DAMAGE AT HOLES IN BOLTED COMPOSITE/STEEL JOINTS FOR HEAVY VEHICLE CHASSIS COMPONENTS

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Abstract

In May 2003, Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (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 is a “focal project” that will utilize the improved joining methods.

The initial joint design for a composite component to steel member will likely include mechanical fasteners requiring holes in the composite member. Several hole fabrication methods have been evaluated including drilling with tapered and Forstner bits, laser cutting, water jet cutting and punching. Several methods have been used to determine the damage associated with hole fabrication. One non-destructive method, flash thermography, has good correlation with x-ray dye penetrant results, and in some cases shows finer detail and can indicate the location of damage through the thickness of the composite.

A testing methodology has been developed to study the effects of bolt torque level on a pultruded fiberglass composite material. Information derived from this will ultimately support the characterization of bolted composite assemblies and provide insight for the design and manufacture of the composite chassis components. Loss of pre-load data can be used to predict the creep response in the through-the-thickness direction of the composite materials.

Background

Fiber reinforced polymer chassis components offer the opportunity to achieve compelling mass reduction and payload increases in heavy trucks. Numerous technically acceptable but complex and expensive attachment techniques have been developed for advanced composite materials for aerospace applications. However, for heavy vehicles, economically attractive joining techniques need to be developed for successful integration of composite chassis components. The goal of this project is to develop robust and economical attachment techniques along with the associated design and testing framework for composite chassis structures. Initially, the research has focused on joint designs for a composite structural member attached to a metal member.

The successful joint design for the initial composite component joined to an existing steel member will likely include mechanical fasteners requiring holes in the composite material. Although extensive research has been conducted for fasteners for aerospace composite materials, limited information on lower cost, lower performance composite materials is available [1-3]. The holes serve as areas for stress concentration and can have a detrimental effect on strength, stiffness and reliability of the composite by disrupting the fiber load path. Additionally, the method of hole fabrication can cause varying amounts of damage to the composite material

[4-6]. The use of bolts through holes in the heavy vehicle chassis application are a concern especially because of the severe loading conditions and complex random variable fatigue loading during their extensive service lifetime.

In order to gain an understanding of the effect of holes on the performance of composite materials, a commercially available pultruded fiberglass composite, Extren® series 525 manufactured by Strongwell, was chosen for initial component independent study. The composite consists of a continuous strand mat with unidirectional rovings in the axial direction and a surface veil for corrosion and ultraviolet protection. One advantage of this material is that a wide variety of structural shapes are readily available. The results will assist in identification of preferred hole fabrication methods as well as serving as a baseline for further testing. Low cost, light weight design modifications such as the use of modified washers, inserts or adhesive bonding, and various composite architectures and manufacturing methods will be evaluated to improve the performance at the holes.

When a composite assembly is bolted together, the tightened bolts and other hardware (washers, nuts) apply an external compressive stress to the composite through the thickness. This bolt pre-load may be beneficial or detrimental to the composite, depending on the amount of applied pressure. Snug bolts can minimize slippage, or movement of the bolt shank in the composite hole, thereby reducing the possibility of wear and abrasion at the edge of the hole. The additional compressive force may also help clamp the individual composite layers together, resisting delamination propagation when other external forces are applied to the assembly. Alternatively, too high a pre-load could cause the clamping force to exceed the transverse compressive strength of the composite essentially crushing the material, or forcing penetration of the bolt hardware into the composite surface.

Pultruded Fiberglass Composite Static and Fatigue Testing

Baseline static and fatigue tensile testing was conducted to characterize the pultruded fiberglass composite material. Tensile tests were run on dogbone specimens with a gage length of 50 mm and width of 13 mm. There was a high degree of scatter in the tensile strength and modulus for the material and as expected the properties in the axial direction are significantly higher than in the transverse direction (Table I) due to the continuous axial rovings. Fatigue tests were conducted on dogbone specimens with an R value of 0.1 at 70%, 50% and 30% of ultimate strength at a rate of 5 Hz (Figure 1). Although there was a high level of scatter among the static tensile specimens, the fatigue behavior was fairly consistent. Several of the specimens at 30% of ultimate reached run out with over 1,000,000 cycles.

To determine the feasibility of testing at a higher rate, the surface temperature of the composite specimens was monitored at both 5 hz and 20 hz. Room temperature was approximately 23°C. At 70% of ultimate (between 300 and 1250 cycles to failure) the maximum temperature of the samples at 5 Hz was 27.5° compared to 34.5°C for 20 Hz. This is the most severe loading case but has the shortest life so the temperature does not reach equilibrium. For tests at 40% ultimate (40,000-45,000 cycles) the specimens at 5 Hz reached 27.6° while the 20 Hz specimens reached 34.1°C. Because these temperature measurements are for the surface, the material is probably heating more than that internally. In order to keep within the ASTM suggested 10 degree temperature rise for these tests [7], the tests should be run slower than 20 Hz. However, the results indicate that a frequency greater than 5 Hz could possibly be used, allowing for shorter duration tests.

Hole Fabrication Methods

To evaluate and compare hole fabrication methods, 12.7 mm (0.5 inch) diameter holes were machined in the center of 76.2 x 254 x 3.175 mm (3 x 10 x 0.125 inch) pultruded fiberglass composite coupons. By visual observation, the specimens machined by laser and the diamond tipped Forstner drill bit had the least damage. The water jet coupons had varying levels of delamination and damage at the hole. The specimens prepared by traditional tapered drill bits and by punching had some flaring out of the material at the rear side of the hole.

The damage resulting from the water jet cutting of the holes was unexpected because straight water jet cut edges of the composite material were visibly undamaged. Many of the specimens had significant delaminations and cracks around the hole diameter. In some cases, the delamination at the edge of the hole propagated causing puckering of the coupon's surface layer as shown in Figure 2a. Additionally, the cut was jagged instead of smooth and circular (Figure 2b).

The water jet cutting facility initially selected had significant experience with waterjet machining metals, plastics and rubbers, but limited practice with fiber-reinforced composites. To ensure that the damage was not a result of inexperience with composites, a second batch of samples was sent to a facility with significant prior experience with composite materials, including ballistic composite laminates that have very little transverse strength and are prone to delamination. Some of the second batch of specimens had no visible damage, but many had large areas of delamination and damage.

Both facilities were asked for their "best effort" at machining the composites, and to conduct whatever R&D necessary to produce clean holes. The first facility reported that better, more consistent holes resulted while the composite was backed at the top and bottom surfaces with plywood during cutting. However, the final specimen set machined with the backing material still had a significant number of damaged/delaminated coupons. The second vendor speculated that the damage to the composite may occur during the "piercing" process in the middle of the coupon that is required to initiate the hole. Continued waterjet machining to enlarge the hole might eventually remove this delaminated material.

Laser machining of the coupons was accomplished using a conventional laser with a 127 - 152.4 cm/min (50 - 60 in/min) linear feed rate. Although the laser machined holes have no visible damage, there was some residual carbon dust on the cut surfaces, as is normal in laser machined polymers (Figure 3). Femtosecond (fs) laser machining was investigated as a possible alternative because the extremely short pulse reportedly reduces material damage. Preliminary fs laser machining tests, with a time-averaged power < 1 Watt, were attempted at Lawrence Livermore National Laboratory. The fs laser could not penetrate the 3.175 mm (0.125 inch) thick fiberglass composite, and estimated feed rates are very low. Much more powerful fs lasers would be required for practical use in this application.

Methods for Damage Detection

Several methods for evaluating the damage associated with hole fabrication in the composite material have been investigated including dye penetrant analysis and flash thermography. The non-destructive flash thermography method has good correlation with the x-ray dye-penetrant results (Figure 4) and may be a useful tool to assess damage progression in composite coupons during cyclic fatigue tests.

For dye penetrant analysis, an HP 43804N X-Ray System Faxitron Series was used to examine the damage in several composite plates with holes fabricated from several different methods. The specimens were first soaked for one hour in a zinc iodide solution prepared by melting 60g ZnI_2 in 10 ml of 99% isopropyl alcohol then adding 10 ml each of water and Kodak Photo Flo 200. Polaroid Polapan 52 102 x 127 mm (4 x 5 inch) black and white instant sheet film was used with a Polaroid Model 545 film holder. The specimen was placed on top of the film holder inside the x-ray machine and the film was exposed for 30 seconds at an x-ray peak energy level of 60 kVp. Layers of Polaroid film were separated 20 seconds after removal from the film holder in the 'R' position. The images were then coated with Kodak protective coating supplied with the film. Although the results from the dye penetrant can be very good, the drawbacks include the time required for the soaking, the contamination of the composite with the solution and the requirement for an x-ray source. Additionally, for each material density and thickness, the time of exposure and power level must be optimized to get the desired results.

The flash thermography method was used to evaluate the water jet cut coupons. Thermography is a non-destructive technique that involves applying a heating (or cooling) stimulus to the surface of a test piece and imaging its thermal response with an infrared (IR) camera. In flash thermography, the thermal stimulus is in the form of a short duration flash uniformly applied to one side of the part. The IR camera records the surface temperature of the opposite side of the part as a function of time. If sufficient temperature contrast can be obtained, changes in through-the-thickness diffusivity of the material can be measured.

Thermal diffusivity is the property governing the rate at which heat flows within a material, and any delaminations or cracks will affect the heat diffusion rate, thereby changing the surface thermal response. Therefore, by studying the time evolution of the surface temperature distribution, it is possible to obtain information on the depth, spatial extent and thermal character of subsurface structures and defects. Flash thermography has been used successfully to evaluate composite materials including consolidation quality, damage development and adhesive bond quality [8-10].

The camera that was used in this study was a Raytheon Radiance-HS IR camera with a 50 mm lens, and that operates in the 3-5 µm spectral range. With this camera, data is recorded as full field-of-view at a rate of 142 images/second and with a time resolution of 0.007 seconds. The flash system used was an Acute2 (2400 Watt·s) xenon flash lamp. The thermal images after flash were recorded for both sides of the coupons.

One advantage of flash thermography is that it can provide an indication of depth below surface that X-ray and visual examination can not. The depth limit of flash thermography with this particular set-up appeared to be about one-half of coupon thickness (1.5 mm). Additionally, the flash thermography is non-contact and can be used to monitor damage propagation during fatigue testing. Possibilities to further enhance the thermal images and depth resolution of the flash thermography technique include the step-heat and lock-in techniques [11].

Bolt Torque Level – Damage and Creep

Figure 5 is a schematic of the basic test set-up used to characterize the effects of bolt pre-load on the pultruded fiberglass composite material. An Interface washer load cell, model LW2050, was positioned between the composite laminate backed by a hardened flat steel backing plate and a second backing plate. Applying a torque to the bolt applied a compressive force to the assembly which was then measured by the washer load cell. For a given material and thickness, the washer load cell can provide important information for joint design including 1) composite pre-load as a function of bolt torque; 2) the effects of multiple bolt tightening/loosening cycles; 3) specimen-to-specimen variability; 4) the effects of re-tightening bolts; and 5) the loss of bolt pre-load with time.

Hardened flat steel plates are required on both sides of the washer load cell to ensure that the load is aligned correctly on the load cell. The use of this stack-up in bolted assemblies for static and fatigue testing may be unacceptable. Strain gaged bolt load cells may be used as an alternative to monitor the bolt load during mechanical testing.

Figure 6 shows the loss of pre-load as a function of time for various test materials that have been bolted together with a 67.8 N-m (50 ft-lb) applied torque. The loss of pre-load with time is relatively low for a steel-to-steel bolted assembly, and increases for the composite assemblies. The greatest loss of pre-load occurs with the 6.35 mm thick composite indicating that it has the most significant level of creep in the transverse direction. Figure 7 provides a closer look at the loss of pre-load that occurs for these samples during the first five minutes after tightening the bolt. There is a rapid decrease in pre-load which occurs within the first 30 seconds after application of torque. Again, the greatest loss of pre-load occurs with the thick composite substrates while the steel assembly shows relatively little loss of pre-load.

Figure 8 shows the effect of re-tightening the bolted 6.35 mm composite following the initial drop in pre-load. Initial results suggest that retightening the bolts may help reduce the pre-load loss rate as well as the overall loss of pre-load.

Summary and Next Steps

Mechanical property characterization, hole fabrication method comparison and bolt torquing evaluation have been conducted on a commercially available pultruded fiberglass composite material. Although this material may not be suitable for structural chassis components it is being used to develop methodology for evaluating alternative composite materials as well as to investigate material independent design modifications that can be made to improve the performance of the composite at bolted holes.

Several hole fabrication techniques have been investigated including water jet cutting, laser cutting, as well as drilling with a standard drill bit and Forstner bit. Damage around the hole was evaluated with several non-destructive techniques. Thermography has shown to compare well with x-ray dye penetrant and is non contact and can be used during fatigue and joint testing to monitor damage initiation and crack propagation. A preferred hole fabrication method will be chosen with input from the industrial team, based on the results from open hole tensile and fatigue tests as well as consideration of the costs and complexity of the fabrication method. Specimens with the preferred hole fabrication method will then be tested in bolt bearing and fatigue to evaluate design modifications, such as bolt pre-load, inserts, molded-in holes and 3d reinforcement of the composite. The goal will be to minimize the damage in the composite and improve the fatigue performance of the resulting composite/metal joint.

The effect of bolt torque level and the loss of pre-load were experimentally determined for the pultruded fiberglass composite material. Information derived from this will ultimately support the characterization of bolted composite assemblies and provide insight for the design and manufacture of the composite chassis components. Loss of pre-load data can be used to predict the creep response in the through-the-thickness direction of the composite materials.

In order to determine the effects of damage caused by the pre-loading and any loss of pre-load on the static and fatigue properties of the composite materials, bearing tensile and fatigue tests will be conducted. Varying levels of pre-load will be used for both torqued bolts and huck bolts. It is anticipated that the huck bolts will yield a more consistent pre-load level.

Data

Table I: Tensile Properties of Commercial Pultruded Fiberglass Composite

Orientation	Tensile Strength (MPa)	COV (%)	Tensile Modulus (GPa)	COV (%)	Strain to Failure (%)	COV (%)
Axial (measured)	227.6	25.80	15.3	22.89	1.727	7.27
Axial (reported [12])	138	n/a	12.4	n/a	n/a	n/a
Transverse (measured)	87.3	6.97	9.10	6.24	1.191	12.14
Transverse (reported [12])	75	n/a	4.83	n/a	n/a	n/a

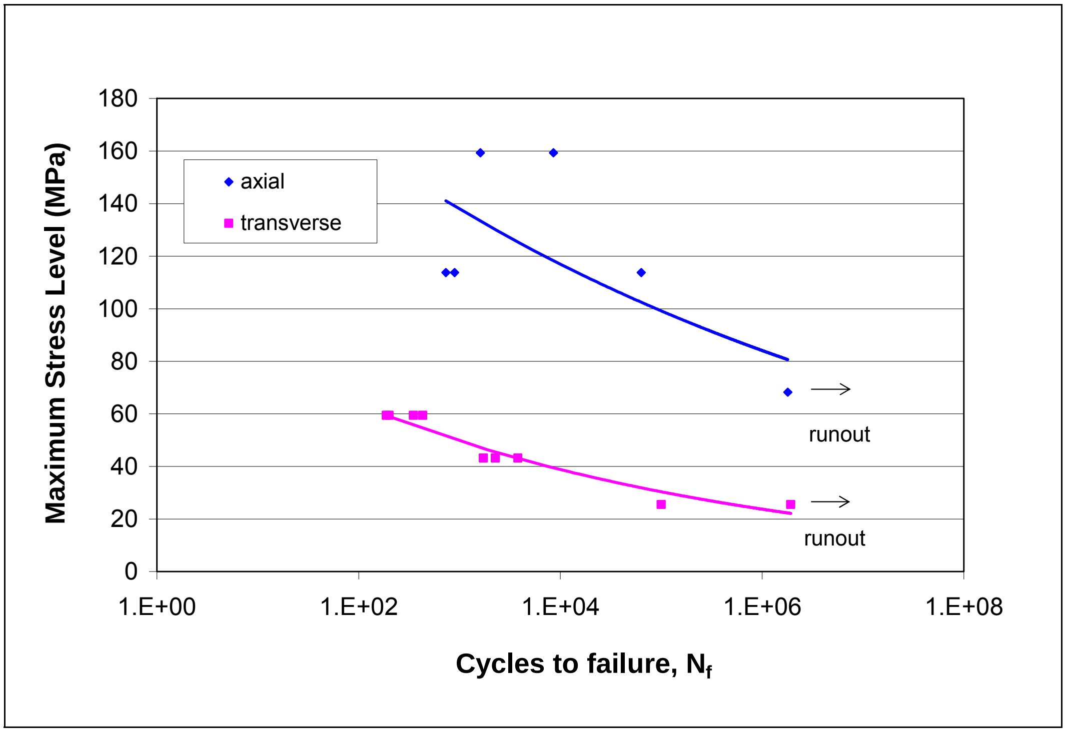
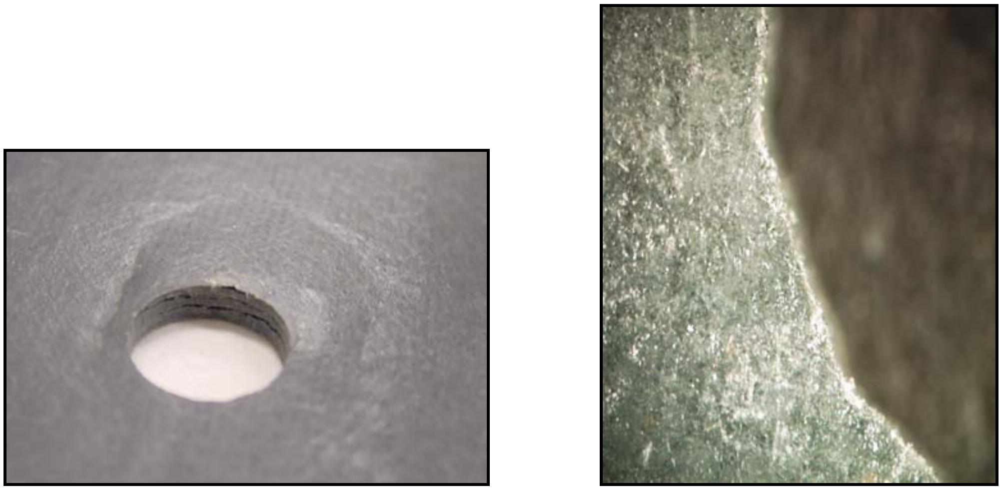


Figure 1. Tensile fatigue behavior of pultruded fiberglass composite.



(a) (b)

Figure 2. (a) Delaminations and cracks visible in a water jet cut specimen (b) jagged edge at hole diameter.

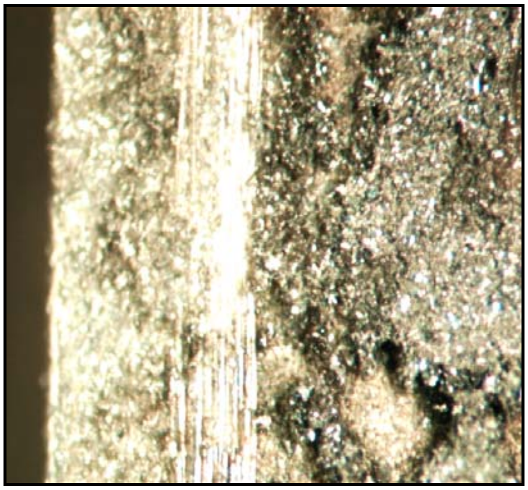
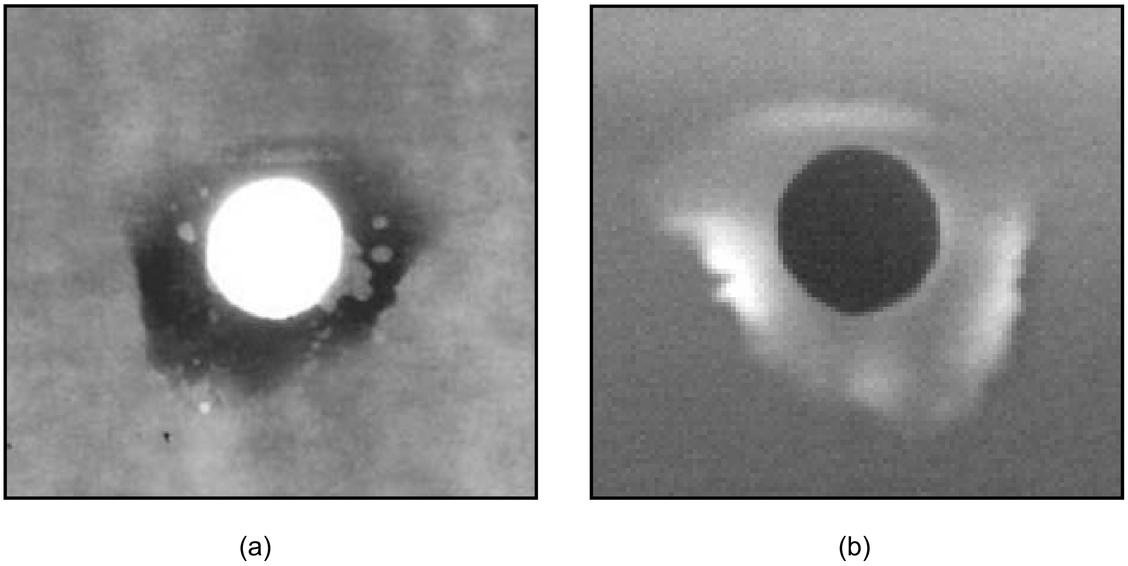


Figure 3. Optical micrograph of laser cut hole showing charred residue.



(a) (b)

Figure 4. Damage detection in water jet cut specimen by (a) x-ray analysis and (b) flash thermography.

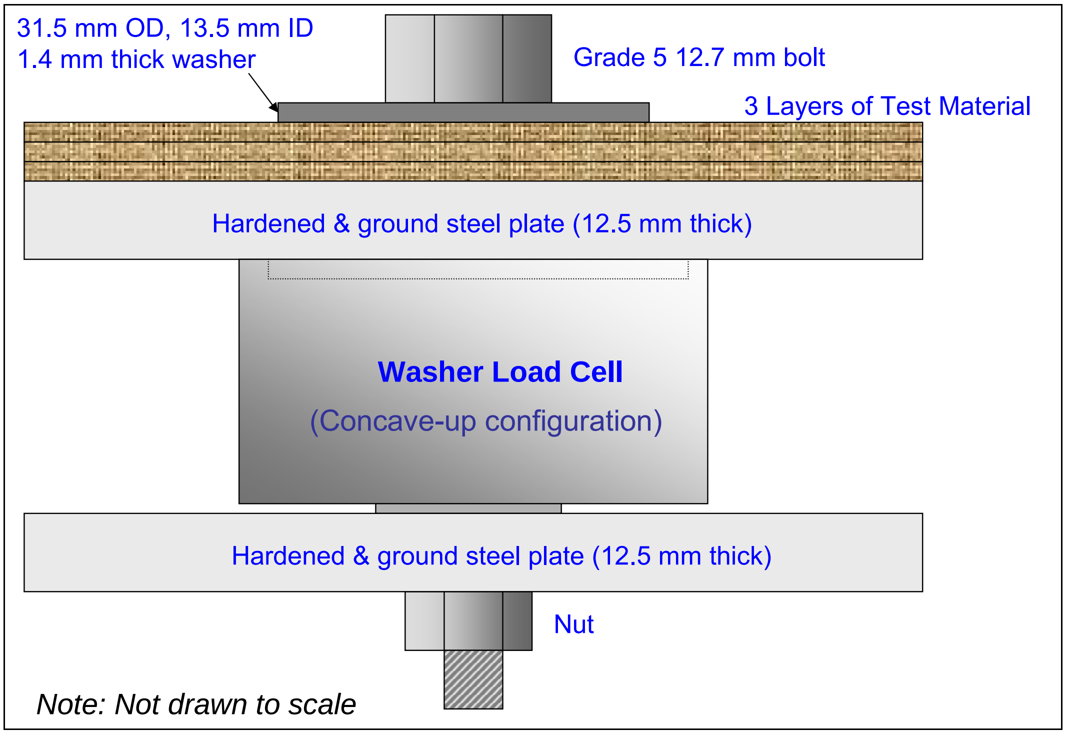


Figure 5. Bolt pre-load test schematic.

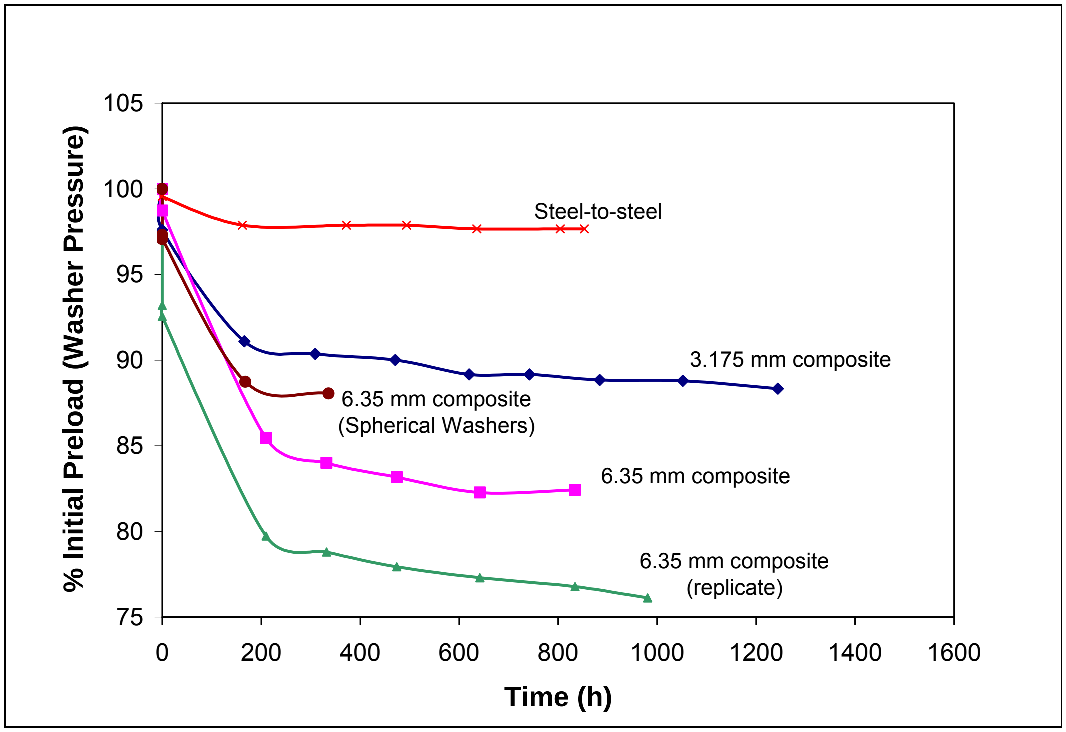


Figure 6. Loss of pre-load for various bolted assemblies.

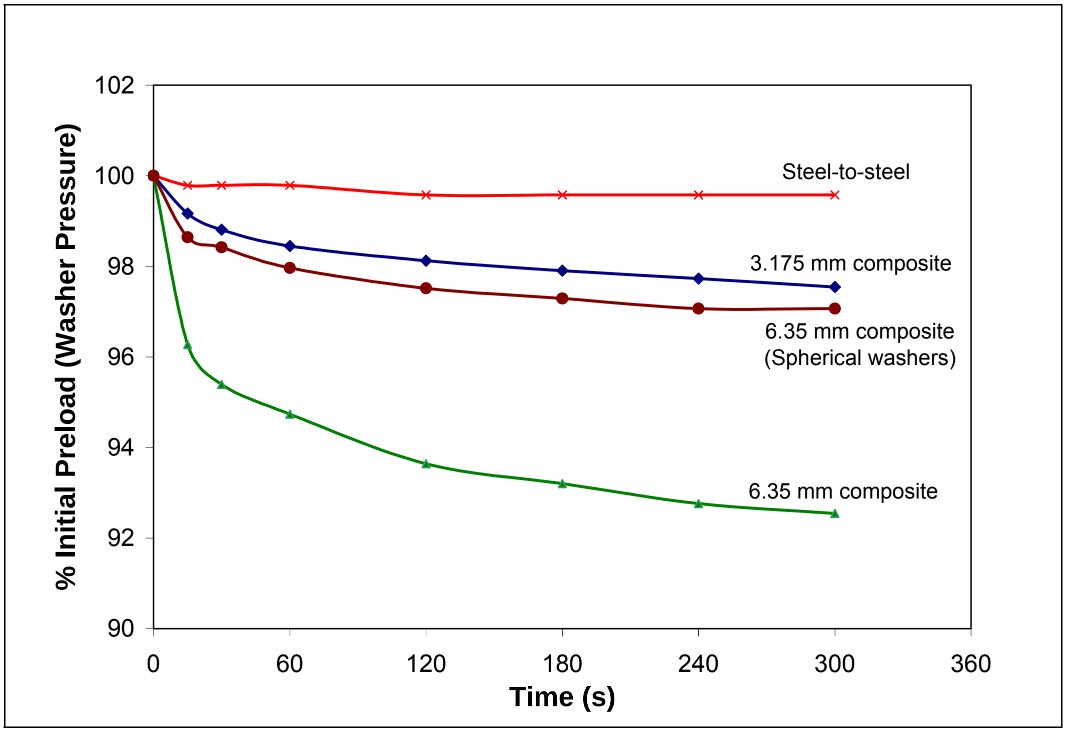


Figure 7. Initial loss of pre-load for various bolted assemblies.

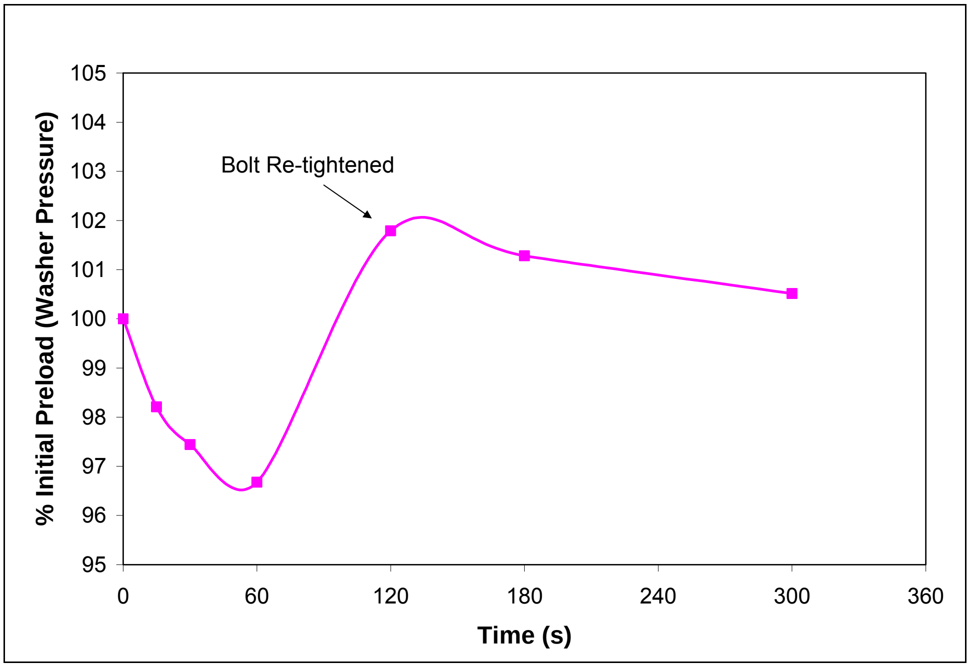


Figure 8. Initial loss of pre-load with bolt retightening for 6.35 mm pultruded fiberglass composite.

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