

Impact of Rivet Head Height on the Tensile and Fatigue Properties of Lap Shear Self-Pierced Riveted CFRP to Aluminum

Harish M. Rao and Jidong Kang
 CanmetMATERIALS Technology Laboratory

Garret Huff, Katherine Avery, and Xuming Su
 Ford Motor Company

ABSTRACT

Tensile and fatigue properties of continuous braided carbon fiber reinforced polymer (CFRP) composite to AA6111 self-piercing riveted (SPR) lap shear joints are presented. Rivets were inserted at two target head heights separated by 0.3 mm. Even within the narrow range of head heights considered, the flushness of the rivet head was found to have a dominant effect on both the monotonic and fatigue properties of the lap shear SPR joints. Joints created with a flush head resulted in a greater degree of fiber breakage in the top ply of the CFRP laminate, which resulted in lower lap shear failure load as compared to SPR joints produced with a proud rivet head. Irrespective of the lap shear failure load, rivet pullout was the most common failure mode observed for both rivet head heights. In fatigue tests, the SPR joints produced with a proud head exhibited higher fatigue life compared to SPR joints produced with a flush head. Joints produced with a proud head resulted in slightly longer fatigue life. However, the failure mode in fatigue tests for both head heights was due to crack growth in the plastically deformed region of the bottom aluminum sheet. Microhardness maps of the bottom aluminum sheet showed a lesser degree of plastic deformation in joints produced with a proud head height. A structural stress model commonly used for spot welded joints was adapted to generate a master curve to predict the fatigue life of the SPR joints.

CITATION: Rao, H., Kang, J., Huff, G., Avery, K. et al., "Impact of Rivet Head Height on the Tensile and Fatigue Properties of Lap Shear Self-Pierced Riveted CFRP to Aluminum," *SAE Int. J. Mater. Manf.* 10(2):2017, doi:10.4271/2017-01-0477.

INTRODUCTION

Vehicle mass reduction is an important strategy to improve fuel efficiency and reduce emissions in passenger cars and trucks. Fiber reinforced polymers are becoming increasingly attractive alternatives to traditional structural automotive materials due to their potential to achieve a high strength-to-density ratio [1]. In particular, structural and non-structural components made of carbon fiber reinforced polymer (CFRP) composites are considered for use in passenger vehicles. The introduction of CFRP in an automotive body structure can result in weight savings up to 10% greater than the use of aluminum and other lightweight metals, and can contribute up to 50% weight savings when compared to a steel structure [1,2].

One major challenge of CFRP implementation in automotive structures is joining. CFRP structures may be joined to other composite components, lightweight metals, or steels. Traditionally, resistance spot welds (RSW) have been used extensively in the automotive industry, but cannot be applied to thermoset polymer materials. Other alternatives for joining composites include mechanical fasteners and adhesives which have cycle-times that are not conducive to mass production. Recently, self-piercing rivets (SPR) have emerged as an economical and effective technique to join lightweight metals, and they have been widely used by auto

manufacturers to join aluminum sheets for vehicle bodies [3, 4, 5]. SPR joints between metal sheets have shown superior peel and fatigue strength compared to RSW joints [3,6, 7, 8, 9, 10]. SPRs require neither heating of materials, nor pre-processing steps, which make them ideal for mass-market automotive assembly cycle times. Recent studies have indicated that a SPR can be effectively used to join fiber reinforced plastics to metals [11, 12, 13, 14, 15].

SPR joints are best characterized by the deformation and subsequent interlock between the rivet and substrates. In metal to metal SPR joints, the amount of rivet engagement, which can be characterized in part by the rivet head height, has been shown to play a critical role in the quasi-static strength and fatigue performance of the joint [16,17]. While prior studies on SPR joints between metals and fiber reinforced composites focused on the joint quality affected by die geometry [18], in-plane distance between the rivets [19], and oil pressure in a hydraulic system [20,21], no literature is available on the strength and fatigue performance of SPR joints in composites and metals with consideration of the rivet head height (and corresponding extent of rivet engagement). However, this effect is important to quantify as a head height range must be identified that can produce joints with adequate performance.

Hence, in the present study, the effort is focused on determining the effect of rivet head height on the mechanical properties of a lap shear joint configuration, including the quasi-static failure load and fatigue performance of SPR joints in dissimilar CFRP to AA6111. Two distinct rivet head heights chosen for the study are based on a previous proprietary investigation to determine insertion depths, as well as rivet and die combinations, which would result in adequate rivet engagement for the considered stacks. Joints produced with these two rivet head heights are then compared to SPR joints produced in two similar sheets of AA6111. Finally, by utilizing the fatigue test results from this study, the analytical structural stress model developed by Rupp et al. [22] was used to evaluate the performance and develop a master curve.

MATERIALS AND EXPERIMENTAL PROCEDURES

Tested stacks were composed of a 2.5 mm continuous braided fiber CFRP with a thermoset epoxy resin matrix (top sheet) to 2.5 mm AA6111 as shown in Figure 1a, and a homogenous two sheet stack of 2.5 mm AA6111. In all cases, the AA6111 was in the T4 condition when the joints were created. Composite coupons were cut from compression molded plaques using a wet diamond saw. The axial fiber orientation was always transverse to the longest coupon dimension. Aluminum coupons were sheared from blanks with the rolling direction parallel to the longest coupon dimension.

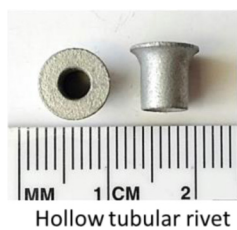
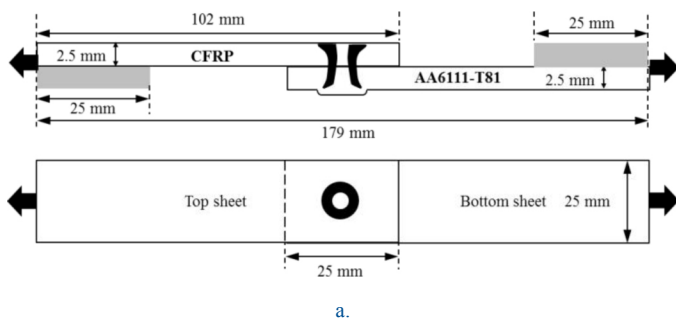


Figure 1. Schematic of (a) the lap shear SPR joint geometry and (b) representative of a hollow, tubular rivet used in this study.

A servo-driven Henrob SPR gun was used to set Henrob tubular-style rivets shown in Figure 1b. The same rivet and die combination was used for all specimens tested in the present work. The rivet insertion process was controlled via adjustment of the punch velocity. The velocity was tuned in 5 mm/s increments to deliver the desired rivet head height or flushness. Specimens were produced with a flush rivet

(no head protrusion) in the mixed material and similar material stacks, and with a head height 0.30 mm above the surface in the mixed material stack. The rivet head height was measured after insertion using a handheld digital indicator with a standardized collar fixture and are presented in Table 1

Table 1. Stack configuration and rivet head height

Stack configuration	Rivet head height (mm) Average (range)
CFRP to Al (proud rivet head height)	0.29 (+0.06/-0.07)
CFRP to Al (flush rivet head height)	0.00 (+0.10/-0.06)
Al to Al (flush rivet head height)	-0.01 (+0.07/-0.04)

Once joined, all specimens were subject to a heat treatment of 180°C for 30 minutes to simulate an automotive paint shop process. The paint bake process aged the AA6111 to stabilize the alloy and prevent further uncontrolled aging effects on test results.

The quasi-static lap shear failure load of the SPR joints was tested on an Instron electromechanical test frame at cross-head speed of 2 mm/min. Load-controlled tension-tension ($R=0.1$) fatigue tests were conducted on the SPR joints using a servo-hydraulic MTS test frame at a frequency of 20 Hz. Doubler with a thickness of 2.5 mm were used during fatigue tests to maintain the alignment of the specimen.

Metallurgical analysis was conducted on tested and untested specimens by sectioning along the centerline of the rivet parallel to the loading direction. Sectioned specimens were cold mounted in epoxy and subjected to standard metallurgical techniques. Fine polishing was done with 0.5µm colloidal silica. Macrographs were taken with a Zeiss digital optical microscope. Microhardness measurements were performed on an AMH43 automated hardness indenter. A load of 300 g was applied with a dwell time of 13 seconds. Indentations were made with a spacing of 200 µm to avoid inaccurate readings due to plasticity induced by a nearby indentation. Fractography was conducted on tested specimens using a FEI Nova Nano 650 scanning electron microscope (SEM).

RESULTS AND DISCUSSION

Metallurgical Examination

Cross-sections were taken through the centerline of untested joints and subjected to metallurgical preparation as shown in Figure 2a and 2b. Flush rivet head heights, while nominally at zero protrusion from the top surface of the CFRP, resulted in deeper local penetration due to pile-up of the carbon fiber composite from the rivet insertion. As a result, the rivet head damages the composite and delamination is observed between the top ply and the remainder of the sheet, as shown in Figure 2c in the indicated region. While fiber breakage and delamination were also observed in CFRP to aluminum SPR joints produced with proud rivet head height as seen in Figure 2d, the extent of damage was less as compared to SPR joints produced with a flush rivet head height.

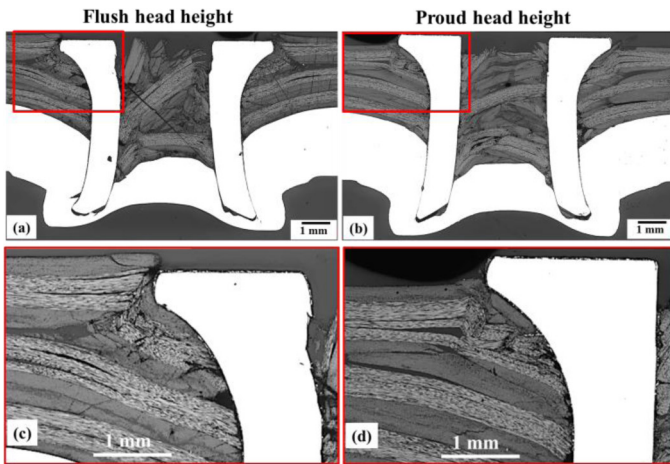


Figure 2. Representative cross-sections of the untested CFRP to Al SPR joints with (a) flush rivet head height, and (b) proud rivet head height, (c) and (d) magnified view of the damage region in CFRP indicating the fiber breakage and delamination in flush head height and proud head height SPR joints respectively.

Monotonic Lap Shear Failure Load

The quasi-static lap shear load-displacement curves of the CFRP to aluminum and aluminum to aluminum SPR joints are presented in Figure 3 for tests conducted in monotonic loading.

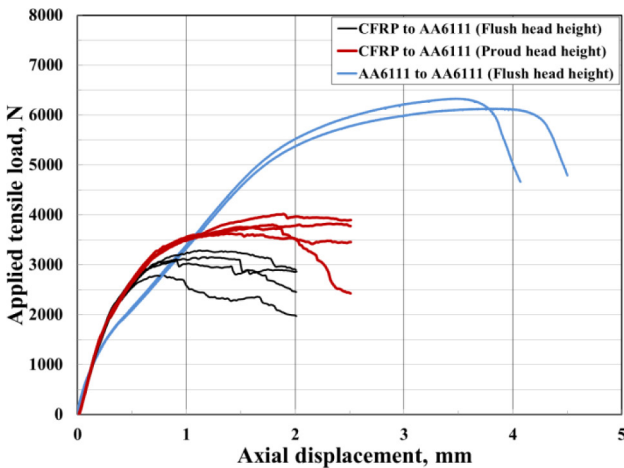


Figure 3. Lap shear load-displacement curves for the SPR joints.

The SPR joints in similar sheets of AA6111 produced the highest overall lap shear failure load of 6231 N. For the joints in CFRP to AA6111, the specimens produced with proud rivet exhibited higher lap shear failure load of 4010 N, while those produced with a flush rivet head height exhibited the lowest lap shear failure load of 2800 N. For all joints considered, failure occurred under monotonic loading by rivet tail pullout in similar AA6111 SPR joints and by head pull-through in both of the CFRP to AA6111 SPR joints as shown in Figure 4.

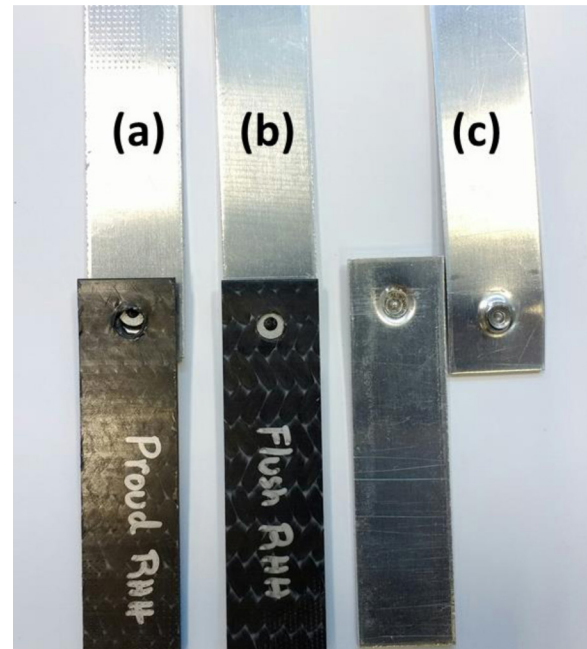


Figure 4. Monotonic lap-shear tensile test failure modes (a) CFRP to Al (proud RHH), (b) CFRP to Al (flush RHH) and (c) Al to Al (flush RHH). The top sheets are toward the bottom of the figure.

These findings are consistent with a prior study and suggest that deeper local penetration of the rivet head can result in delamination and fiber breakage in a continuous fiber composite, thereby leading to lower monotonic performance of the SPR joints [23]. This clearly indicates that the damage induced to the laminate by the punched hole at the rivet head plays a crucial role in controlling the failure load of SPR joints with a continuous fiber CFRP top sheet in monotonic loading. Hence, even for the small change in rivet head protrusion considered in this study (+0.29 mm and 0 mm from the top CFRP sheet surface for proud and flush head heights, respectively) could lead to variance in lap shear failure load of the SPR joints by about 1200 N.

Fatigue Test Results

The results of fatigue tests conducted on the CFRP to AA6111 and AA6111 to AA6111 lap shear SPR joints are presented in Figure 5. Each point represents one specimen, and the lines indicate the trends of the data for the three specimen types. All tests presented here were conducted with a load ratio of $R=0.1$. Tests conducted on SPR joints in similar sheets of AA6111 resulted in the shortest fatigue life. Despite their lower monotonic failure load, the CFRP to AA6111 SPR lap shear joints produced with proud rivet head height exhibited superior fatigue life compared to CFRP to AA6111 SPR joints produced with flush rivet head height. However, for maximum loads above 2500 N, it appears the rivet head height has little to no impact on the fatigue life of SPR joints with a CFRP top sheet.