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COMPARATIVE ANALYSIS OF IN-PLANE AND OUT-OF-PLANE MECHANICAL BEHAVIOUR OF SPOT-WELDED AND MECHAINCALLY FASTENED JOINTS IN THERMOPLASTIC COMPOSITES

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Keywords: Thermoplastic composites, spot-welded joint, mechanical behaviour, fracture analysis

Abstract
Ultrasonic welding is a promising assembly technique for thermoplastic composites and it is well-suited for spot welding. In this paper, the in-plane and out-of-plane mechanical behaviour of ultrasonically spot-welded and mechanically fastened joints are investigated by double-lap shear and pull-through tests, respectively. Special attention was paid to the comparison of onset failure load and joint stiffness of both types of joints in either type of test. Fractography was utilized to analyse the teste specimens. Failure of welded specimens was found limited in the joints but catastrophic damage was introduced into composite substrates of mechanically fastened specimens. The possibility of the substitution for mechanically fastened joints by spot-welded joints is discussed.

1. Introduction

Thermoplastic composites (TPCs) are becoming increasingly attractive for their usage in aircraft structures owing to their high-grade mechanical properties and cost-effective manufacturing process [1-4]. Since thermoplastic polymers can be melted when heated to a certain temperature and recover their initial properties after cooling down, TPCs can be welded, which is regarded as a promising alternative to the traditional joining techniques applied on thermoset composites, such as mechanical fastening and adhesive bonding. Different from the continuous welding seams enabled by the well-known induction and resistance welding, spot-welded joints, which can be manufactured via ultrasonic welding, provide smaller welded areas and hence lower consumed energy and faster welding time. Although spot welding techniques have been extensively studied on metal structures [5, 6], the knowledge on TPCs is still limited, including both the welding process and the mechanical behaviour of the joints. This paper aims to study the in-plane and out-of-plane failure and mechanical behaviour of ultrasonically spot-welded joints through mechanical tests.

As it is known, various problems can be introduced when mechanical fasteners are used in composite structures [3, 4], therefore spot-welded joints could be considered as a possible alternative for joining TPCs due to the similar configuration. Therefore, the testing techniques for characterizing the mechanical behaviour of mechanically fastened joints, which have been extensively used, can provide a reference for the research on spot-welded joints. For instance, a combination of experimental and numerical studies was carried out to study the effect mechanisms of different fasteners (protruding head vs. countersink) on mechanical behaviour of double-lap shear composite bolted joints [7]. Benefiting from the symmetrical geometry of the double-lap specimens, the in-plane mechanical performance and failure process of both types of fasteners were well characterized. Apart from this, pull-through tests were performed in [8] and [9] to study the out-of-plane failure of mechanically fastened composite joints. The pull-through resistance of composite substrates was characterized and delaminations were observed within the laminates and propagating away from the vicinity of bolted hole.

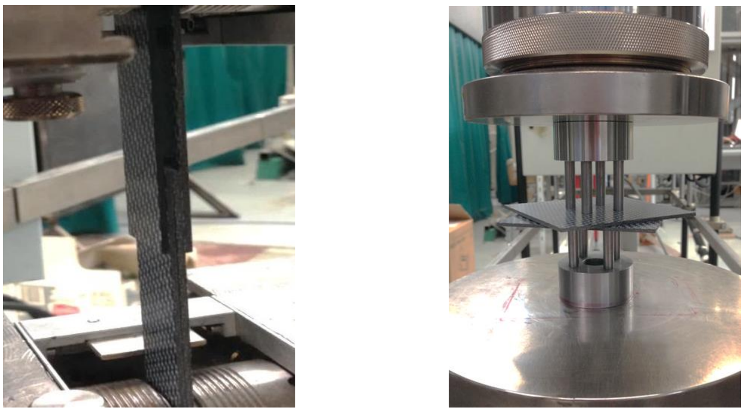
Based on the literature, two sets of mechanical tests, i.e. double-lap shear and pull-through were performed in this research to characterize the in-plane and out-of-plane failure of ultrasonically spot-welded joints. To provide an objective evaluation, a similar study was conducted on mechanically fastened joints followed by a comparative analysis.

2. Experimental

2.1. Mechanical Testing and Analysis

Double-lap shear (DLS) tests were performed to characterize the in-plane failure and mechanical performance of both spot-welded and mechanically fastened joints since the effect of out-of-plane bending can be effectively diminished in this configuration [7, 10]. As shown in Fig. 1 (a), specimens were clamped with hydraulic grips and tested on a Zwick/Roell 250kN universal testing machine. Following ASTM D5332, specimens consisting of 4 rectangular composite plates (114.4×25.4 mm^2) were tested with a crosshead speed of 1.3 mm/min. The process was stopped when the applied load had a 30% decrease of the maximum to prevent an over distortion of the specimens. Five specimens were tested for both the welded and mechanically fastened joints.

Pull-through (PT) tests were performed on both spot-welded joints and mechanically fastened joints following the ASTM D7332 standard. Tensile behaviour (out-of-plane failure) of welded joints was investigated during the tests. Two square composite substrates with 80 mm-side-length were placed between the text fixture, as shown in Fig. 1 (b). Testing was performed in a Zwick/Roell 250kN universal testing machine with a crosshead displacement rate of 0.5 mm/min. Five specimens were tested for both the welded and mechanically fastened of joints.



(a) (b)

Figure 1. DLS (a) and PT (b) test specimen configuration.

Mechanical behaviour of both welded and mechanically fastened joints was characterized by the Load-Displacement (L-D) response. Based on the L-D curves, the load-carrying capability and joint stiffness were utilized to evaluate the mechanical performance of both types of joints. As indicated in [7, 9, 11], the load-carrying capability of the mechanically fastened joints should be considered as the point of onset failure for the joint rather than the point of ultimate failure. In this paper, the onset failure load (OFL) was calculated by the bilinear approximation and the joint stiffness (JS) was the linear fitting of the elastic stage of L-D curves before the joint onset failure. The fracture surfaces of tested samples were inspected by using a Zeiss Stereo Microscope. In addition, the failure mechanisms of spot-welded joints were assessed with a JSM-7500F Scanning Electron Microscope (SEM).

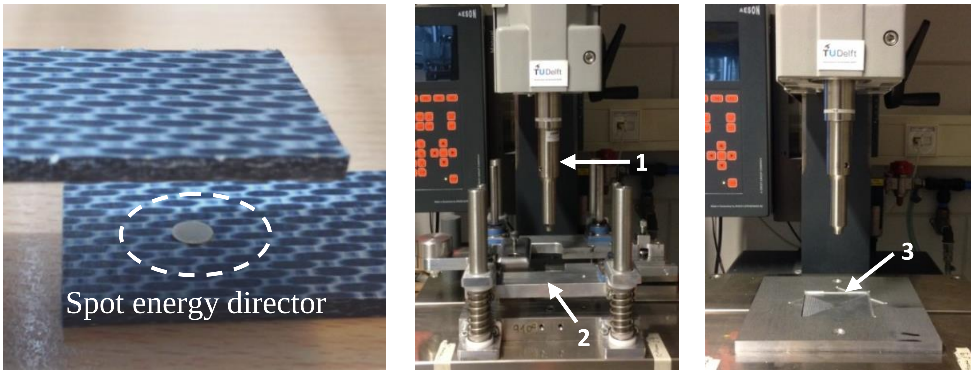
2.2. Materials

The material used in this study was 5 harness satin fabric CF/PEEK (carbon-fibre reinforced poly-ether-ether ketone), which was supplied by TenCate Advanced Composites, The Netherlands. With a $[0/90]_{3s}$ stacking sequence, 580 mm × 580 mm laminates were consolidated in a hot-platen press at 385℃ with a pressure of 1 MPa for 20 min. The final thickness of the laminates was approximately 1.90 mm. Samples were cut into the required dimensions according to the ASTM D7332 and D5332 standards with a water cooled diamond saw.

2.3. Assembly Techniques

A 20 kHz Rinco Dynamic micro-processor controlled ultrasonic welder was used in this study to weld individual samples. Different from the continuous welds, the spot-welded joints are created by the usage of a circular spot energy director (ED), as shown in Fig. 2 (a). In this study, a 4 mm-fixed-diameter ED was utilized to keep close to the pin diameter of the employed mechanical fasteners (4.8 mm). The spot ED was manually fixed on the central point of the overlap prior to the welding process. Correspondingly, a circular titanium sonotrode (Fig. 2 (b)) with a 10 mm diameter was employed to avoid secondary welding on the edge of the overlap. Two different custom-designed jigs were used in the welding process for the DLS and PT configurations, as shown in Fig. 2 (b) and (c). Welding force,vibration amplitude and welding energy were selected as 1500N, 60.8 μm (peak-to-peak) and 600J, respectively. The solidification force and time were set to 1500N and 4000ms.

The mechanically fastened composite specimens were assembled by Hi-Lok™ fasteners. Two types of titanium Hi-Lok™ fasteners with protruding head, i.e. HL10V6 and HL 12V6, were used for DLS and PT tests, respectively. The fastener hole was drilled with a 0.1 mm diametric interference [12] and the fasteners were installed with a ratchet wrench.



(a) (b) (c)

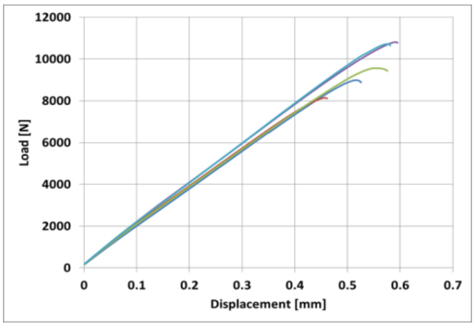
Figure 2. Spot energy director (a) and the ultrasonic welding machine (b and c) used in this study. 1: 10 mm-diameter-circular sonotrode, 2: welding jig for DLS samples, 3: welding jig for PT samples.

3. Results and Discussion

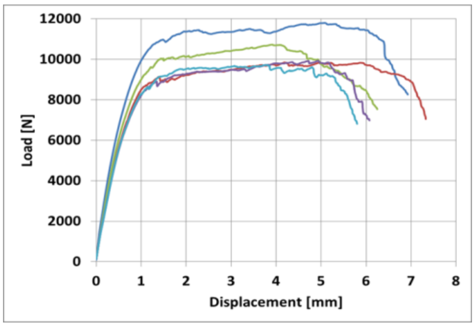
3.1. Double-Lap Shear (DLS) Tests

The L-D response of both spot-welded and mechanically fastened joints is illustrated in Fig. 3 (a) and (b), respectively. The applied load of all welded samples linearly increases until a maximum is reached. Neither load drop nor stiffness (slope) reduction is observed from the L-D curves before reaching the maximum. In contrast, test results of mechanically fastened specimens show a good agreement with the study in [7], indicating that the joint failure experiences several stages: (1) the initial linear stage; (2) the stage of slight slope decrease (bearing initiation); (3) the stage of significant slope decrease (bearing damage present); (4) the stage of constant load-carrying (damage propagation); (5) sharp drop of the applied load (the final failure).

Fig. 4 shows the comparison of average onset failure load (OFL) and joint stiffness (JS) of both types of joints. Based on the indication in Fig. 3, the onset failure load for welded specimen is equal to the ultimate failure load. Therefore, it can be noted that the spot-welded joints have a comparable OFL compared to the mechanically fastened counterparts. However, the average JS of the mechanically fastened joints is approximately half of the welded joints, which is considered to be attributed to the presence of the bolted hole and thus leading to a stiffness reduction for the composite substrates.



(a)



(b)

Figure 3. Load-displacement (L-D) curves of spot-welded (a) and mechanically fastened (b) joints in DLS tests.

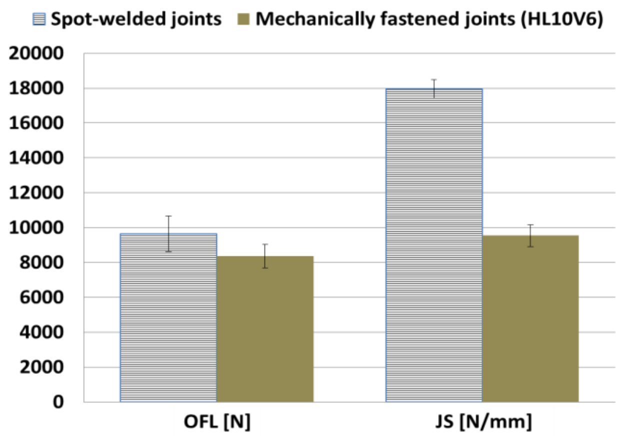


Figure 4. Comparison of mechanical performance between spot-welded and mechanically fastened joints in DLS tests. (OFL: onset failure load, JS: joint stiffness)

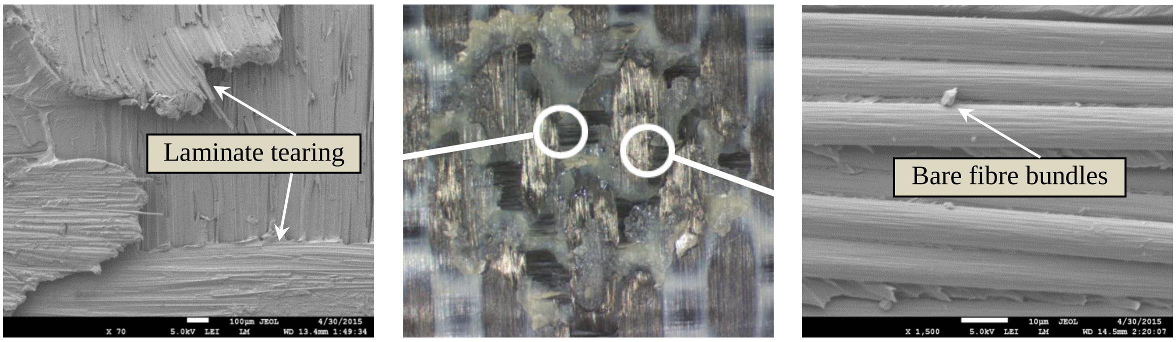


Figure 5. Fracture surface of the spot-welded joint after DLS tests (middle). The left and right images show SEM details for the failure modes, indicated by the left and right white circles on the fracture surface, respectively. Welding parameters: energy 600 J, welding force 1500 N, peak-to-peak amplitude 60.8 μm.

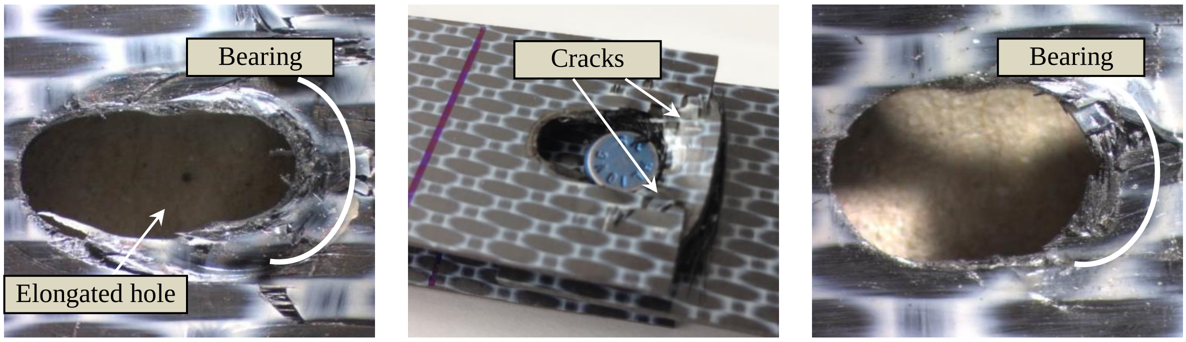


Figure 6. Fracture surface of the mechanically fastened joint after DLS tests (middle). The left and right images show the damaged area and elongated hole of outer and inner substrate after removing the Hi-Lok™ fastener, respectively.

Based on the post-mortem visual inspection of fracture surfaces, the welded area is found as a circular spot with a diameter of approximately 10 mm (shown in the middle of Fig. 5). Further analysis was performed by using SEM to determine the failure mechanisms of the spot-welded joints. Intralaminar failure is found as the major failure mode. Sections of the first ply with broken fibres show the failure on the outmost surface of the substrates (left side of Fig. 5). Bare fibre bundles are observed in the resin starved region, shown in the right side of Fig. 5, which indicates the separation of fibres and polymer matrix. It should be noted that the fracture surface is limited in the welded area and no further damage is observed on the sample surface. However, apparent bearing damage can be found on the mechanically fastened specimens after DLS tests (shown in the middle of Fig. 6). The penetration of the fastener head and pin are indicated by the trace on the surface of the outer and inner plates, respectively. Two cracks are found propagating away from the bolted hole, implying the damage affected zone is not limited in the vicinity of the hole and that eventual shear-tear out damage develops in the substrates.

3.2. Pull-through (PT) Tests

The L-D response of spot-welded samples in PT tests also shows a linear increasing trend and no stiffness reduction (Fig. 7 (a)). The stiffness (slope) reduction indicates that the joint failure is initiated when the applied load increases to approximately 2500 N (Fig. 7 (b)). Different from the outcomes of DLS tests, the mechanically fastened joints still perform continuously increasing load-carrying capability after the failure onset and until the ultimate failure.

Correspondingly, the comparison of the onset failure load and joint stiffness of both types of joints are shown in Fig. 8. Compared to spot-welded joints, the mechanically fastened specimens show significantly higher onset failure load for carrying the peel load due to the through-the-thickness reinforcement effectively provided by the mechanical fasteners. Nevertheless, due to the presence of the bolted hole, the joint stiffness of welded samples is slightly better than the mechanically fastened counterparts.

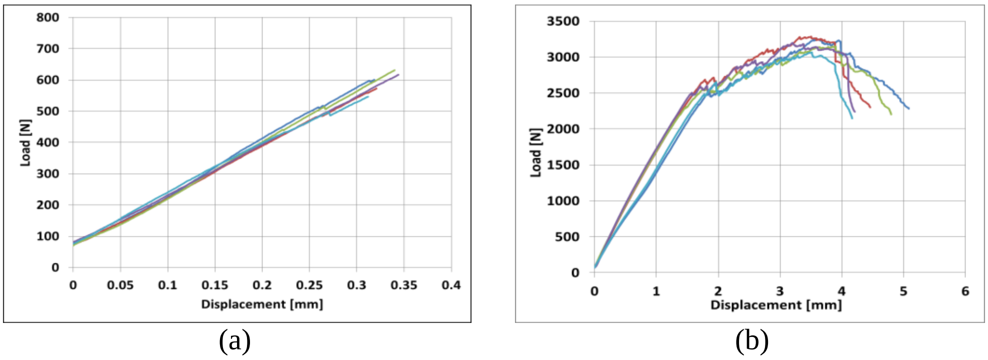


Figure 7. Load-displacement (L-D) curves of spot-welded (a) and mechanically fastened (b) joints in PT tests.

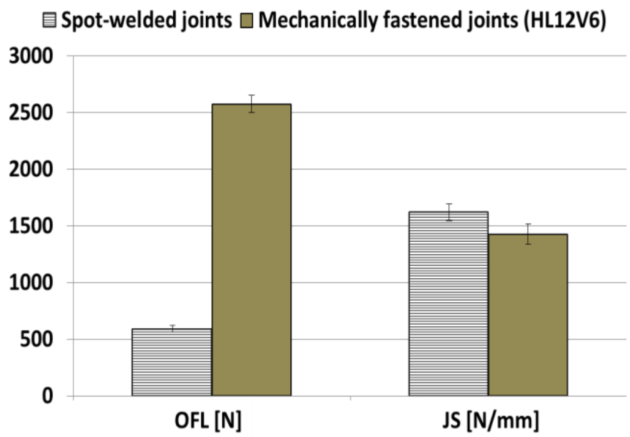


Figure 8. Comparison of mechanical performance between spot-welded and mechanically fastened joints in PT tests. (OFL: onset failure load, JS: joint stiffness)

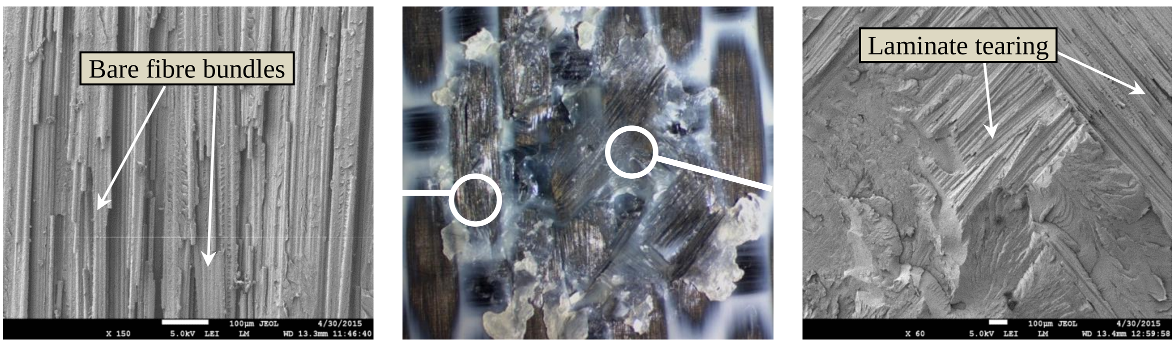


Figure 9. Fracture surface of the spot-welded joint after PT tests (middle). The left and right images show SEM details for the failure modes, indicated by the left and right white circles on the fracture

surface, respectively. Welding parameters: energy 600 J, welding force 1500 N, peak-to-peak amplitude 60.8 μm.

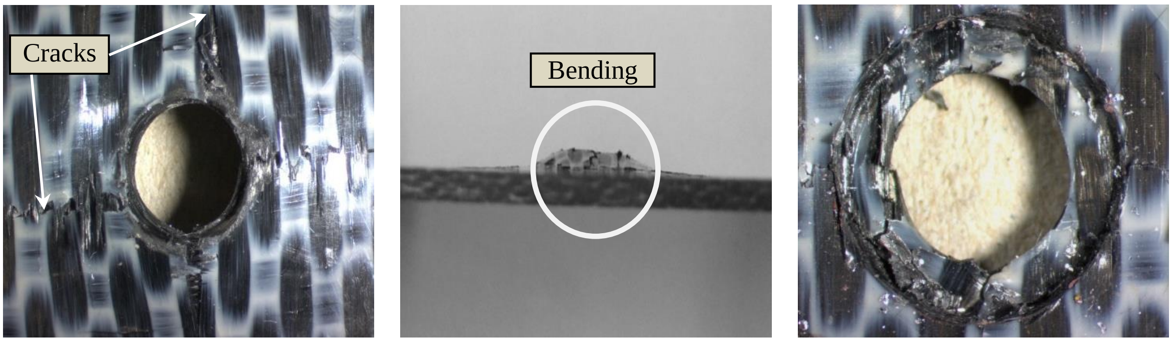


Figure 10. Side view of the bottom substrate of mechanically fastened specimen after PT tests (middle). The left and right images show the top and bottom view of the bottom substrate after removing the Hi-Lok™ fastener, respectively.

Similar to the observation in DLS tests, the visual inspection on welded samples after PT tests reports that a circular welded joint (approximately 9 mm in diameter) presents on the central point of overlap (Fig. 9) and no further failure appears on the sample surface. Meanwhile, SEM analysis indicates that intralaminar failure, consisting of fibre-matrix debonding and laminate tearing, is still the major failure modes for welded joints. As a comparison, bending failure happens on the bottom substrate of mechanically fastened specimens due to the penetration of the Hi-Lok™ collar during tests (Fig. 10). Cracks are found radially propagating away from the bolted hole and thus leading to a significant size of damaged zone in the substrates [8].

4. Conclusions

Two different sets of mechanical tests, i.e. double-lap shear and pull-through tests, were carried out to provide a comparative study on the in-plane and out-of-plane mechanical performance between ultrasonically spot-welded and mechanically fastened joints employing Hi-Lok™ fasteners on thermoplastic composites. Furthermore, the fracture surfaces of tested specimens were visually inspected and the failure modes for both types of joints were determined. Based on the experimental results, the following conclusions can be made:

- The spot-welded joints show comparable OFL and significant higher JS compared to the mechanically fastened joints in DLS tests, which implies that spot-welded joints can be a competitive substitution for the structures carrying shear load. However, it should be noted that the OFL of mechanically fastened joints could become higher if the thickness of substrates increases. Therefore, the welded joints are suggested to be used for assembling relatively thin structures.
- In PT tests, although the onset failure load of welded samples is lower than the mechanically fastened counterpart, benefiting from the absence of the bolted hole, the joint stiffness of welded samples is still slightly higher than the mechanically fastened one. In addition, although peel load is inevitable in real applications, the spot-welded joints are still adequate when the out-of-plane load is lower than the failure value of the joint.
- For both in-plane and out-of-plane tests, the failure of spot-welded samples was found restricted in the joint area, in the form of fibre-matrix debonding and laminate tearing, providing the reusability and repairability for the composite structures. In contrast, severe damage was introduced in composite substrates of mechanically fastened joints during both types of tests. The damage affected zone was much larger than the bolted hole.

Acknowledgments

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