Tensile and fatigue behaviour of self-piercing rivets of CFRP to aluminium for automotive application

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Abstract. In this study, the tensile and fatigue behaviour of self-piercing rivets (SPRs) in carbon fibre reinforced plastic (CFRP) to aluminium 6111 T82 alloys were evaluated. An average maximum lap-shear tensile load capacity of 3858 N was achieved, which is comparable to metal-to-metal SPR lap-shear joints. The CFRP-Al SPRs failed in lap-shear tension due to pull-out of the rivet head from the CFRP upper sheet. The CFRP-Al SPR lap-shear specimens exhibited superior fatigue life compared to previously studied aluminium-to-aluminium SPR lap-shear joints. The SPR lap-shear joints under fatigue loads failed predominantly due to kinked crack growth along the width of the bottom aluminium sheet. The fatigue cracks initiated in the plastically deformed region of the aluminium sheet close to the rivet shank in the rivet-sheet interlock region. Scatter in fatigue life and failure modes was observed in SPR lap-shear specimens tested close to maximum tensile load.

1. Introduction
The mandatory fuel efficiency requirements established in the Corporate Average Fuel Economy (CAFE) standards compel every auto manufacturer in the US to build new cars and light trucks that meet the minimum fuel efficiency targets. One way to achieve improved fuel efficiency is vehicle light weighting, wherein aluminum and magnesium alloys, high strength steels, and polymer composites are used extensively in structural members. With the advancement in research, fiber reinforced polymer composite materials have shown a number of advantages over other lightweight alloys due to their high strength-to-weight and stiffness-to-weight ratios[1]. Studies have shown that the introduction of fiber reinforced plastics in automotive body structures could achieve weight savings up to 50-60% when compared to other lightweight metals, such as aluminum (which can only obtain weight savings up to 40-55% over the baseline steel structures) [2,3].

The use of lightweight fiber reinforced composites in automotive structural members yet faces a new challenge in terms of joining. Resistance spot welding (RSW), as a conventional joining method which has been widely used in automotive industry, is not feasible if one of the materials in use is a fiber-reinforced polymer composite. Instead, commonly-used joining process involving polymer and metallic materials include adhesive bonding and mechanical fastening [4]. Self-piercing riveting (SPR) is a high speed mechanical fastening technique where a tubular rivet is pierced through the top sheet and partially through the bottom overlapping sheet which are held against a die of asymmetrical cavity[5]. SPR is widely used by several automotive manufacturers as an economical and effective technique to join aluminum vehicle bodies [6–9]. SPR joints of aluminum to aluminum [6,10–14],
magnesium to magnesium [15], and aluminum to steel [16–18] alloys have shown superior peel and fatigue strength compared to RSW joints. Unlike welding, SPR does not involve any heating or melting of material, nor does it require additional manufacturing processes, like pre-drilling holes, which could add additional manufacturing time and cost [5]. Therefore, it is feasible to use this technique when joining polymer-based fiber reinforced composite materials. Studies have shown that SPR technique can be effectively used in joining fiber reinforced composites to metals like steels [19] and aluminum alloys [1,20–24]. A majority of the studies on SPR in fiber-reinforced composites to metals focus on the influence of the process parameters on joint quality, including die geometry [25], distance between rivets [21], and oil pressure in the riveting system [1,26,27]. Very few studies have been conducted on the fatigue performance of SPR in composite to metal joints [1,21,23]. During the SPR process, the piercing of rivets through the composite panel causes localized damage by cutting the fibers; it also brings about deformation of the bottom aluminum sheet which results in a stress concentration and causes local changes in the material properties around the rivet shank. These changes in material properties can influence the mechanical property and the structural integrity of the SPR joint overall.

In the present study, the effort is focused on determining the mechanical properties, including the quasi-static and fatigue performance, of SPR joints in dissimilar CFRP-to-aluminum alloys for potential automotive applications.

2. Materials and experimental procedures
The CFRP to aluminium 6111 T82 lap-shear SPR specimens were fabricated on a Henrob servo-electronic riveting gun using steel rivets. Each sheet measured 2.5 mm in thickness and the rivets measured 7.8 mm in diameter. The CFRP panels used in this study were carbon fibre reinforced epoxy comprised of a three-layer braided fabric (0°/±60°)₃. The rivets were installed while the aluminum alloy was in the T4 condition. Then, after the joints were created, the entire specimen was subjected to a heat treatment similar to that experienced by structural members of the vehicle during the manufacturing process, resulting in a final heat treatment of T82. The final geometric configuration of the SPR joined test specimen is shown in Figure 1 and the cross-section of the SPR joint is shown in Figure 2. The macro image of cross-section (Figure 2(a)) shows the top CFRP sheet, the steel rivet, and the bottom aluminium sheet which is interlocked with the rivet. Both Figure 2(b) and 2(c) show the magnified regions closer to rivet shank indicating the presence of a thin sandwich layer of CFRP between the steel rivet surface and the aluminium sheet.

Quasi-static lap-shear testing of the specimens was performed on a MTS servo-hydraulic test frame in displacement control at a crosshead speed of 2 mm/min. The load-controlled fatigue test was performed on a MTS servo-hydraulic testing machine at a frequency of 20 Hz in a tension-tension mode at a load ratio of R=0.1. Shims of 2.5 mm thickness were used on both ends of the lap-shear specimens to ensure alignment during testing.

![Figure 1. Geometrical dimensions of the representative SPR lap-shear CFRP-Al 6111 T82 test specimens.](image-url)
After testing, fractography was performed on the SPR lap-shear specimens using an FEI Nova Nano 650 scanning electron microscope (SEM). Some of the tested and untested SPR lap-shear specimens were then cut parallel to the loading direction along the center of the specimen width. These were cold mounted, ground using standard metallurgical techniques, and finely polished using a 0.5 μm colloidal silica solution. The macrographs of the mounted samples were taken under a Zeiss digital optical microscope.

![Image](image_url)

**Figure 2.** Representative cross-section of an untested SPR CFRP-Al test specimen; (a) macrograph showing the CFRP and aluminium sheet interlocked by a steel rivet; (b) and (c) magnified view of the rivet and aluminium surface interface under SEM showing the presence of a thin layer of CFRP.

### 3. Results and discussion

#### 3.1. Tensile test

The lap-shear tensile test results of the SPR CFRP to aluminium 6111 T82 joints are shown in Figure 3. A maximum load of 3890 N was achieved with an average of 3858 N maximum load between the two specimens tested. Both of the tested lap-shear specimens failed due to pull-out of the rivet from the top CFRP facilitated by the damage to the CFRP around the rivet head. The inset in Figure 3 shows the resulting damage of the CFRP after the lap-shear tensile test. Note that the steel rivet is more rigid than the CFRP panel and thus a compressive force is applied at the interface of the rivet head and the CFRP panel. This results in penetration of the rivet head into the laminate forming a relief on the CFRP panel [1,20]. In this study, the rivet head entered the top CFRP laminate and damaged the top carbon fiber ply leading to the pull-out of the CFRP panel. This type of failure, where the top fiber reinforced composite panel fails due to the damage induced in the laminate by cutting of fibers, is generally referred to as the bearing failure [1,23].
3.2. Fatigue test

The fatigue test results of the CFRP to aluminium 6111 T82 SPR lap-shear specimens are presented in Figure 4. The plot in Figure 4 also compares the fatigue life of AA6111-AA6111 (2 mm thickness) SPR lap-shear specimens [10]. From Figure 4, it is seen that the fatigue life of CFRP-Al SPR lap-shear specimens are higher than that of the Al-Al SPR lap-shear specimens of 2 mm thickness, despite the lower quasi-static load of the CFRP to aluminium 6111 T82 joints compared to AA6111-AA6111 SPR lap-shear specimens. The fatigue test results of the CFRP to aluminium 6111 T82 SPR lap-shear specimens also displayed a large scatter in fatigue life as the maximum fatigue load approached the maximum quasi-static load (3857 N). A similar scatter in fatigue life was also reported elsewhere in studies performed on SPR in composite to aluminum alloys [1,21,23]. This scatter in fatigue life close to maximum static load may be due to the scatter in the quasi-static behavior of the joints, which is suggested in Figure 3. This scatter in maximum load bearing capacity of the SPR joints may be due to the riveting process, the localized damage of the CFRP during the riveting process or other factors, which are yet to be fully understood. In general, the scatter in lap-shear tensile test is within the nominal range; however, the scatter in the fatigue data close to the maximum load level is significantly larger, as observed in this study.

The dominant mode of failure observed in this study was the fatigue cracks growing in a kinked manner along the width of the bottom aluminum sheet. The fracture surface of a representative tested aluminum coupon is shown in Figure 5 (loading direction is out of the plane of the page). Observation of the aluminum fracture surface in Figure 5(a) reveals the fatigue crack initiated at the periphery of the cold-worked region close to the aluminum-rivet interlock, as seen in Figure 5(b) and 5(c). The SEM micrographs indicate that the probable cause of crack initiation was the local stress concentration in the plastically deformed region. During the SPR process, the bottom aluminum sheet locally undergoes plastic deformation between the rivet shank and die, which results in cold working of the aluminum sheet [24]. Generally speaking, cold working not only increases the strength of the aluminum alloy but also introduces the high stress concentration in the region [1]. Outside the plastically deformed region, the material property of aluminum is that of the base metal. Hence, this plastically deformed region is small, and is localized to the area around the rivet and aluminum sheet interface. From the fatigue striations seen in Figures 5(d) and 5(e), it appears that the fatigue cracks grow steadily in the cold-worked plastically deformed region of the aluminum sheet. Once the fatigue crack reaches the base metal, catastrophic failure can occur in the bottom aluminum sheet.
Figure 4. Fatigue test plot comparing the fatigue life of CFRP to aluminium 6111 T82, and AA6111 to AA611 [10] SPR lap-shear joint (R=0.1).

Figure 5. Fracture surface analysis of aluminum sheet that failed due to kinked cracks (a) macrograph of the fractured aluminum sheet (loading direction out of the page); (b) and (c) SEM images of the crack initiation region on the left and right side of the rivet respectively, the bold black arrows indicate the crack propagation direction; (d) and (e) magnified SEM images region R1 and R2 showing the fatigue striation in the crack propagation region.
The superior fatigue life performance of the CFRP to aluminium 6111 T82 SPR lap-shear joints compared to AA6111-to-AA6111 lap-shear joints may be attributed, in part, to the absence of fretting damage in the former. In several studies of metal-to-metal SPR lap-shear joints, fretting has been observed to be one of the dominant causes for crack initiation and significantly accelerated the crack growth in these SPR lap-shear joints [8,10,28–30]. Even though fretting was also observed in SPR lap-shear joints of aluminum to glass-fiber reinforced thermoplastic composite [23], no traces of fretting were observed in any of the SPR lap-shear test specimens tested in this study. Absence of fretting in this study may be attributed to the presence of a thin layer of CFRP sandwiched between the interfaces of the rivet and the aluminum sheet, as seen in Figure 2(b) and 2(c). The friction coefficient between the CFRP and the aluminum sheet is around 0.2, while the friction coefficient between two faying aluminum sheets is around 1.2 [31]. Hence the low friction coefficient between the CFRP and aluminum sheet produced no fretting which otherwise could reduce the fatigue life of the CFRP-Al SPR lap-shear specimens.

![Damage of CFRP after fatigue test](image)
![Damage of CFRP after tensile test](image)

**Figure 6.** Top view of the damaged CFRP panel in (a) fatigue test; (b) tensile test; (c) and (d) are the magnified view of the region R3 and R4 showing the carbon fibre breakage and matrix damage in SPR lap-shear specimens tested under fatigue and quasi-static load respectively.

In quasi-static lap-shear tension, significant damage to the CFRP panel close to rivet head was observed which led to bearing failure. It is interesting to observe a similar failure mode also occurred in some SPR lap-shear specimens that were fatigue tested close to maximum static tensile load. In the two SPR lap-shear specimens that were fatigue tested at a maximum load of 3664 N (95% of the maximum tensile load), bearing failure was observed in one of the SPR lap-shear specimen that failed at 689 cycles, while the other suffered failure in the bottom aluminum sheet at 159,730 cycles. Figure
6 shows the SEM pictures comparing the bearing failure due to the damage in the CFRP panel in fatigue and tensile tested specimens. Comparison of Figure 6(a) and Figure 6(b) shows that the damage of the CFRP panel in an SPR lap-shear specimen tested close to the maximum quasi-static load is very similar to that observed in the quasi-static tensile specimens, respectively. Magnified views of the regions R3 and R4 show severe damage to polymer matrix and fiber breakage in both the fatigue and quasi-static tested SPR lap-shear specimens. In addition, once the top ply of carbon fibers and the polymer matrix are damaged, the compacting or locking mechanism between the rivet and CFRP panel can be released. The significant disparities in fatigue failure mode and fatigue life at this load level may be due to manufacturing variation of the joints. Further researches should be done to understand the impact of possible differences in the manufacturing process on the fatigue performance of the CFRP to aluminium 6111 T82 joints at both high and load low levels.

![Image](image_url)

**Figure 7.** Failure modes observed in SPR joints tested at a load of 2778 N.

Figure 8 shows the comparison of two SPR lap-shear specimens, i.e. #3 and #20 that failed due to rivet pull-out (#3) and one-sided fracture of the aluminum sheet (#20). Delamination of the top CFRP panel close to the rivet head interface was observed in SPR lap-shear specimen #3 (Figure 8(b)) and no delamination was observed in SPR lap-shear specimen #20 (Figure 8(c)). The probable reason for delamination and rivet pull-out failure still needs to find. It is expected that variations in the manufacturing process may lead to the observed scatter in fatigue life, as well as the failure mode.

**4. Conclusions**

Tensile and fatigue properties of dissimilar CFRP to aluminium 6111 T82 alloy SPR joints were evaluated in this study. A comprehensive failure analysis was performed to study the failure modes and factors influencing the mechanical properties. The following conclusions can be drawn from this study:
The SPR technique can be used to effectively join dissimilar CFRP and AA6111 T82 alloy for automotive structural applications. The average maximum lap-shear tensile load capacity of the CFRP to aluminium 6111 T82 SPR lap-shear joints in this study is 3858 N, which is comparable to the metal-to-metal SPR lap-shear joints studied earlier.

In quasi-static lap-shear tensile tests, damage to the top ply of the CFRP panel around the rivet head interface could lead to bearing failure. No further damage to CFRP panel was observed either in static or fatigue tests.

In fatigue tests, the dominant mode of failure was crack growth along the width of the bottom aluminium sheet. Fatigue cracks initiated at the high stress concentration region in the plastically deformed area close to the rivet-aluminium interlock.

The CFRP to aluminium 6111 T82 SPR lap-shear joints in this study exhibited superior fatigue life compared to AA6111 to AA6111 SPR lap-shear joints studied earlier. The absence of fretting may have contributed to the improved fatigue life.

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