H. Attachment Techniques for Heavy Truck Composite Chassis Members

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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 satisfy 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 for joining structural composite members in heavy vehicles, and 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 Delphi and the National Composites Center (NCC) and their 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, spacing, location, hole fabrication method, bolt preload, inserts, combined loading, vibration, fatigue, and durability.
- Validate joint design for the composite structural member through track testing.

Accomplishments

- Participated in the Value Added Value Engineering workshop with Delphi and its industrial partners to identify design concepts and technical barriers.
- Conducted a literature survey on attachment technologies for composites with a focus on solutions for hybrid joints, including the effects of three-dimensional (3D) reinforcement, bolted joints, and fatigue testing.
- Reviewed the modeling and testing capabilities at Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Delphi in order to most effectively distribute tasks in testing, design, and analysis while avoiding duplication of efforts.
- Acquired equipment to upgrade a 220-kip testing machine (actuator, grip supply, etc.) to allow for structural component and joint testing.
- Established a test matrix for coupon testing for baseline steel-steel joints, as well as for the steel-composite system of interest.
- Selected commercially available, component-independent material and identified appropriate mechanical tests to investigate levels of damage resulting from various hole fabrication methods and bolt preload levels as well as ways to mitigate the negative effects of the damage.

Future Direction

- Conduct static and fatigue tests of composite specimens with holes fabricated by various methods such as drilling, water jet cutting, drilling undersized components, and reaming. Investigate design modifications, such as inserts, molded-in holes, and 3D reinforcement to minimize the damage in the composite and improve the fatigue life of the joint.
- Evaluate steel-steel joints through lap shear and cross-tension testing to establish fatigue performance of the existing configuration, which will be used to design and optimize the composite-steel joint.
- Utilize finite element modeling with input from the composite and joint tests to optimize and predict the performance of the composite-steel joint.
- Continue discussions with various OEMs to gain an understanding of the successes and failures associated with previous research efforts to incorporate composite materials into chassis structures.

Introduction

Currently, polymer matrix composites are used for several nonstructural components for heavy vehicles, including hoods and roof fairings. In these cases, relatively inexpensive materials, such as sheet molding compound (SMC) with short, randomly oriented reinforcing fibers, are used to reduce weight, improve aerodynamics, and reduce part count. Potential exists for additional weight reduction in the chassis, which accounts for approximately 12% of the weight of a raised-roof sleeper, by replacing heavy steel structural members (Figure 1) with fiber-reinforced composites. Likely, these structural components will be made with more expensive composites reinforced with

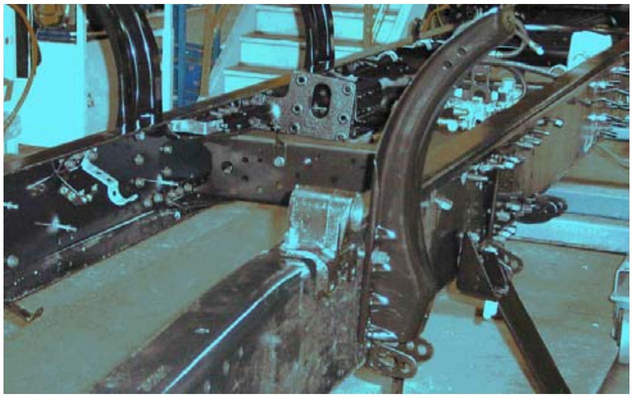

Figure 1. Representative chassis assembly for a Class 8 truck showing a variety of steel members bolted together.

oriented long fibers. The financial incentives for weight reduction in heavy vehicles, which will offset some increase in materials cost, include improved fuel efficiency, increased payload, and reduced truck traffic volume.

In May 2003, ORNL and PNNL began collaboration on a four-year research effort focused on developing technically robust and economically attractive joining techniques to overcome the technical issues associated with joining lightweight materials in heavy vehicles. This work is being performed concurrently with an industry program, led by Delphi, to develop and commercialize composite chassis components, which will require resolution of the joining challenges. 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 the truck chassis structural requirements both economically and reliably. Broadening the effort to include other structural joints, including composite-to-composite joints, is anticipated. Durability track testing of the first prototype composite component and joint is planned for the last half of 2005.

Major Technical Issues

Economics is one of the main hurdles for developing successful composite structural members and joining technologies for a heavy vehicle chassis. Attachment solutions have been developed and are fairly well understood for aerospace applications, but both the composite and joint materials are high performance and expensive. For the heavy vehicle industry, only a modest cost premium can be justified based on weight savings. Therefore, the joint design must have an acceptable cost, which includes costs for raw material, fabrication, tooling, assembly, repair, and replacement costs. Additionally, the chassis structural components will have a life expectancy of a million miles, which is many times that of automotive components.

Mechanical fasteners, such as bolts, have several advantages for structural joints, including ease of assembly and disassembly and the existence of well established design guidelines. However, these guidelines were developed primarily for metals and are not directly applicable to polymer matrix composites.

A major concern for composite materials is stress risers due to the presence of holes through the composite thickness. Holes can have a detrimental effect on strength, stiffness, and reliability by disrupting the fiber load path. If the composite and joint are not designed properly, damage and failure can occur as a result of creep or fatigue. Introduction of the holes through drilling, stamping, or piercing can also cause differing amounts of damage in the composite, which may result in delamination and crack initiation sites. This damage can also expose the fibers to the harsh environment of the roadway and lead to degradation of the composite member. Although some preliminary research has been done, the issue of holes in thick composites is not well understood.

Adhesive bonding is attractive for use with composite materials because of the continuous connection the bond line creates. This bond line distributes loads over a large area, thereby reducing stresses at the holes. The proper use of adhesives can also improve fatigue resistance by damping vibrations while allowing for reduced joint weight. However, several drawbacks are present with the use of adhesives: difficult disassembly without destroying the substrate, potential degradation due to environmental factors, difficulty in inspection to ensure adequate bonding, and difficulty with surface treatment requirements. Additionally, the joint must be properly designed so that the adhesive is loaded primarily in shear, tension and/or compression, while avoiding peeling and cleaving forces.

With proper design, continuous-fiber reinforced, as well as short-fiber reinforced, composite materials can be highly fatigue resistant, even under high load. This includes both carbon and glass-reinforced composites. Additionally, 2D and 3D composite structures can be reasonably damage tolerant because of their ability to distribute stresses around damage zones. Typically, in a cross-ply laminate or a braided or woven fabric composite under fatigue loading, a slow accumulation of damage occurs which eventually leads to failure. Also, in flexural fatigue, the stress state is complex and not easy to model with an S/N curve. A significant technical hurdle is the inability to efficiently model damage accumulation and fatigue resistance of such 2D and 3D composite structures and predict performance with classical laminate theory.

Both selection of the composite material and the composite fabrication method can have a great impact on the tolerance of the material to holes and fatigue. The variety of choices of fiber and matrix materials, fiber reinforcement configurations, and processing methods leads to the high degree to which these composite materials can be tailored for specific applications; however, it also contributes to the difficulty in designing for structural applications. There is neither a comprehensive database of material properties nor a complete understanding of material behavior under different loading conditions with different stress risers. The material and processing variables also make composite materials difficult to model numerically.

ORNL researchers have extensive experience in adhesive bonding technology for and durability testing of automotive composites, and they are currently investigating the performance and durability prediction of hybrid joints (riveted and adhesively bonded) for attachment of automotive composites to metals. Where appropriate, the design and testing methodologies and lessons learned from these research efforts will be applied to this project.

Damage Caused by Hole Fabrication and Bolt Preloading

The initial joint design will likely include mechanical fasteners requiring holes in the composite member. In order to gain an understanding of the effect of hole-drilling method on the performance of the composite materials, a testing matrix has been developed for a commercially available pultruded fiberglass composite. These tests will be component independent, and the results will serve as a baseline for further testing of composites with 3D reinforcement and with design modifications to improve the performance at the holes such as the use of large washers to distribute the load, inserts, adhesive bonding, etc. The pultruded fiberglass composite was selected for these baseline tests because of the good availability of material and relatively low cost. It is anticipated that the results of the tests will translate to long fiber-reinforced materials manufactured using other fabrication methods.

The test coupons will have a thickness of 3.2 mm (1/8 in.) with a hole size of 12.7 mm (1/2 in.). Open hole tension and fatigue tests will be conducted on coupons with holes fabricated by different methods that may include water jet cutting, drilling undersized and reaming to final dimension, diamond hole saw machining, and traditional drilling. PNNL has nondestructive evaluation capabilities for quantifying the damage in materials associated with processes such as hole drilling, and will examine the test specimens prior to and after the test to compare the levels of damage associated with each hole fabrication method and the mechanical loading. A preferred hole fabrication method will be chosen, with input from the industrial team, based on the test results and consideration of the costs and complexity of the fabrication method. The selected hole fabrication method will be used for the remainder of the coupon and component tests.

In order to determine the effects of the level of bolt preloading on the mechanical properties of the composite materials, bearing tensile and fatigue tests will be conducted on the pultruded fiberglass composites. Two levels of preload will be used for torqued bolts, and one level of preload using huck bolts. It is anticipated that the huck bolts will yield a more consistent preload level. Typically, preload levels for torqued bolts have a higher degree of scatter. The next step will be to include design modifications, such as inserts, post-hole treatement (i.e., resin wicking), molded-in holes, and 3D reinforcement of the composite, in an attempt to minimize the damage in the composite (see Figure 2) and improve the fatigue performance of the resulting composite-metal joint.

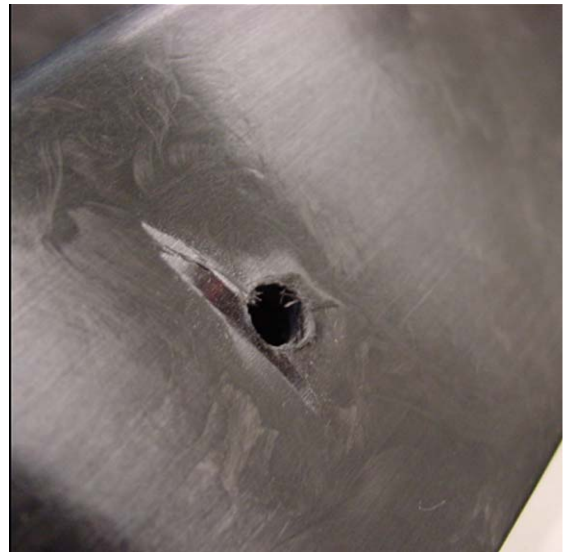

Figure 2. Damage in backside of composite from standard metal drill bit in drill press with thin steel backing plate.

Mode I and II Joint Testing

In previous work at PNNL, different joining technologies for dissimilar metal assemblies were developed and evaluated. One of the project goals was to develop a complementary experimental and numerical approach that would result in a more thorough understanding of the effects of different joining methods on vehicle structural integrity and long-term performance. This previous work provides knowledge regarding the joining of dissimilar materials and performance characterization of these joints.

To be consistent with existing performance testing methods of steel joints, the experimental work in this investigation will consist of lap-shear and cross-tension specimen designs (Figures 3 and 4) for one-directional loading conditions. Uni-directional tension tests are performed to characterize the joint strength of the bolted joints.

Tension-tension cyclic fatigue tests with a stress ratio of 0.1 are performed to characterize the fatigue behavior of the joints. The same fixtures and assemblies used in the static tests are used in the fatigue tests. The cyclic fatigue tests are conducted in load control with constant amplitude until failure or a run-out criterion of 5,000,000 cycles is reached. Failure is defined as total separation or fracture of the specimen into two parts. Specimens are tested at varying load levels to evenly distribute the failures between 10,000 cycles and run-out. A minimum of 10 fatigue tests will be performed for each coupon configuration. Tests are conducted at room temperature with a test frequency of approximately 20 Hz and with a sine

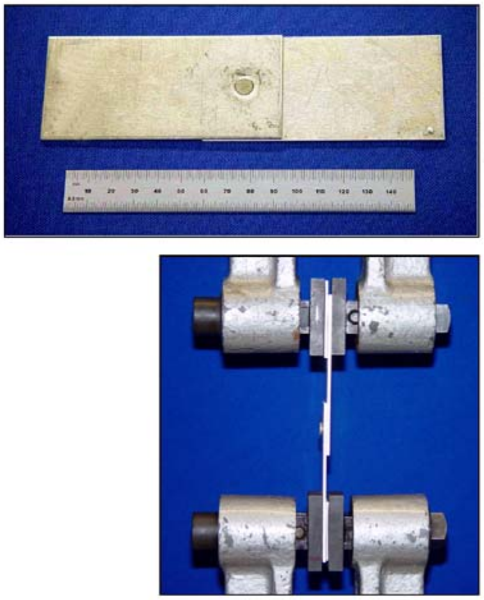
(a)
(b)

Figure 3. Fixture for static and fatigue testing: (a) lap shear specimen, (b) lap shear assembly.

waveform. The fatigue tests results are plotted in the form of *S-N* curves.

A combined experimental/analytical approach will be used for the hybrid joint development. First, the experimental methods described above will establish the fatigue behavior targets for the current steel-steel joint configurations based on the existing design. The baseline testing results will then be converted to a single fatigue master curve for the joining method using equivalent stress intensity factor vs. life or structural stress vs. life approach. This master curve will be used in the subsequent design and evaluation of hybrid composite-steel joints.

After the composite component design is identified, composite-steel joint coupons will be fabricated for hybrid joint master curve generation. Force components from the system finite element analysis will then be used to predict the expected life of the joint subjected to the specified global loading

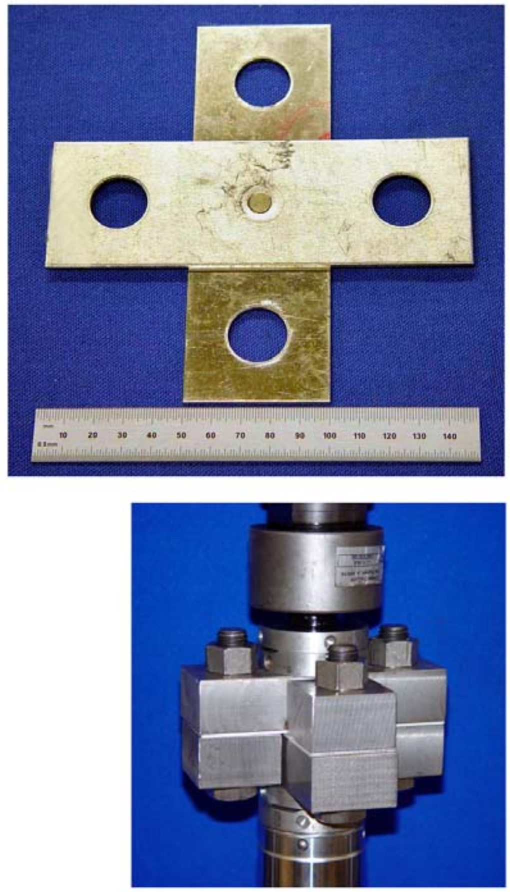
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Figure 4. Static and fatigue testing (a) cross tension specimen and (b) cross tension assembly fixture.

conditions. Several iterations of this process are envisioned to improve the fatigue life of the joints so that the final joint design meets the desired cycle value or percentage of the baseline steel joint value.

Modeling Tools

The composite member that will be prototyped initially is a replacement for an existing metal component and bolted joint, which has been characterized for loads and stress distributions. The finite element method (FEM) will be used for the design of the structural member and the joint, taking into account the geometry, fastening methods, and hole size and spacing. Existing commercial solvers can be applied in this initial stage of design. Three such codes that are currently used by the project partners include NASTRAN (one of the first available codes and considered to be the industry standard), ABAQUS, and Genesis. The goal will be to design a joint that effectively spreads the load over a large area.

In addition to these well established codes, Genoa, a package developed specifically for composite material analyses, may be used. This software uses an iterative process to solve finite element problems on the structural part level and on the microscopic fiber-matrix level. Genoa offers unique damage and fatigue life prediction capabilities for composite materials. Although the code has been released to the public only recently, it has an impressive record in the aerospace industry. If Genoa is adopted for this project, it will be the first use of this code for non-aerospace application.

In addition to these tools, software previously developed for automotive composite projects at ORNL or PNNL might be used in later stages of the project for detailed analysis of microscopic damage in the composite part. For modeling fiber loading and damage in composite material system at the macroscopic scale, a continuum mechanics approach can be adopted. In this usually phenomenological approach, the actual damage and deformation mechanisms are ignored and just their effect on the overall response is accounted for through one or more variables, called damage parameters. Another option is to use a micromechanical approach to model the development of microcracks in the matrix, fibers, and fiber-matrix interface.

PNNL has developed a method of linking these two approaches to more accurately predict composite performance for complex situations such as damage propagation in hybrid polymer composites. As necessary, this modeling methodology will be applied to the composite joint design, especially as it relates to predicting changes in load distribution around bolt holes due to composite damage (mechanical or environmental) and hole production methods.

Modeling Approach

A submodeling technique is planned for the design of the composite structural component and joint. First, a system model will be evaluated and divided into subsystems, which will be analyzed in greater detail. If necessary, the model can be further subdivided. Specifically, the system model will consist of the entire truck chassis. The relevant subsystem, in terms of joining, is the single joint assembly of the composite and steel members. If needed, the joint at a single fastener can be modeled as a subsystem of the joint assembly. This approach allows separation of the structural member design task from the joining task, and the modeling effort can be accelerated by processing smaller models.

As a first step, the structural member design team will use existing system models from the industrial partners as well as newly developed models to design a replacement of the existing steel component with an equivalent composite counterpart. The goal will be to match the stiffness and strength of the steel part without significantly changing the footprint of the existing joint. The bolts in the joint will be modeled initially as rigid links, yielding approximate loads in the bolts. The bolt loads combined with information about stress and strain fields will be useful in the joint design. The initial composite design will most likely be unacceptable to meet the cost and weight reduction goals. However, it will provide a baseline for subsequent design iterations in this project.

As a result of the hole-fabrication and bolt preload testing, the relationship between damage in the composite material and fatigue life will be established. The finite element analysis results from the system model will indicate the clamping forces expected in the joint. Acceptable levels for the clamping force and the corresponding damage in the composite material will guide redesign efforts.