STATIC AND FATIGUE STRENGTH EVALUATIONS FOR BOLTED COMPOSITE/STEEL JOINTS FOR HEAVY VEHICLE CHASSIS COMPONENTS

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Abstract

This paper summarizes the Pacific Northwest National Laboratory (PNNL's) progress-to-date on the development of joint designs for a composite structural member attached to a metal member for heavy vehicle chassis components. The joint design baseline was first established by characterizing the static and fatigue strength of a steel/steel Huck bolt joint assembly. The effects of various manufacturing factors and operational conditions on the static and fatigue strength of the hybrid joint were studied with a commercially available composite material. It was found that loading mode and washer size have significant influence on the static and fatigue strength of the hybrid joint. In addition, it was found that a test frequency of 15 Hz can be used for the hybrid joints without inducing significant temperature changes during fatigue testing.

Introduction

Increasingly stringent government regulations and growing pressure from fuel price have prompted the heavy vehicle manufacturers to use more and more lightweight composite materials in vehicle constructions. Currently, these composite materials are primarily used for non-structural parts such as hood and roof fairings. Realizing more significant weight savings can be achieved by using more composite materials as structural members, and various researchers have attempted at developing composite chassis members. In most of these efforts, the main road block and technical challenge appear to be the undesirable fatigue failure in the joint area. In May 2003, Oak Ridge National Laboratory (ORNL) and PNNL began collaboration on a four year research effort focused on developing joining techniques to overcome the technical issues associated with joining lightweight materials in heavy vehicles. The initial focus of research is the development and validation of joint designs for a composite structural member attached to a metal member that satisfy the structural requirements both economically and reliably.

Composite materials have been used in spacecraft design and civil engineering applications for many years offering advantages in weight reduction, strength, and stiffness when compared to conventional materials. To utilize composites fully, a thorough understanding of the joint strength is required to prevent premature failure of a component at an interface. Two aspects of joint strength are usually considered for the joint design: static strength and fatigue strength.

Many papers and studies on static strength of composite joints can be found in the open literature. Pin-type bearing test of the bolt hole has been the primary method used because the existence of holes damages the integrity of the composite structure (Refs. 1-2). It is believed that in a composite structure, the problems of bolted joints are much more severe than those for metal structures because the destruction of the continuity of long fiber by the hole. Micro-buckling of the fibers under the compressive load at the bearing surface and the delamination of plies under through-thickness stress can promote failure at much lower bearing stress. For example, Fox and Swaim (Ref. 3) evaluated the influence of various hole parameters on the structural strength characteristics of mechanically fastened composite joints. Pin-type bearing tests were performed to determine the strength characteristics for composite samples with different hole sizes, edge ratios and width ratios. Kelly et al. (Ref. 4) used pin-type bearing test to study the effects of local strengthening of bolt hole by fiber steering. They reported that by using only 1% (by weight) additional fiber delivered to 70x290 mm^2 specimens, the bolted joint of composite coupons were strengthened by 18% of peak load and 14% of bearing strength with an increase in thickness from 1.32 mm to 1.36 mm.

However, since every composite bolted joint is a mechanical assembly of composite plates with bolt, nut and washers, it is also very important to study the effects of washers and bolting parameters on the strength of the bolted joints. The basic failure mode in bolted fiber reinforced composite materials is usually a combination of bearing failure, net-tension and shear-out failure. It occurs in the materials immediately adjacent to the contacting bolt surface due primarily to compressive stresses. A major goal of many bolted joint research has been to determine the effects of various material and bolting parameters on the bearing strength of the joint (Ref. 5-9). The bolting parameters studied include: geometric factors such as laminate thickness, hole diameter, width/diameter and edge/diameter ratios, and other factors such as stacking sequence, coefficient of friction, lateral constraint, bolt clamping force and radial clearance between bolt and washer. Oh et al. (Ref. 10) reported that the bearing strength of the composite/steel hybrid joint increased as the clamping pressure increased, and then converged to a constant value which is 30% higher than the value for joints with no preload. Delamination of the carbon-epoxy specimen on the loaded side of the holes and extensive damage at the washer edge outside the constrained region was observed on the fracture surfaces of the failed specimens. This type of washer edge failure was also reported by Tong (Ref. 11), see Figure 1.

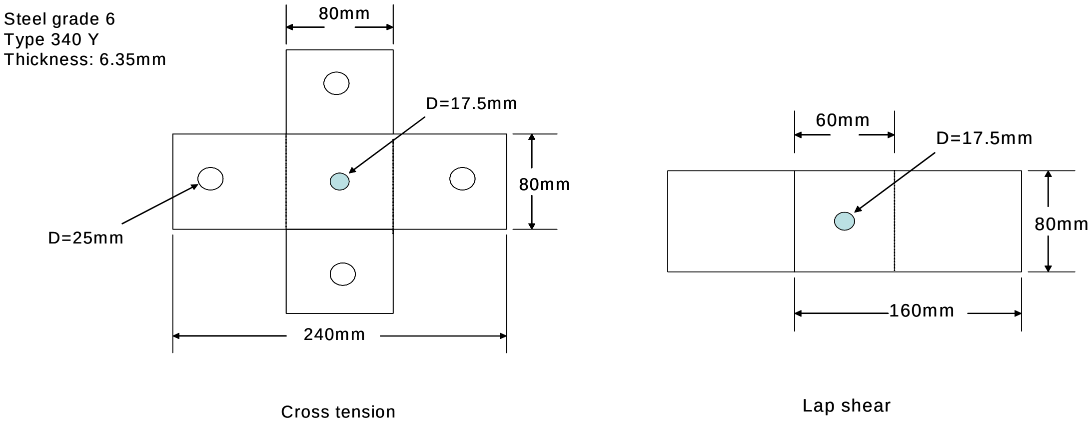
Figure 1. Re-plot from Figure 6(b) of Ref. 11: damage at washer edge for bolted joint

The issues of washer types and damage at washer edges are more relevant to the fatigue behavior of composite bolt joints. It should be mentioned that the cyclic fatigue behaviors of the bolted joints are addressed less often in the open literature than the static behaviors. Whitney et al. (Ref. 12) studied the singular stress fields near contact boundaries in a composite bolted joint. Asymptotic stress analysis was performed to obtain the power of singularity in these regions as a function of the bolt head (washer) stiffness. It was found that the characteristics of the stress singularity for such practically important combinations as titanium bolt-head and carbon fiber composite plate are similar to a crack in terms of the power of singularity and the uniqueness of the singular term. Such a high singular stress state would promote through-thickness fatigue crack growth at the washer edges. Indeed, fatigue failures around washer edges by fiber tearing were reported by Fu and Mallick (Ref. 13) for single bolted joints in SRIM (structural reaction injection molding) composites under various testing conditions.

The goal of this study is to support the development of composite components for heavy vehicle chassis components by providing affordable and reliable joining technology. This study focuses on the effects of different bolting parameters on static as well as fatigue performance of the hybrid composite/steel joints. A commercially available pultruded composite was used to study the generic issues related with composite/steel bolted joints.

Establishment of Design Baseline for Joint Static and Fatigue Strength

Huck bolting is a common joining method currently used in heavy truck chassis structures. The first task of this joining project is to establish the design baseline for joint strength by evaluating the static and fatigue performance of the steel/steel Huck bolt on a single joint level. Both tension and shear loading conditions were considered. The resulting static and fatigue strength will serve as the design benchmark for the composite/composite or composite/steel joint. Figure 2 shows the coupon design and material used in the baseline joints. The material used is typical for the chassis component of Class 8 trucks. A grade 8 Huck-spin fastener was used to join the steel plates together, and the samples were assembled by a truck OEM at their manufacturing facility.



Cross tension

Lap shear

Figure 2. Steel sample configurations

Static strength tests were performed on both joint configurations using servo-hydraulic test frames using cross head speed of 10mm/min, and fatigue tests were performed using test frequency of 3-8 Hz.

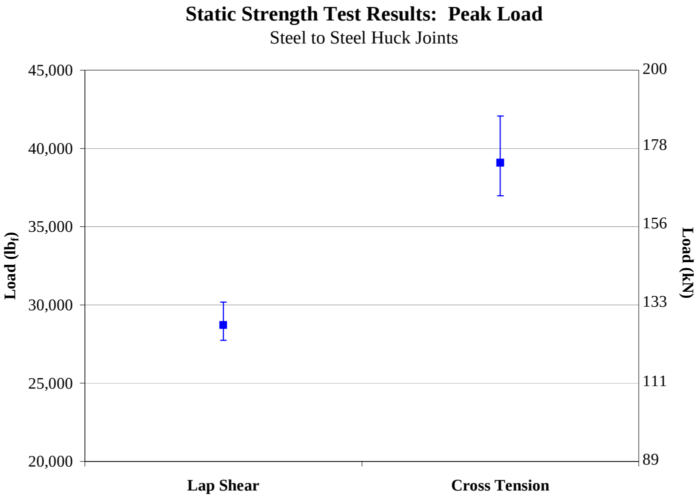
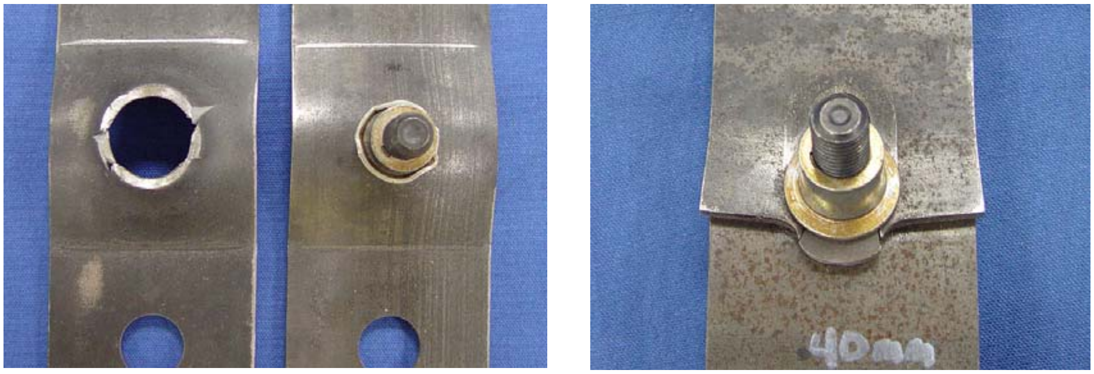


Figure 3. Static strength of the steel/steel joints



Static Cross Tension

Static Lap-Shear

Huck bolt collar stripped out

Shear out of sheet through edge margin

Figure 4. Static failure modes for steel/steel joints

Figure 3 illustrates the measured static strength (averaged over 10 samples) of the steel/steel joints under cross tension and lap shear loading condition. Figure 4 shows the failure modes of the joints under these two loading conditions. Under static loading, the joint strength shows a strong load mode dependency: its cross tension strength is much higher than its lap shear strength. This is different from the typical observations for joints made of thin metal sheets. A closer examination of Figure 4 reveals that different loading modes lead to different failure modes: under cross tension loading mode, the Huck bolt nut collar was stripped out by the base metal and the rivet hole expanded due to plate bending and stretching. Under lap shear, however, little plate bending was observed and the joint failed due to material shear-out through edge margin. Figure 3 also illustrates that the degree of strength variation for the cross tension samples is higher than the lap shear samples.

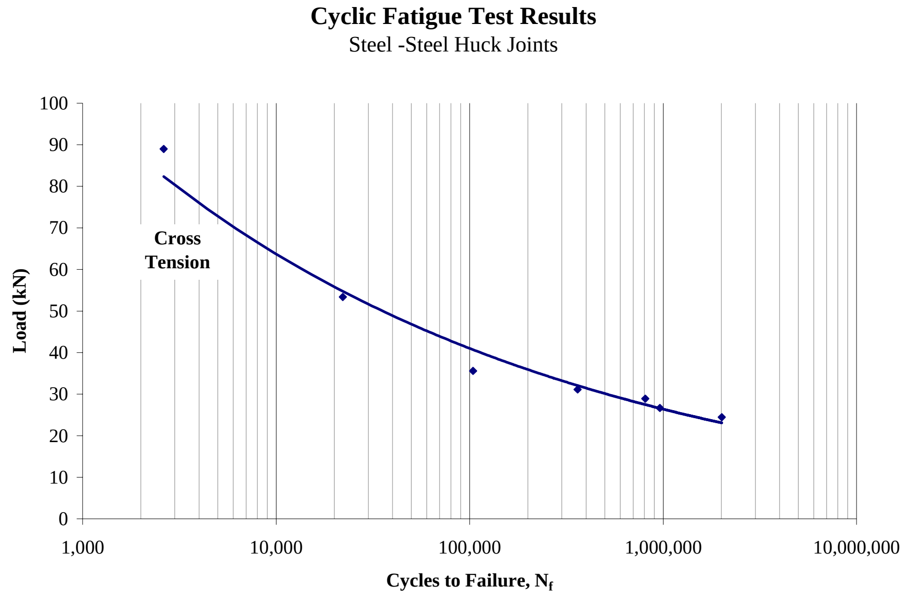


Figure 5. Fatigue load versus cycle (S-N) curve under cross tension loading condition

Cross tension fatigue failure mode

Figure 6. Fatigue failure modes for steel/steel joints

The cross tension load versus fatigue cycle curve and the corresponding failure mode are shown in Figures 5 and 6 respectively. Unlike the failure mode under static loading where the Huck bolt nut collar was stripped out, fatigue failure for the cross tension sample initiated from the steel/steel contact periphery on the faying interface where the structural stress including the bending stress and out-of-plane shear is maximum (Ref. 14). The application of structural stress approach in fatigue life prediction for composite/steel joint will be further studied in this project. Again, the static and fatigue strength obtained here will be used as the design guideline for the actual composite/steel joint for the truck chassis member.

Composite/Steel Hybrid Joints

The generic issues related with composite/steel joints were studied. Since the final material and gage for the final part design is not yet available, we chose a commercially available composite material, EXTREN®, to study the various aspects of composite/steel bolted joints. This composite material is produced by Strongwell, and it is a pultruded fiberglass reinforcement of thermosetting polyester or vinyl ester resin systems. Series 525, a polyester resin system, was used in this study.

In this project, 1/8" thick composite sheet was joined to 1.4mm SAE1008 steel sheet with a standard grade 5 bolt with ¼" diameter. Both cross tension and lap shear loading modes were considered for the single hybrid joint under static and fatigue loading conditions. Since fiberglass reinforced thermoset polymer composites are a non-homogenous material, their strengths and behavior are dependent upon the design of the composite and reinforcement. The composite sheet stock was cut along the longitudinal direction to achieve maximum net-section strength. Figure 7 shows the typical axial and transverse stress-strain curves for the composite material used.

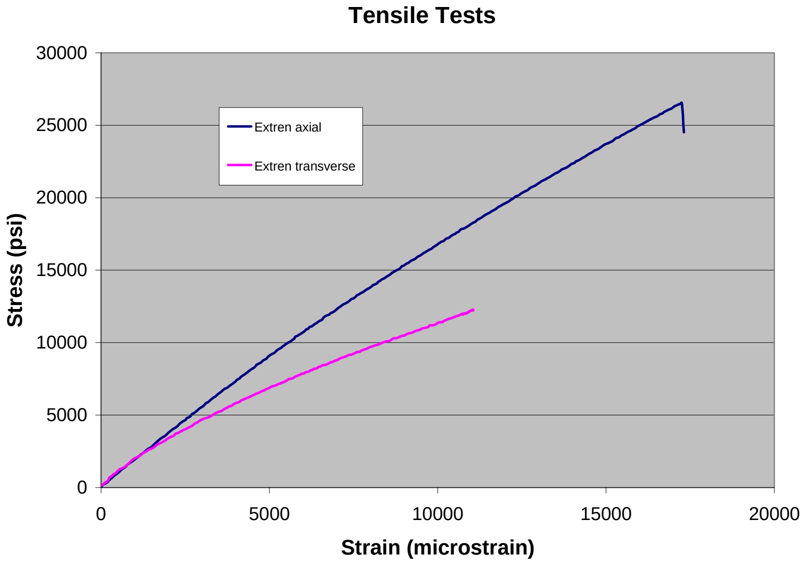


Figure 7. Typical axial and transverse stress-strain curve for the composite material

Effects of Washer Size and Shape

The effects of various manufacturing factors and loading conditions on the static and fatigue strength of the hybrid joint were investigated. First, the effects of washer size and shape on the static and fatigue strength of the joints were studied. Three washer sizes and shapes were considered:

- Nominal washer – 5/8" OD, 0.060" (~1.524 mm) thick
- Large washer - 1" OD, 0.052" (~1.32 mm) thick
- Plate – 50 mm x 35 mm, 6 mm thick

For coupon assembly, the bolt holes on the composite plates were drilled with a regular drill bit, and the same torque value of 10 ft-lb was applied to all the samples. This indicates that for coupons with larger washers, the average compressive stress on the washer/composite interface is lower than the coupons with nominal washers.

A typical load versus displacement curve for composite bolted joint under bearing type of failure is shown in Figure 8 (re-plot from Ref. 4). More than one failure point is usually observed (Refs. 4 and 11). The curve usually starts with a linear portion. The slope of this linear portion of the bearing stress-bearing strain curve is called the bearing chord stiffness. Then an initiation of damage triggers a non-linear part of the curve (Point A in Figure 8). Shortly after, a bearing failure causes the load to drop (initial failure, Point B). After this point, a bolted joint of composite material can usually carry an additional load, experiencing a new height (ultimate failure, Point C). In this case the bearing strength of the bolted joint depends on how the failure is defined. Points B and C generate initial and ultimate bearing strengths, respectively. In the following work, the strength of the hybrid composite/steel joints is defined with Point C, the ultimate strength.

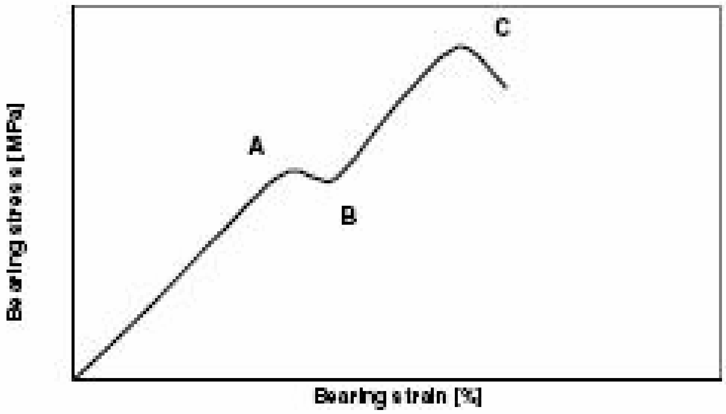


Figure 8. Typical load-displacement curve of composite bolted joints

Figure 9 shows the static load versus displacement curves for the lap shear samples with different washer sizes and shapes. The samples with nominal and large washers show the typical characteristics of a bearing type of failure, but the samples with the constraining plate do not show a clear load drop prior to the peak strength. The samples with nominal washer have the lowest static strength and the samples with thick steel plate have the highest static strength. This is because with stronger lateral constraints, the sample is restricted from out-of-plane bending and therefore the stiffness of the samples under lap shear loading is increased. Similar observations have been made with spot welded and riveted lap shear samples (see Ref. 15). The strength for samples with large washers is approximately 7% higher than those of nominal washers, but approximately 13% lower than those with steel plates.

The typical failure modes for the three static samples are shown in Figure 10. A similar failure mode was observed in all three washer types. A cleavage tension failure mode was observed (Ref. 16). It should be pointed out that in all the static cases, damage initiated from the periphery of the bolt hole.

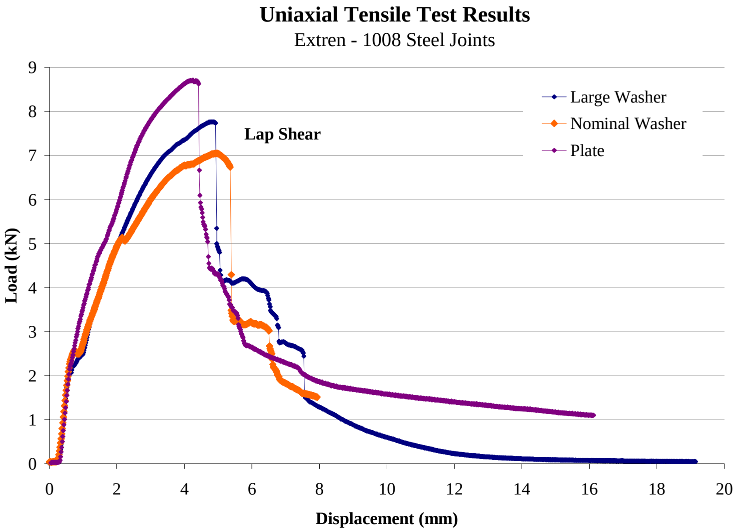
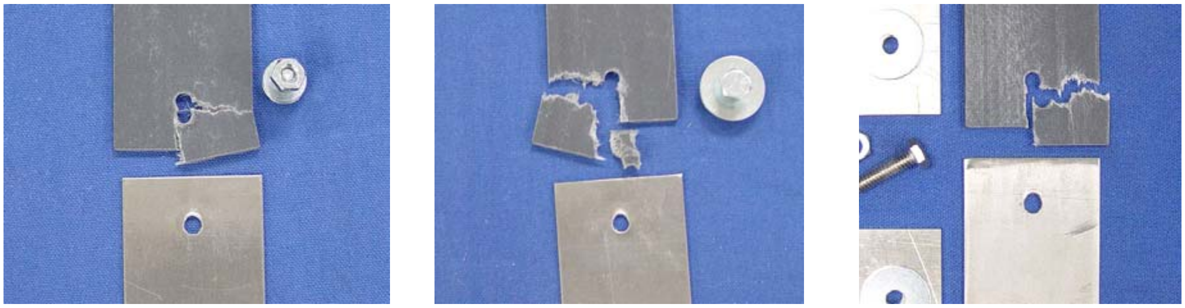


Figure 9. Static load versus displacement curves for lap shear samples with different washer size and shape



Typical static failure mode of lap shear joints with nominal washer.

Typical static failure mode of lap shear joints with large washer.

Typical static failure mode of lap shear joints with plate.

Figure 10. Typical static lap shear sample failure modes

Cyclic fatigue behaviors of lap shear joints made with nominal and large washers are shown in Figure 11. Tension-tension cyclic fatigue tests with stress ratio of 0.1 were performed to characterize the fatigue behavior of the joints. All cyclic fatigue tests were conducted in load control with constant amplitude until failure or a run-out criterion of 10,000,000 cycles was reached. Failure is defined as total separation or fracture of the specimen into two parts. The test frequency of 20Hz was used for samples with nominal washer and 15Hz for samples with large washer. The effects of fatigue test frequency on samples' fatigue behavior and temperature rise will be discussed in the following section.

The fatigue test results shown in Figure 11 clearly demonstrate the advantages of using a large washer: samples with a large washer have about 10% higher fatigue strength than samples with a nominal washer. This is particularly true under lap shear loading condition. Similar to typical welded joints, the fatigue strength of the composite/steel bolted joint has a dependency on loading mode: lap shear samples have much higher fatigue strength than cross tension samples. This is because different loading mode generates different local stress field around the washer edge and the bolt hole. A structural stress approach similar to those in Ref. 13 will be used to study the fatigue strength of samples with different washer size and loading configurations.

The typical fatigue failure modes under lap shear and cross tension loading conditions are shown in Figure 12. It should be noted that under fatigue loading, damage on the composite plates initiated right underneath the periphery of the washer. This is true for both lap shear and cross tension loading conditions. Under lap shear loading, fatigue crack first propagated along the washer periphery and the final fatigue failure occurred in the composite sheet perpendicular to the loading direction with some degree of delamination. Under cross tension loading condition, fatigue crack propagated through the thickness of the washer periphery and the final fatigue failure mode was composite shear-through at the washer edge.

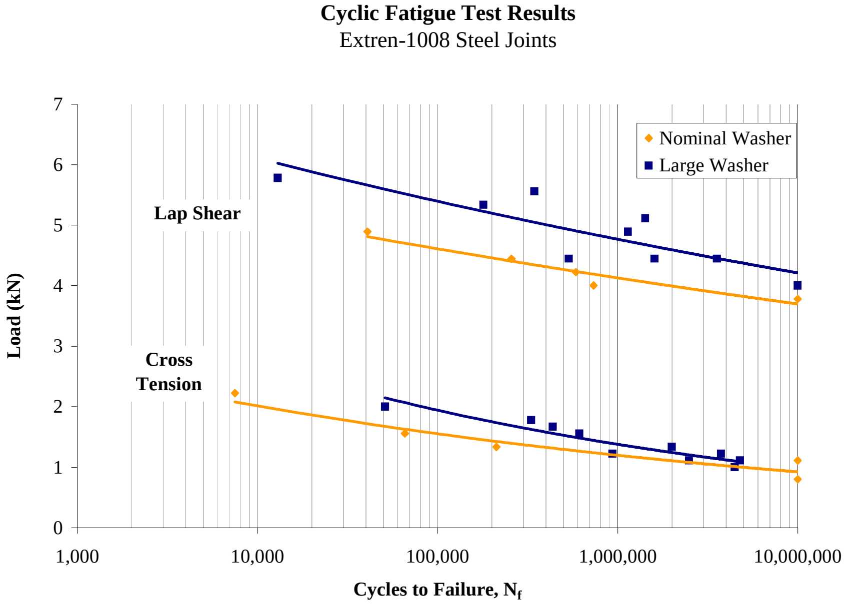


Figure 11. Effect of washer size on fatigue strength of lap shear samples

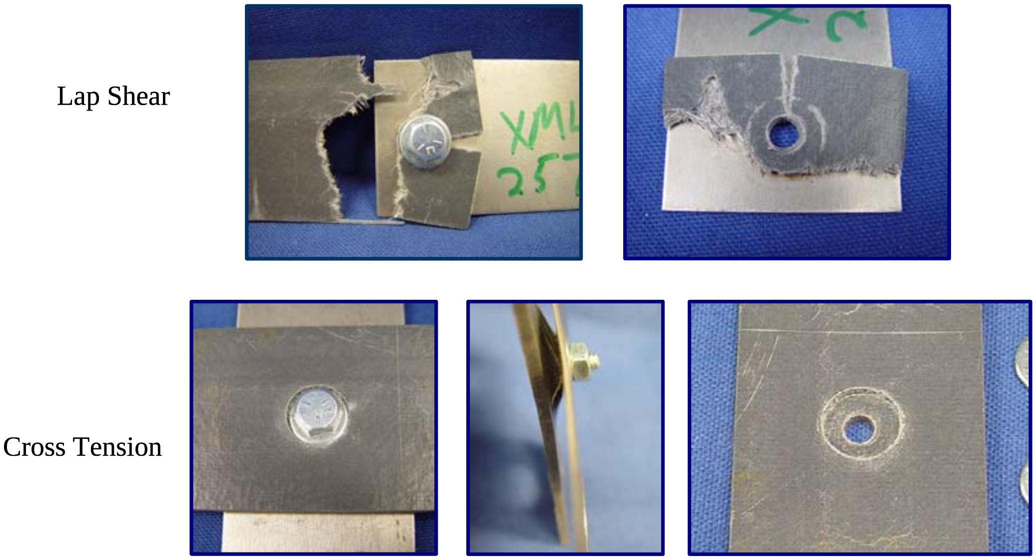


Figure 12. Typical fatigue failure mode: damage initiated from washer edge

Effect of Fatigue Test Frequency

Fatigue tests are normally carried out at the highest frequency possible in order to minimize test duration. Restrictions on test frequency can arise due to test equipment limitations (response time), time-dependent processes and hysteretic heating. Hysteretic heating can precipitate a rise in temperature causing thermal degradation of the material. The increase in temperature is dependent on strain or frequency rate, stress amplitude, specimen geometry, loading mode and thermal conductivity of the material. Hysteretic heating, which increases with stress amplitude and frequency, was observed to adversely affect the compression fatigue performance of carbon and some glass woven specimens. Typically, the maximum temperature rise should be less than 10°C during the fatigue test (Ref. 17).

To study the effects of different fatigue test frequency on the composite/steel joint temperature rise and the resulted fatigue life, lap shear sample fatigue tests were conducted at test frequencies of 5 Hz, 15 Hz and 20 Hz under the load level of 100-1000 lbs (R = 0.1). The coupon temperatures during tests were monitored with thermal couples (Figure 13) and the maximum temperature rise for each test frequency was recorded along with the corresponding fatigue life, see Table 1. The test results summarized in Table 1 indicate that with a test frequency of 15 Hz, the maximum temperature rise during the test was 5°C, well below the threshold of 10°C. Even at 20 Hz, the maximum temperature rise was 9°C for the hybrid joint, still below the threshold value. This is probably because the composite sheet used in this joint is relatively thin and that the hysteretic heating is a volumetric effect. Also, the steel plate at the other side of the joint acts as a heat sink during fatigue tests and can quickly conduct the heat away. In this sense, the degree of the temperature rise for a composite/steel joint should be less severe than that for a composite/composite joint.

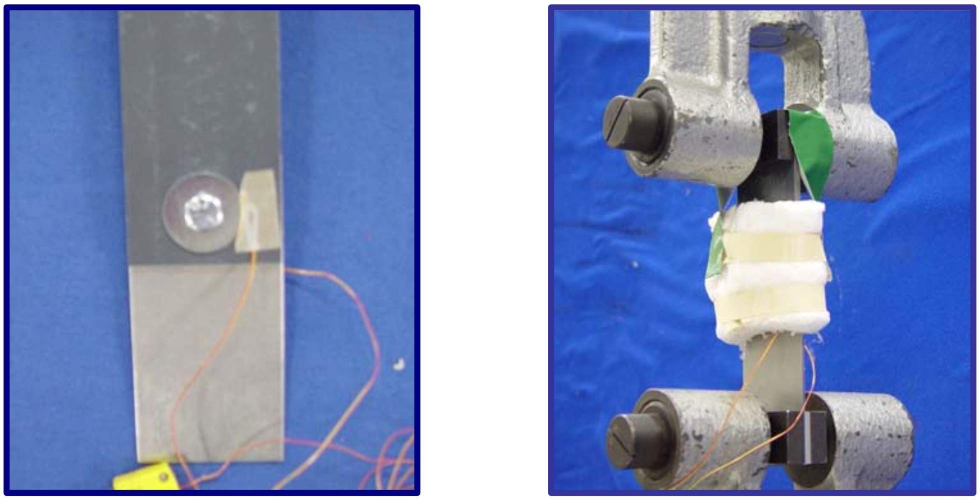


Figure 13. Temperature monitoring during lap shear fatigue test

The fatigue test results in Table 1 also show a high degree of scatter for the fatigue strength of the hybrid joint. For both tests conducted at 5 Hz, even with the same degree of temperature rise, one sample survived 1.6 million cycles while the other only survived 0.5 million cycles. For the sample tested at 15 Hz, the temperature rise was 5°C but its fatigue life was over 3.5 million cycles. The reason for the fatigue strength scatter for the hybrid joints might be related to the high level of property scatter of the composite material. According to the tensile tests conducted by ORNL, the coefficient of variation for its longitudinal strength is ~26%.

The main finding of this session is that a maximum testing frequency of 15Hz can be used for the composite/steel joint without inducing significant temperature change to the samples during fatigue test. Again, the level of temperature rise depends on the type and thickness of the specific composite material, therefore the maximum allowable fatigue test frequency for different composite joints should be established individually.

Table 1. Temperature rise and fatigue life under different testing frequency

Cycles	*Test Frequency*	*Temperature Rise (C)*
1,601,748	5	3
535,111	5	3
3,561,412	15	5
317,485	20	9

Summary and Next Steps

This study aims at developing reliable and affordable joint designs for a composite structural member attached to a metal member for heavy truck chassis components. This paper summarizes our progress-to-date on the project which is in parallel with the work performed at ORNL. First, the joint design baseline was established by characterizing the static and fatigue strength of the steel/steel Huck bolt joint assembly. It was found that the static Huck bolt strength is very sensitive to loading mode. Unlike joints made of thin metal sheets, the Huck bolt joints have much lower lap shear strength than cross tension strength.

The effects of various manufacturing factors and operational conditions on the static and fatigue strength of the hybrid joint were then studied with a commercially available material. The purpose was to obtain some generic observations and fundamental understandings for a composite/steel joint such that some design guidelines can be established once the final material selection and gauge are determined for the project. The effects of washer size and shape and loading mode as well as fatigue test frequency were studied. It was found that loading mode and washer size have significant influence on the strength of the hybrid joint. Under static loading conditions, failure for the composite/steel joints initiated from the bolt hole and the load-displacement curves for the lap shear samples resemble a typical load-displacement curve of composite bolted joints under bearing type failure. Also, lateral constraints on the lap shear sample tend to stiffen the sample and yield higher shear strength.

Under fatigue loading, however, failure initiated from the washer edge and eventually sheared through the composite material under cross tension loading. These observations suggest that the fatigue behavior of these hybrid joints is more dependent on local stress fields around the washer edge, and factors such as washer size, geometry and bolt torque level can significantly influence the fatigue strength of a composite/steel joint. In fact, approximately a 10% increase in fatigue strength was observed in the joints with a large washer in comparison to joints with a nominal washer.

The effect of different fatigue test frequencies on the sample temperature and the resulting fatigue strength was also examined. It was found that testing frequency of 15Hz can be used for the composite/steel joint without inducing significant temperature change to the samples during fatigue testing. Again, the maximum allowable fatigue test frequency for different composite joints should be established individually.

As a next step, this project will continue studying the effects of different manufacturing parameters on composite/steel hybrid joints. Different composite materials as well as different joining methods will be examined to continue efforts in joint development. Meanwhile, structural stress based fatigue analysis will be performed on the steel/steel Huck bolt and composite/steel joints. Progressive failure analyses will also be performed to simulate the static and fatigue behaviors of the composite/steel joints to gain better understanding and predictability of the joint performance.

Acknowledgement

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