COST EFFICIENT METAL TO FIBRE REINFORCED COMPOSITE JOINING

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Abstract

In this paper, a conceptual simplified joining methodology is proposed for the cost and time efficient metal to Fiber Reinforced Plastic (FRP) joining. In this joining technique, three dimensional vertical metallic reinforcements (pins) are welded on metallic part of joint overlap. Preheated thermoplast sheets are pressed onto these pin arrays. The pins perforate the layers of the uncured FRP by displacing the continuous fibers in liquid matrix without damaging or cutting them. When cured, the pins provide a through thickness form fit with the consolidated FRP. In this paper, it is shown that pin reinforced metal to FRP joints can be produced by the described methodology in a cost and time efficient manner. Furthermore, verification of the proposed novel method has been carried out by performing preliminary tests on the produced coupons under tension, shear and tension – shear loading.

1 Introduction

Within the last decades, multi-material designs consisting of metallic and non-metallic materials are becoming popular for light weight construction in modern energy efficient automobile, aeronautic and naval industries. FRP is one of the most prominent nonmetallic materials used in light weight structural applications due to their superior static and fatigue properties. Efficient joining of **M**etals to fiber reinforced **C**omposites (MC) is essential for the application of multi-material design approaches in above mentioned industries [7].

Mechanical fastening (e.g. riveting, bolting…) is an easy, fast, commonly practiced and cost effective manufacturing process. In case of FRP, the bore holes which are drilled to install the fasteners, disadvantageously cut the reinforced fibers and hence reduce the effective cross sections. Drilling operation causes the delamination and peeling through the plies of FRP [10, 14]. Furthermore, bore holes create singular point loads at the contact points, which leads to localized failure. Fasteners are vulnerable to corrosion and increase the weight of structures due to the additional mass input [11, 15].

Adhesive bonding could be more appropriate to join metals with FRPs as the load distribution would be almost uniform over the joining interface. Design flexibility, ease of fabrication and potential advantages of strength-to-weight ratio has made adhesive bonding a favorable joining methodology for automotive, aerospace and construction industries [15, 16]. However, adhesive joints are vulnerable to harsh environmental condition and show premature failures due to higher peel stress near the ends of adhesive interface [18]. Additionally, they lack a distinct damage tolerance capacity after first failure onset. The lack of appropriate criterions has led to the over design of the adhesive joints which in turn increases the weight of structures [17, 18]. Qualification and inspection of adhesives for crack and debonding detection over the joint interface is time consuming, challenging task and generates maintenance related issues [11].

The drawbacks of conventional MC joining techniques are motivating researchers for actively developing new MC joining technologies which utilize three dimensional through thickness metallic reinforcements (pins) [8, 9, 11]. The pins provide an additional mechanical form fit between the metal substrate and different layers of composite plies in the joints. This results in an increased strength and improved damage tolerance when compared to conventional MC joining methods. Moreover, overdesigning of joints can be achieved by increasing the number of pins on the overlap with negligible weight penalty.

Until present, pin reinforced MC joints, due to their thermoset resin matrix; have been fabricated by a state of art low pressure open molding process [11]. Although the novel pin-reinforced MC joint has shown promising results, the fabrication methodology is difficult, slow, inflexible and expensive for high volume production [2, 7]. This is one of the reasons for the automotive Original Equipment Manufacturers (OEMs) to continue with metal intensive design approaches for their large volume segment products [7].

In the present study, a simple, cost effective and energy efficient MC joining method is presented which can help to provide lighter multi-material joints in the future. The conceptual MC joining methodology is proposed as well as verified through different tensile tests of KS-2 joint specimens.

2 Methodology

- *Step 0: Selection and preparation of Metal and GFRP materials*

Figure 1 (left) shows the metallic U section of the joint which is made by bending 2.0 mm thick stainless steel sheets. Six 15×15mm square arrays of ball head spike pins were welded on the joint surface. Each array (Figure 1 right) is a group of sixteen pins (i.e. a matrix of 4*4 at an equal pitch distance of 5mm) in a square shape. The pin arrays were welded by the “Cold Metal Transfer” – (CMT) process of Fronius on a computer controlled, automated welding machinery [11].

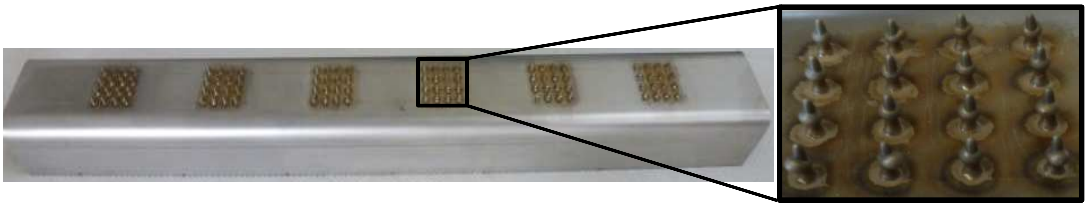

Figure 1 Metallic U section with six arrays of ball head spike pin (left) & a 4x4 pin array (right)

Glass Fiber reinforced PolyPropylene composite (GF/PP) provides a combination of low material cost and high mechanical performance [12]. In comparison to traditional thermoset matrix composites, they possess higher impact tolerance, abrasion and chemical resistance, better toughness and recyclability. As thermoplastics are “melt processable polymers”, they provide a better re-work reparability when compared to thermoset matrix composites [20].

GF/PP enables more possibilities for faster production processes and an unlimited shelf life [3, 5, 6, 13]. State of the art isothermal production methods for processing FRP are slow. That is why the production times and costs are high for glass fiber reinforced plastic parts. On the other hand, non-isothermal processes like stamp forming are relatively fast processes, which can be adopted for large volume production [13].

Modern ready to use, Thermopreg™ [1] is a commingled glass fibre reinforced polypropylene matrix composite from Owens Corning Corporation. Thermopreg™ is available in two forms including woven fabric and pre-consolidated sheets. Balanced 2 x 2 twill weave pre-consolidated Thermopreg™ plates, with 60% glass fibers by weight were selected for the fabrication of the composite part of the MC joint.

The non-isothermal fabrication process began with the cutting of 1 mm thick pre-consolidated Thermopreg™ sheets in a 350×180mm rectangular shape on a guillotine. A stack of four Thermopreg™ sheets were heated in a separate convection oven for 13-15 minutes in order to reach the melting temperature (180°C-230°C) of the Polypropylene matrix [1] .

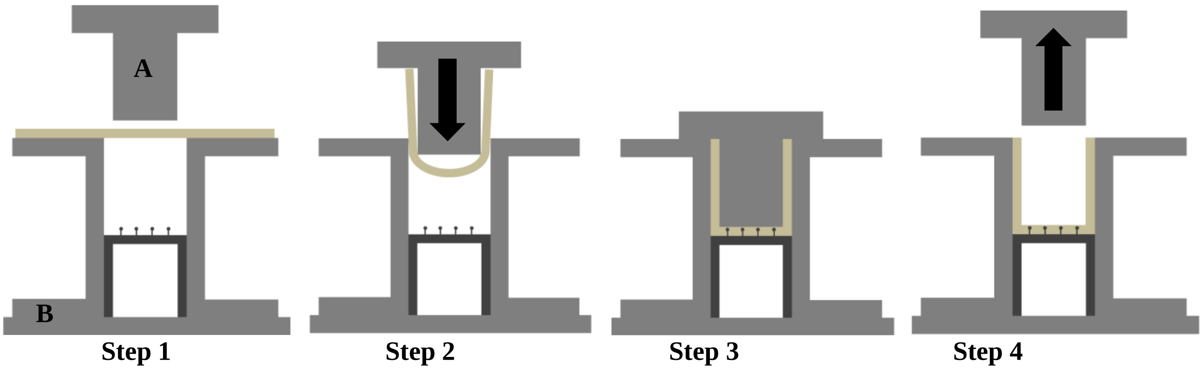

Figure 2 Schematic representations of a one cycle of the joining process

- *Step 1*

Figure 2 shows the schematic representation of joining process cycle. In order to combine thermoforming and joining of the FRP with the metal component in a single step, a temporary tooling setup was used. The tool setup consisted of a rectangular male punch (A) and a U shaped female die (B). The female die was made from two aluminum C sections clamped on a press table. This created the required U shaped cavity.

The metal U profile with pins was placed at the bottom of the die. The tool setup and the metal profile were at room temperature. The preheated 4 mm thick FRP stack was positioned on the horizontal top surface of the female die (see Figure 2 step 1).

- *Step 2*

The top male punch (A) was then driven down into the female die at a speed of 10 mm/second (Figure 2 step 2). At contact with the male punch, the pre-heated FRP starts bending and sliding down into the open cavity along the sidewalls. At contact the pins perforate the FRP stacks in a fiber gentle manner by displacing continuous glass fibers in the semiliquid viscous polypropylene matrix due to the spiked shape of the pin heads.

- *Step 3*

When the pins fully submerged in the FRP, an additional compaction was applied in a displacement controlled manner until the temperature of the pre-heated FRP fell below 40°C (Figure 2 step 3). Consolidation of the U shaped FRP (step 3) took app proximately 3 minutes.

- *Step 4*

Once the FRP was consolidated, the punch was redrawn out of the female die. De-moulding of the resulting 350 mm long H shaped joint components (Figure 3) lead to one batch of pin reinforced MC joints. The overall thermoforming process lasted approximately 20 minutes.

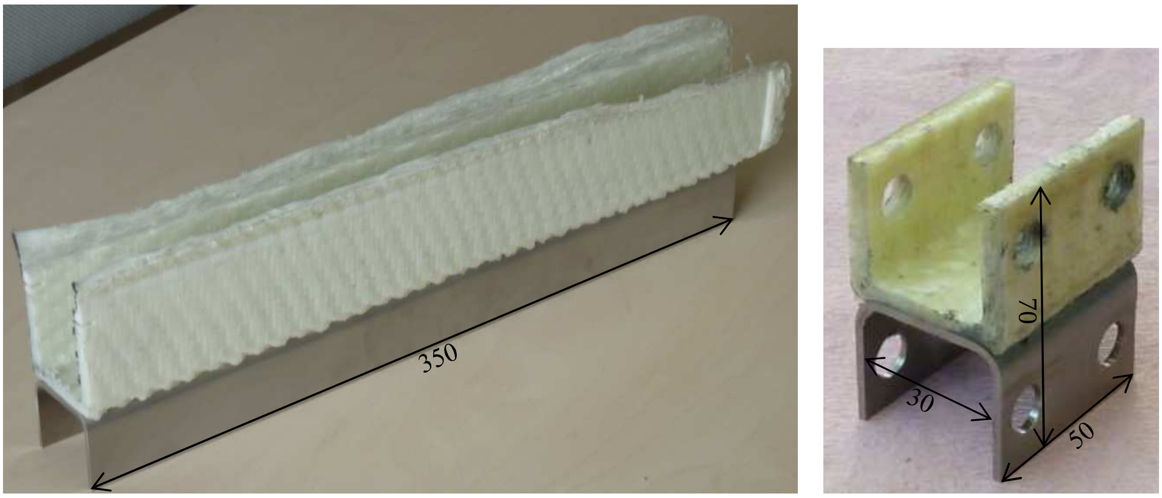

Figure 3 A batch of MC joints (H profile) at end of step 4 (left) and final KS-2 specimen at end of step 5 (right)

- *Step 5*

Out of the one MC H profile, a batch of six equal KS-2 specimens was cut on a precision bench roller cutter. Each specimen had over all dimensions of 70×50×30 mm and final GFRP wall thickness of 4 mm (see figure 3 right). Two clamping holes were drilled in the metallic and composite components of the joints for later clamping in the fixture. For accurate drilling of the holes, a special fixture was used.

3 Experimental testing

The verification of the conceptual joining methodology of section 2 has been carried out by preliminary testing of the MC joint coupons under three different load directions; normal load (0°), shear load (90°) and combined load (45°).

For this, the LWF KS-2 measuring concept [4] (Figure 4) was utilized. The LWF KS-2 measuring concept has been developed by Laboratorium für Werkstoff und Fügetechnik-LWF Paderborn for the characterization of joints [4]. It prescribes a unique joint geometry (Figure 4 left), consisting of two separate U sections joined together by means of any joining technique. This H (KS-2) geometry can be fixed at different angles in specific specimen fixtures in tensile test machines (see Figure 4 right).

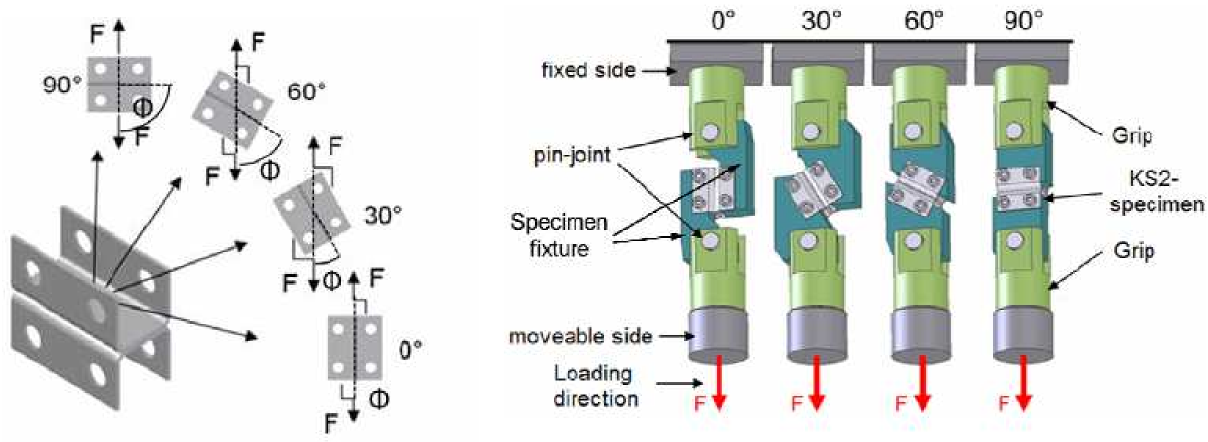

Figure 4 LWF-KS-2 specimen with different load angles (left) and clamping conditions (right) [19]

The joints on the structures are shown to fail in mixed modes. Mode mixity is directly associated with the load transfer behavior of the joints. With the LWF KS-2 measuring concept, it is possible to characterize the strength of the different joining technologies as a function of the loading direction in static, dynamic and monotonic cyclic tests. The dependencies of the joint strengths on the load mode mixity can be determined by using one single specimen geometry. Due to this key advantage, the LWF KS-2 measuring concept had been utilized in this study.

3.1 Test procedure

For the verification purpose, MC KS-2 joint specimens were loaded in normal (90°), shear (0°) and normal-shear (45°) directions on a Zwick/Roell-Z100 tensile test machine. For each different load direction, separate clamping fixtures similar to figure 5 were utilized. Tests were performed at a constant cross head displacement rate of 2 mm/minute.

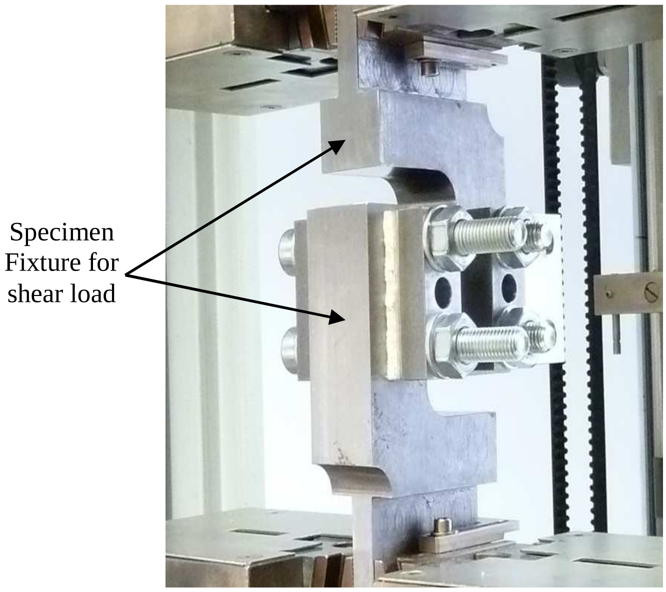

Figure 5 0° shear load test setup with clamped specimen

The specimens were mounted in the fixture by a total of four bolts as shown in figure 5. Test results were recorded in terms of reaction forces and crosshead displacements.

4 Results and discussions

Figure 6 shows the relationship between reaction forces and crosshead displacement for six KS-2 specimens under shear, normal and combined mixed loading. In case of shear loading, mean maximum reaction forces reached up to 5.57 kN +/- 2.50% at a mean crosshead displacement of 3.18 mm +/- 12.00%. In case of 90°- normal loading mean maximum reaction force reached up to 2.77 kN +/- 0.63% at a mean crosshead displacement of 1.52 mm +/- 3.76%. Whereas, in case of 45°- shear-normal mixed loading mean maximum reaction force reached up to 3.30 kN +/- 1.13% at a mean crosshead displacement of 1.50 mm +/- 4.50%. The maximum reaction forces (F_{max}) in mixed loading was 59.1% compared to F_{max} in shear; while for normal loading, F_{max} was 49.7% compared to F_{max} in shear.

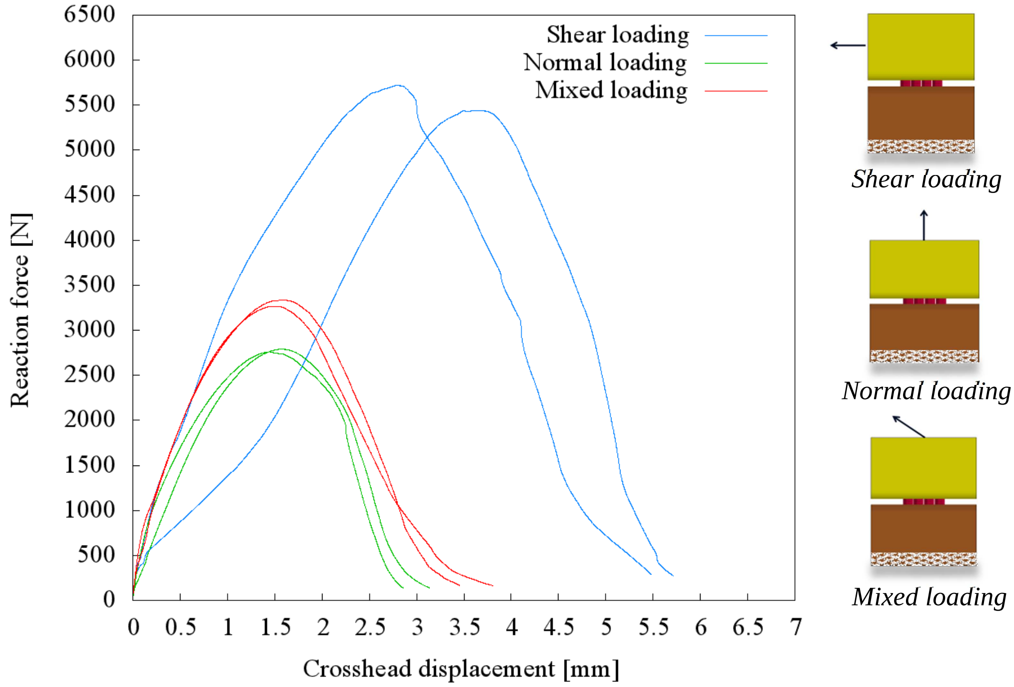

Figure 6 Reaction forces vs. Crosshead displacement for the KS – 2 specimen under shear, normal and mixed mode loading

Pin arrays of the failed metallic KS-2 specimens are shown in Figure 7. These specimens were loaded under the three explained load modes (Figure 6). The highest deformations of the pins have been observed in shear loading of the MC joint. The pins dissipated highest amounts of energy due to plastic deformations in the pins under shear load. As a result, the pin reinforced MC joints could reach the highest average mean reaction force and withstood largest average mean crosshead displacement before failure in shear loading.

The load curves were identical for mixed and normal loading conditions. The load curves showed less than 5% scatter in the maximum reaction forces for all three different loading conditions. Crosshead displacements at F_{max} scattered 12% for shear loaded specimens. It is assumed that this initial stiffness miss-match originated from improper clamping or preliminary induced damage in the joint during the clamping procedure.

Figure 7 Pin arrays after failure of the KS-2 joints under normal (left), mixed (center) and shear (right) load

In Figure 7 it is visible that the pin arrays are not positioned fully centered on the joining overlap areas. This asymmetry in the pin-positioning may have also affected the load transfer results of the joints. This asymmetry in the pin positioning is a combined result of imprecise welding of the metal U profiles and inaccurate cutting of the KS-2 specimen batches.

5 Conclusion and Outlook

The research work herein presented a methodology for setting up joints between metal U profiles with interfaced pins and fiber reinforced thermoplast composites. The preliminary thermoforming trials lead to the conclusion that pin reinforced MC joints can be produced in a time and cost efficient manner as described in this paper by using pre-consolidated sheets of fibre reinforced thermoplast matrix composite sheets. The methodology was verified by successful tests of the final finished KS-2 joint specimens under different loading directions.

Further efforts will be made to develop the conceptual joining routine to a robust MC joining method. New batches of joints will be produced using a special designed and manufactured stiff metal punch and die tool. The key composite processing parameters (temperature and pressure) will be varied to evaluate their influence on the performance of the joints. Detailed experimental and numerical analysis will be performed for a better understanding of the load transfer mechanisms, including load angle dependency (mode mixity) of the joints.

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