JOINING COMPOSITE CHASSIS COMPONENTS ON HEAVY TRUCKS

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Abstract

Class 8 trucks offer substantial opportunities for weight reduction with cost incentives resulting from increased payload and improved fuel efficiency. The chassis, suspension, drive train, and wheels contribute to approximately 40% of the truck weight and have components that are excellent candidates, in terms of material performance requirements, for replacement with low-density structural composite materials. However, actual or perceived deficiencies in joint reliability have, up to now, limited the use of polymer composites in this application.

Researchers at Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) have begun a project to overcome the major technical issues associated with joining thick fiber-reinforced composite sections. The initial objective is to develop both economical and robust attachment techniques for composite members joined to steel members. The research will be coordinated with an industry team led by Delphi Corporation that is developing and commercializing composite chassis members through funding from the Department of Energy's (DOE's) High Strength Weight Reduction Materials Program, under the Office of FreedomCAR and Vehicle Technologies.

Background

For years, polymer matrix composites have been successfully incorporated into aircraft, spacecraft, race cars and sporting goods. In these applications, a high cost premium is tolerated for both weight reduction and improved performance. Solutions for joining these high performance composite components have been developed but are not economically optimized. Typically, the materials selected are relatively thin, anisotropic, and tailored to meet the specific loading requirements.

Currently, polymer matrix composites are used for several non-structural components for heavy vehicles including hoods and roof fairings. In these cases, relatively inexpensive materials, such as sheet molding compound (SMC) with short reinforcing fibers, are used to reduce weight, improve aerodynamics and reduce part count. There is potential for additional weight reduction in the chassis, which accounts for approximately 12% of the weight of a raised roof sleeper (Figure 1), by replacing heavy steel structural members (Figure 2) with fiber-reinforced composites. The financial incentives for weight reduction in heavy vehicles include improved fuel efficiency, increased payload and reduced truck traffic volume.

To overcome the technical issues associated with joining lightweight materials in heavy vehicles, researchers at ORNL and PNNL are collaborating on a four year research effort focused on developing technically robust and economically attractive joining techniques. 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

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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 will be conducted in the last half of 2005.

Major Technical Issues

Economics is one of the main hurdles for developing successful composite structural member 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 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 due to 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 due to the continuous connection the bond line creates that distributes loads over a larger 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, there are several drawbacks with the use of adhesives including: difficult disassembly without destroying the substrate, potential degradation due to environmental factors, difficulty in inspection to ensure adequate bonding, and 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, two and three dimensional (2d and 3d) composite structures can be reasonably damage tolerant due to their ability to distribute stresses around damage zones. Typically, in a crossply laminate or a braided or woven fabric composite under fatigue loading, there is a slow accumulation of damage which eventually leads to failure. 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. Additionally, in flexural fatigue the stress state is complex, and not easy to model with an S/N curve.

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 of tailorability of the composite material for specific applications, but 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 numerically model.

Potential Design Solutions

The successful joint design will likely have mechanical fasteners which will require holes in the composite member. The choice of fiber architecture can greatly affect the stress concentrations due to holes. For instance, a 3d woven or braided reinforcement may result in a composite that resists delamination. The preform could potentially be made with holes to allow for no fiber path disruption at the fasteners. In any case, the volume fraction and complexity of reinforcement must be balanced with the associated cost tradeoffs. Perhaps the reinforcement can be preferentially concentrated at the fastener locations and where the highest stresses will be seen.

The selected composite material used at the joint may be a metal/composite hybrid structure such as a metal skeleton with composite skin or a composite material with molded in metal reinforcements. Alternatively, metal inserts could be used to reinforce the composite at a bolt hole. A relatively soft composite can yield and creep under the bearing loads of the bolt head, causing failure via composite fatigue or bolt pullout. The metal insert through the thickness of the hole would act to support the crush of the bolt, reducing the tendency for the composite to creep, while still adequately securing the joint. Metal washers can distribute the bolt crush load over a larger area and reduce hole damage.

A hybrid joint design could take advantage of both mechanical fastening and adhesive bonding to reduce stress concentrations and increase the reliability of the joint. In any case the component costs, weight and ease of assembly must be considered in the design downselection.

Anticipated Modeling and Testing for Joint Design and Validation

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 design requirements for the new joint will be heavily dependant on the material and processing selections that will be industry led. Initial tests for basic mechanical properties will be conducted at the coupon level to screen candidate composite materials. The composite materials will then be downselected based on both cost and structural suitability under the required loading conditions. The most promising materials will likely require additional coupon level tests to determine mechanical properties in tension, compression, shear and flexure which may be required for modeling and structural design. These tests may include lap-shear, coach peel, and cross tension and fatigue coupons, with and without the use of an adhesive in the joint.

Component level testing will be conducted for hole and fastener effects to define hole spacing, allowable clamping forces, insert or reinforcement requirements, and environmental stability. The tests at this level will include cyclic fatigue and creep.

Various joint configurations will be evaluated on subscale components with combined loadings representative of those that will be seen in the heavy vehicle application. Additionally, high cycle fatigue will be conducted to ensure the long-term durability of the joints.

All of the testing and joint design will be done in close coordination with the industrial team. Modifications to the composite material and the component geometry will directly impact the joint design and requirements.

ORNL researchers have extensive experience in adhesive bonding and durability testing of automotive composites. Currently, ORNL is 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.

It will be important to model the joint structure and loading as a function of the joint geometry, fastening methods employed, hole size effects, and hole spacing effects. This will be accomplished by a finite element analysis (FEA) approach, using the ABAQUS code. The results of the FEA will provide guidance for the joint design and prediction of the anticipated loading paths. The goal is to design a joint that effectively spreads the load over a large area to minimize stress concentrations.

The structural analysis of the joint and loading is considered to be straightforward. However, it will be important for the modeling to take into account hole production techniques, the use of metal inserts, fiber architecture, and fiber damage, especially under fatigue conditions. The fiber architecture and placement around features such as holes is expected to be a critical aspect of the joint design, and will therefore require considerable attention in order to design a durable composite-to-metal joint design.

In order to use composite materials efficiently, it is essential to understand and predict their mechanical properties and nonlinear behavior due to damage and other adverse effects. The fiber and matrix properties, fiber volume fractions as well as orientation strongly influence the mechanical and physical responses.

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 micro-cracks 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, PNNL will employ this modeling methodology 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.

Economic analysis, including impact on the assembly process will be conducted for each potential attachment design.

By the 4th quarter of 2005, a prototype joint design that meets the structural, durability and cost requirements will be selected and validated for use in the durability track testing.

Anticipated Results and Benefits

Composite materials allow for a great deal of design flexibility due to the tailorability of the reinforcement, resin and manufacturing method. This flexibility makes composites attractive for a wide variety of applications, but also makes the design process much more difficult.

The principal objective of this research is to develop enabling joining technologies for composite chassis structures for heavy vehicles. The design, modeling and testing methodologies that are developed will be published so that composite materials can more readily be incorporated into other chassis components without sacrificing strength, functionality and durability.

Figures

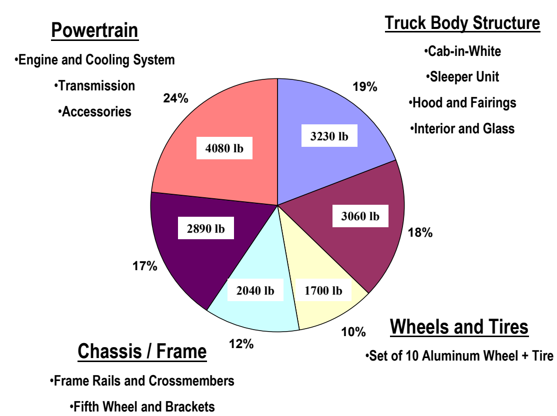

Figure 1: Weight breakdown for a class 8 tractor with 70” raised roof sleeper.

Figure 2: Representative chassis assembly for a Class 8 truck showing a variety of steel members bolted together.