the pre-load continued to drop to 86% of the initial bolt preload after 70 hours. Although the bolt load cell would be desirable for use in static and fatigue joint tests from a simplicity standpoint, it is unsuitable for monitoring bolt preload due to this drift or creep of the load cell itself. An Interface washer load cell, Model LW2550-30K, was chosen for use for the static and fatigue joint testing to monitor the loss of bolt preload.

Loss of Pre-Load in Huck Bolted Composite to Steel Joint

Several composite and steel plates were Huck bolted together to evaluate the loss of bolt pre-load at the high torque levels seen in this common joining technique for chassis components. A 9.53 mm thick hybrid glass/carbon reinforced composite as well as a 6.35 mm thick Extren® composite were used with 12.7 mm thick steel and 12.7 mm bolts. After 500 hours, the thicker hybrid composite/steel assembly retained slightly more of the initial preload compared to the 6.35 mm Extren®/steel assembly (Figure 2). As expected, the composite/steel assemblies have significantly more loss of preload than the corresponding steel/steel assembly. Note that the Huck bolt preload was simulated by a torqued bolt for the steel/steel assembly due to restrictions on the length of available Huck bolts.

Static and Fatigue Double Lap Shear Joint Testing

Initial testing to monitor the loss of bolt preload during static and fatigue loading has focused on the double lap shear tensile test geometry in which a composite specimen was bolted between two steel plates with a Grade 8 12.7 mm bolt (Figure 3).

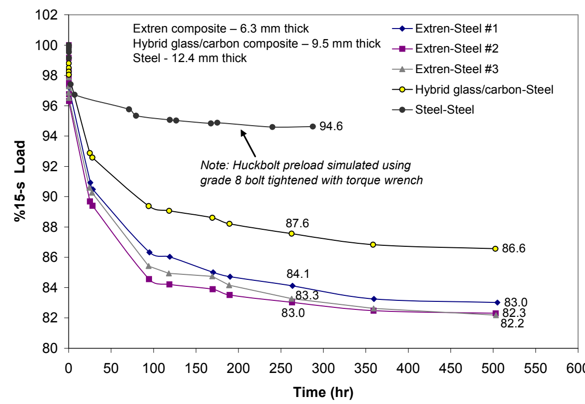

Figure 2. Normalized loss of preload for Huck bolted composite to steel assemblies.

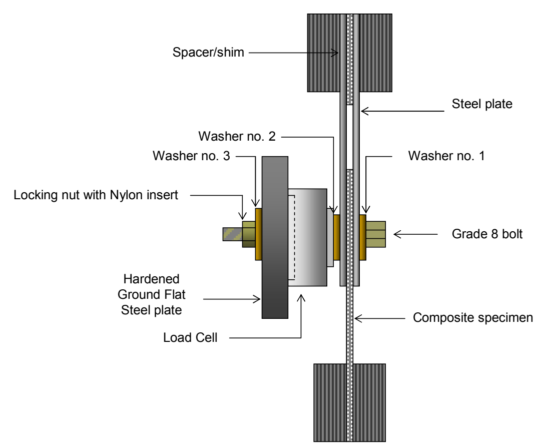

Figure 3. Test schematic for the double lap shear tests for composite/steel assemblies.

Joint testing has been conducted with specimens of both 3.17 mm thick Extren® pultruded fiberglass and 2.54 mm thick 3D glass reinforced vinyl ester composite material provided by the NCC. For these tests, the torque level and corresponding bolt preload were varied. The maximum fatigue stress was established as a percentage of the ultimate tensile strength of comparably prepared specimens. The fatigue tests were run with a stress cycle R factor of 0.1 and a frequency of 5 Hz.

In static tensile tests, the higher bolt preloads increase the ultimate strength of the assembly (Figure 4). Failure modes shift from a bearing type failure at the lowest preloads, typified by local composite crushing at the washer perimeter, to composite material tensile failure initiating from the perimeter of the hole. There was a steady reduction in bolt preload during the static tests, which was up to 15% at the initial load peak for the specimens with the highest bolt preload with a continuing decrease up to failure. At very low preloads (finger-tight) the load cell indicated a slight increase in bolt load during loading.

Double lap shear composite/steel assemblies withstand reasonably high fatigue stress levels without failure. For instance, an Extren®/steel double lap shear specimen achieved runout with over 3 million cycles at a fatigue level of 50% of the ultimate failure stress for a torque level of 41 Nm. The higher torque levels drive the fatigue failure location away from the hole and into the bulk composite.

For specimens assembled with higher bolt torques, there is a steady decrease in the bolt preload with additional fatigue cycles up to failure (Figure 5). This occurs both for specimens with and without failure at the hole and is partly attributed to composite relaxation. A number of specimens failed with 85-95% of the original bolt preload, regardless of the original torque level. There has been no indication thus far of a change in the monitored bolt preload which would indicate imminent failure.

For specimens prepared with low bolt preload (finger-tightened), the bolt preload increased with number of fatigue cycles until failure. This increase may be due to a localized material deformation at the hole perimeter resulting in increased compression of the load cell.

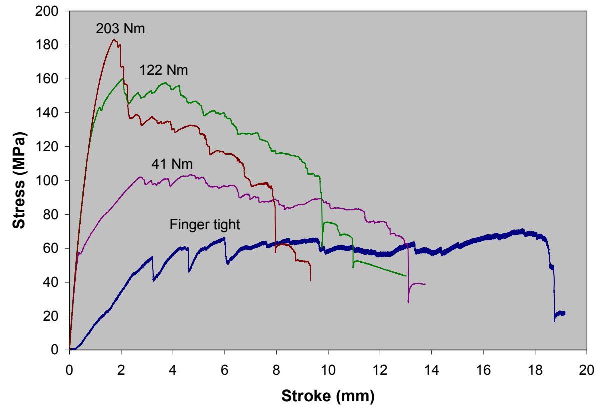

Figure 4. Tensile stress vs. stroke curves for composite/steel double lap shear assemblies with varying bolt torque levels.

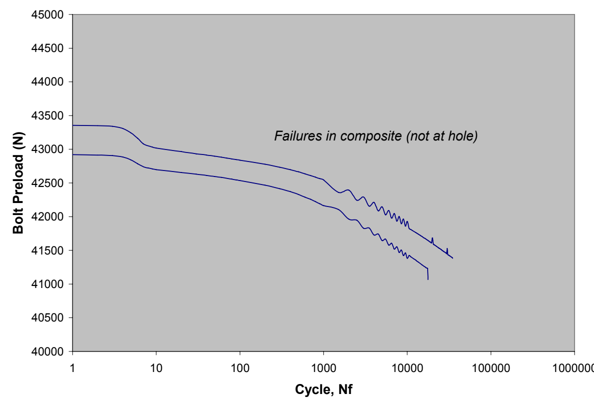

Figure 5. Bolt preload vs. fatigue cycle number for Extren®/steel double lap shear joint with initial bolt torque of 122 Nm.

Experiments have demonstrated that the fatigue life of double lap shear specimens assembled with a minimal bolt preload can be significantly enhanced by applying an epoxy adhesive between the composite and steel plates prior to bolting. Figure 6 shows that the fatigue life for the joint with a combination of bolt and adhesive increases from 10,000 to over 1 million cycles for both the Extren® and the 3D reinforced composite materials. Additionally, the joints which included the adhesive tolerated increased stress amplitudes. As expected, the adhesive facilitates the transfer of stresses away from the hole perimeter and lowers the stress concentration factor for the joints with low clamp forces.

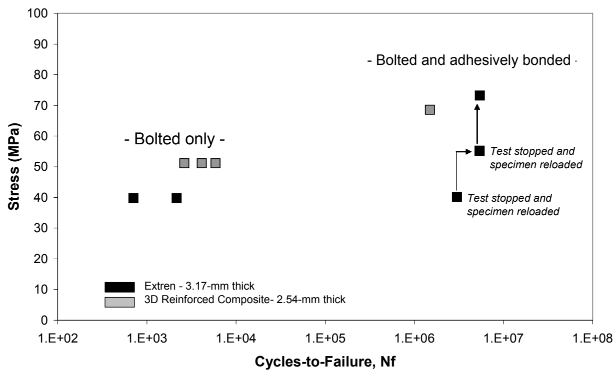

Figure 6. Fatigue data for finger tight double lap shear composite/steel bolted joints with and without adhesive.

<u>3D Reinforced Composite-to-Steel Joint Evaluation</u>

Joint Strength Characterization with Thick Composite Materials

In evaluating composite/steel joint assemblies, 3D woven carbon/glass hybrid composites and 3D glass-polymer composites were investigated. The hybrid composite consisted of two layers of carbon (each 1.02 mm thick) and three layers of glass (each 2.5 mm thick) for a total composite thickness of 9.53 mm. The glass composite consisted of four layers of glass for a total composite thickness of 9.53 mm also. Lap shear specimens of both composite types and 6.35 mm thick Grade 6 steel were assembled with a Grade 8 bolt.

For the hybrid composite/steel joints, the bolt was torqued to 393 N-m. For the glass composite/ steel joints, the bolt was torqued to 325 N-m to simulate joints assembled with a Huck bolt. For the hybrid composite/steel joints, the joints were assembled with the hybrid composite on top and the glass layer of the composite at the faying surface of the joint.

Due to limited material, only two static strength tests were conducted for each joint assembly configuration. The average static strength of the hybrid/steel jointed assemblies was 61.5 kN (about one-half of the strength of the baseline steel/steel Huck bolted design discussed during the last reporting period) and the average static strength of the glass/steel assemblies was 60.3 kN. These peak loads served as a guide for the fatigue strength tests.

Effect of Structural Adhesive

Experiments were performed to investigate the effect of structural adhesive on the joint performance of composite/steel assemblies. 3D-reinforced glass composite (2.54 mm thick) and 1008 steel (~1.4 mm thick) lap shear joints were assembled with Betamate 4601 and PL731 SIA adhesive to understand the fatigue behavior and failure mechanisms of joining composite to steel with adhesive only.

Again, due to limited material, two static tests were conducted for each configuration to serve as a guide for the fatigue tests. The average static strength of the assembled joints was 15.6 kN using the Betamate adhesive and 9.7 kN for assemblies using the SIA adhesive.

At 10^6 cycles, the fatigue strength of the joints assembled with Betamate adhesive is approximately 2 times greater than the joints assembled with PL731 SIA adhesive. An adhesive failure was observed in joints assembled with the SIA adhesive. Failure occurred at the adhesive-steel substrate interface where the adhesive separated from the steel. This is typically indicative of a bonding or adhesion problem. However, joints assembled with the Betamate adhesive, failed cohesively, illustrating the bond with the substrate was adequate, but the strength of the adhesive may need to be enhanced.

At 10^6 cycles, the fatigue strength of the joints assembled with the Betamate adhesive was approximately 30% higher than the same joint assembled with a bolt. These results illustrate the potential of utilizing adhesives to join composite and steel substrates.

Joint Strength Characterization with Steel Inserts

In order to mitigate the loss of bolt preload due to the through thickness properties of the composite material, cylindrical and tapered steel inserts have been evaluated experimentally.

Initially, a steel cylindrical insert with a 15.9 mm inner diameter and a 25.4 mm outer diameter and an equivalent 30^o angular (tapered) insert with a 15.9 mm inner diameter and a 35.3 mm (top) and

25.4 mm (bottom) outer diameter were placed in a 9.5 mm thick, 3D reinforced glass composite. Preliminary composite/steel lap shear specimens were assembled with the metal inserts adhesively bonded to the composite substrate.

The average joint strength for the composite/steel lap shear assemblies with an insert is approximately 20% less than the assemblies without inserts. Premature interfacial failure between the steel insert and the composite material always preceded the final composite failure.

The fatigue performance of the joints with inserts was also evaluated and compared to the same joint configuration without inserts. At 10^6 cycles, the fatigue strength of the joints assembled with inserts is also approximately 20% less than the comparable joint without an insert. As for the static tests, interfacial bond failure was the dominant failure mode under fatigue loading (Figure 7). The conclusion is that one can not assume that a perfect bond exists between the metal insert and composite panel. In this geometry, the metal insert does reduce the creep in the joint, but reduces the overall strength because of the increased size of the hole in the composite material. Therefore, unless the geometry of the composite or the bolt pattern can change for a given joint design, the steel inserts have a negative impact on the joint strength.

Joint Strength Characterization with Steel Plate Reinforcements

Next, the concept of a steel plate sleeve was developed to reduce the loss of pre-load due to creep and improve the fatigue performance of a composite/steel joint assembly. 76.2 mm x 61.0 mm x 1.52 mm steel plates were adhesively bonded to both sides of the composite substrate for the lap shear joint (Figure 8). Both static and fatigue strength tests were conducted on lap shear specimens. The static joint strength increased approximately 25% and the fatigue strength increased approximately 23% at 10^6 cycles compared to the equivalent joint without inserts. Figure 9 illustrates the fatigue test results for several of the joint designs investigated in this study in comparison to the baseline steel to steel joint assembly.

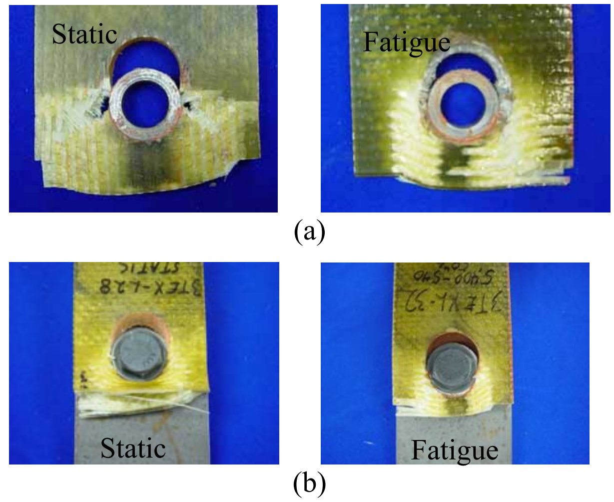

Figure 7. Typical joint static and fatigue failure mode observed for (a) the cylindrical steel insert and (b) the tapered steel insert composite/steel lap assemblies.

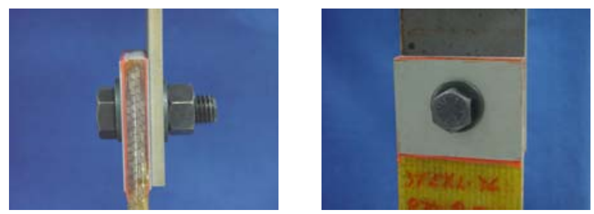

Figure 8. The 3D composite/steel lap shear joint assembly with adhesively bonded steel plates.

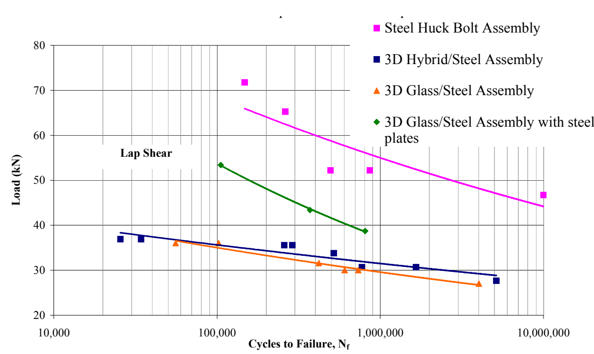

Figure 9. Fatigue strength test results of 3D-reinforced composite/steel lap shear assemblies with various design modifications compared to the baseline steel/steel assembly.

Modeling

Different modeling techniques are being evaluated and developed to assist in the performance prediction of various joint designs taking into account damage mechanisms and fatigue and life requirements. Having reliable models will allow for more efficient design optimization of structural composite joints to minimize and focus the expensive and time consuming mechanical testing.

Washer Size Effects

Creep in the composite due to the initial bolt torque was evaluated for two different washer sizes. Material creep was assumed in the following form:

$$\varepsilon^{cr} = \alpha\sigma t^{n},$$

where material coefficients $\alpha = 1.8\text{x}10^{-8}$ and $n = 0.19$ were estimated by curve fitting data from a through thickness compression test. Washers of two different sizes from previous experiments were modeled. The smaller washer caused larger stresses in the composite plate during testing, thus a larger magnitude of loss of pre-load was expected. This analysis assumes homogenized material properties with an isotropic creep model (linearly dependent on the stress level) for the composite and linear elastic behavior for the steel. The effect of contact was not considered. In order to accurately model the actual experiments, these assumptions need to be reexamined. Despite these simplifying assumptions, the analysis predicted that the loss of preload would be approximately 10% lower for the larger washer configuration after 24 hours.

Insert Evaluation

Building upon the insert analysis reported on during the last reporting period, further traditional finite element analysis was conducted to determine the effect of both the cylindrical and tapered inserts at the bolt hole in the composite during composite/steel lap shear testing. First, the bolt shank was pulled with controlled displacement to simulate the bolt pre-tensioning. As expected, the model predicts a higher bolt load for the assembly with the steel inserts. Next, the bolt load was held for 25 hours to determine the creep behavior. The model predicts that the inserts help to minimize the creep with little difference between the two insert geometries.

At the last step of the analysis, the steel plate was fixed and the top composite plate was pulled. Assuming no interfacial failure between the insert and composite, it was predicted that joints with inserts would have higher strengths compared to the joint without inserts. However, the experimental lap shear testing results show that the inserts actually cause a significant decrease in the joint strength due to the failure of the bond between the insert and the composite. In this model, perfect contact was assumed between the insert and the composite.

GENOA Progressive Failure Analysis of the Joint with Steel Inserts

AlphaSTAR engineers have assisted in enabling GENOA to run the analyses with ABAQUS as a solver. This new capability allows for the contact algorithm in ABAQUS to be used with GENOA's multiscale progressive failure analysis. The bolt assembly model has been imported into GENOA to predict the damage in the composite around the bolt hole.

Damage due to clamping loads was evaluated for both the cylindrical and tapered inserts. A calibrated material model for 8 mm thick 3-D glass reinforced material was used for the composite plate. The model predicted that damage would occur at the insert-composite interface at 10 times the normal assembly clamping load with five active damage criteria indicating that the existing assembly procedure should not damage the composite.

A two step model simulating the pre-clamp and subsequent loading was developed which included the adhesive layer between the composite and the insert. This model predicts that damage occurs simultaneously in all the layers of the composite and in the adhesive at approximately 26 KN for lap shear loading. At this point, the load carrying capability of the joint is significantly reduced. The threshold for damage for the tapered insert is 32 KN with failure in the composite layer in contact with the steel plate. As shown in the earlier insert analysis, the tapered inset performs better than the cylindrical insert.

Structural Component Sub-Assembly Model

Component level elasto-plastic finite element analyses have been performed to study the detailed loading path and possible failure location/modes of the actual steel to steel joint sub-assembly with displacement controlled loading conditions provided by the OEM.

From this model, the predicted contour of Von Mises stress for the loading conditions shows static and overloading failure near the bolt holes. This suggests that the specified loading conditions are too severe for this sub-assembly.

Next, the components of the steel to steel joint subassembly were replaced with lighter weight composite components with the same topology as the steel components and material properties obtained from the candidate 3D composite. Under the same displacement controlled loading conditions, the FEA model predicts highest stresses at the edges of the bolt holes. However, the magnitude of the stresses is low indicating that the component and joint has become more compliant with the incorporation of the composite. Cast magnesium is being evaluated to incorporate into the design to enhance the stiffness without adding significant weight.

To further assess the effects of light-weighting with composites at the sub assembly level on the system vibration response, modal analyses of the sub-assembly have been performed under free boundary conditions. The predicted natural frequency and vibrational mode for Mode 7 corresponds to the vibrational frequency mode that is of most relevance for the normal heavy truck operating conditions. The natural frequency of the existing design is higher than the lighter weight designs incorporating composites and/or magnesium. Further design modifications are needed to enhance the stiffness of the system to more closely match the performance of the all steel sub-assembly.

Acknowledgements

The principal investigators would like to acknowledge the valuable contributions of other members of the research team, including Barbara Frame, Vlastimil Kunc and Tom Battiste at ORNL and Xin Sun, Elizabeth Stephens and Siva Pilli at PNNL.

Summary

ORNL and PNNL are collaborating on a 4 year research effort focused on the development of technically robust and economically attractive joining techniques to overcome the technical issues associated with joining composite chassis components in heavy vehicles. This work is being performed concurrently with an industry program to develop and commercialize composite chassis components, which will require resolution of the joining challenges. This report discusses the FY 2005 research activities.

Fatigue testing, including tension, compression and variable amplitude, has been conducted on the baseline component independent pultruded material as well as several 3D glass reinforced composites. Loss of bolt pre-load due to through the thickness creep of the composite has been monitored for composite/steel joints under static and fatigue loading. Mode I and Mode II joint fatigue tests have been done to evaluate the design modifications in composite thickness, steel inserts, steel reinforcing plates and adhesives. Modeling activities have focused on developing techniques to evaluate through thickness creep for joints with different washer and steel insert designs. Damage at the bolt holes has been evaluated taking advantage of the progressive failure analysis available in GENOA coupled with the contact algorithm in ABAQUS as the solver.