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Fatigue behaviour of composite–composite joints reinforced with cold metal transfer welded pins

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ABSTRACT

In this paper the fatigue properties of through-the-thickness reinforced joints are studied in detail. Unreinforced specimens, specimens reinforced with cold metal transfer welded titanium and steel pins and specimens reinforced with titanium z-pins are investigated. Besides classical S–N diagrams, hysteresis curves and stiffness based approaches are applied to improve the understanding of the mechanical behaviour of the joints in the progress of their fatigue life. Furthermore full field strain analysis gives information about damage initiation and growth in the joint section.

1. Introduction

Carbon fibre reinforced polymer (CFRP) composites are important for structural applications in the transportation industry and other areas, where lightweight design is advantageous for operational costs. Along with the interest in CFRP based designs comes the demand for joining technologies that account for the anisotropy and layered structure of this material. While adhesive bonding offers many advantages, such as low weight, corrosion resistance, time and cost savings, no need to cut fibres and good fatigue resistance, it is prone to delamination in the presence of out of plane or peel stresses [1]. Such stresses predominantly occur in areas with abrupt stiffness changes or are caused by load eccentricity and/or the resulting bending moment. Due to their geometry, single lap shear (SLS) specimens face peel stresses and increased shear stresses at the ends of their overlap region and often fail as a result of crack initiation and propagation in this area [1].

Thus, many research groups have investigated the effect of reducing these stress peaks with through-the-thickness reinforcements [1–20]. Among these are stitched [1,3–5,20], tufted [2] and z-pin reinforced [6–9] composite–composite joints. More recent studies focussed on the use of metallic rods as joining reinforcement [10–19]. Metallic reinforcements can, in contrast to polymeric yarns, glass or carbon fibres, add to the damage tolerance of the joint by plastic deformation [11,16]. Moreover, metals allow to form pin shapes that are beneficial for the through-the-thickness reinforcement, because they allow form-fit connections. While there is only limited literature available concerning the use of shaped metallic pins as joining reinforcement for CFRP to CFRP joints [16–19], there is additional literature available concerning joining reinforcements for metal to CFRP joints [21–27]. The main focus of these studies was the performance of the joints under monotonic loads. In all cases, the static strength of the joints could be increased significantly (e.g. +24% [18], +55% [17], +100% [25]). The energy absorption could also be increased significantly (e.g. +800% [25], +3000% [22]).

The joining technology presented in this paper aims at combining both joining mechanisms, form-fit and adhesive bonding, with an integrative metallic joint approach. Arrays of vertical elevations are disposed on thin metal sheets. The formation of pins and pin arrays is realized by a cold metal transfer welding process (CMT pin) [28,29]. The pins are small in comparison to the overall specimen dimensions, they have a height of approximately 3 mm and a diameter of 0.8 mm. The pins possess a head which provides an undercut face. When dry or pre-impregnated fibre-textiles are placed onto the arrays of pins, the pins penetrate the single layers. They push aside the fibres and, due to the undercut geometry of the pins, build a first form-fit with the dry fibre laminate. This form-fit is fixed during resin infusion and curing. A through-the-thickness reinforcement of the composite is established at little fibre crimp and fibre distortion (see post failure

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micrographs in Section 3.4), without the need of borehole drilling and hence cutting continuous fibres. In previous studies the monotonic failure behaviour of CMT pin reinforced Single Lap Shear (SLS) CFRP to CFRP joints was investigated [14]. The results indicate an increased damage tolerance of CFRP to CFRP joints compared to unreinforced SLS specimens. Results from literature show that through-the-thickness reinforcements can increase the fatigue life of SLS joints [1,10,13,18,20,30–34]. The most common way to present the fatigue behaviour of SLS joints is a correlation of stress to numbers of cycle at failure, the so-called S–N curve [1,13,18,30–34]. Aymerich et al. showed that by stitching the ends of the overlap region of SLS joints, they could increase the numbers of cycle for both crack initiation and propagation [1,30]. Noguiera et al. showed the use of metallic pins can increase the fatigue life of SLS specimens one order of magnitude compared to co-cured specimens [18].

The present study aims at the mechanical characterization of co-cured, CMT pin and z-pin reinforced CFRP–CFRP SLS specimens under fatigue loads. Both, failure stresses and stiffness changes versus number of cycle will be shown. Additionally, the tests were recorded with digital image correlation (DIC) for a better understanding of the strain distribution and the damage progression during fatigue life of the specimens.

2. Experimental

2.1. Materials and specimens

All SLS specimens tested in this study were made of epoxy resin from Hexcel Composites (Hexflow® RTM6) reinforced with high tensile strength, standard modulus carbon fibres from Toho Tenax (Tenax® HTS, Saertex® non-crimp fabric, 540 g/m^2 areal weight). All laminates possessed a quasi-isotropic stacking sequence of $[0/90/\pm45]_{5s}$.

Metal reinforcements were either made of stainless steel or titanium. Stainless steel inserts, see Fig. 1, were of type AISI 304 with a sheet thickness of $t = 0.6$ mm. Ballhead spike pins, a combination of a ballhead pin with a small spike pin on top of it, were welded onto the steel sheets in a fully automated cold metal transfer welding process (steel CMT pin, see [14] for details). Steel CMT pins were made of filler wire type AISI 316L with a diameter of 0.8 mm. Titanium inserts were made of Ti6Al4V (Ti CMT pin). The titanium sheets had a thickness of 0.4 mm and the filler wire a diameter of 0.8 mm. Ti CMT pin arrays were welded without the support of a laser, which stabilizes the welding arc and hence improves the shaping of the pins and pin geometry. Instead, the pins have been produced with a "drop-by-drop" technique, which builds the pins by multiple drop attachment.

All metal inserts, both steel and titanium, carried coaxially aligned arrays of 4 × 6 pins on top and bottom side. The pins were arranged at the end positions of the inserts (see [14] for details). The outer two rows of 6 CMT pins were each positioned 1.5 mm away from the free edges of the metal insert with a pitch of $p_x = 3.0$ mm to the inner two rows of pins.

Steel CMT pins had an overall height of about 3.3 mm and a tapered shaft with a diameter of about 1.2 mm at the bottom and 0.8 mm below the ballhead. The ballhead had a diameter of 1.3 mm. Ti CMT pins were significantly smaller, with a height of about 1.85 mm. Their shaft and head had diameters of around 0.9 mm and 1.6 mm, respectively. Prior to the draping process the thin metal sheets and CMT pins were surface treated by cleaning and sandblasting in order to remove contaminations such as grease and welding tinder. At the same time sandblasting increased the roughness of the metallic surface and therefore

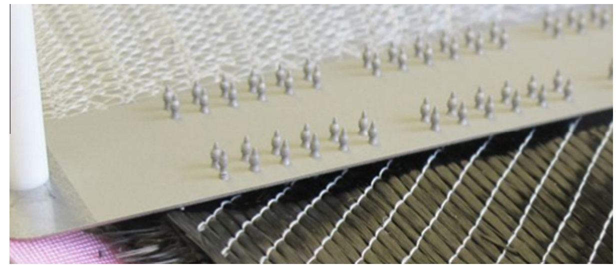

Fig. 1. Metal insert carrying CMT pins fixed in a mould.

increased the adhesion between the metal and the epoxy resin. In a final step the inserts were cleaned with an organic solvent.

Two types of titanium z-pin (Ti z-pin) reinforced specimens were additionally produced for comparison reasons. Type one carried with rods with a diameter of 0.76 mm and type two with rods with a diameter of 1.14 mm. In contrast to the Ti CMT pins, these pins were press fitted into predrilled titanium sheets.

For the preforming process, the metal inserts were fixed in a metal mould (Fig. 1). A set of dry CFRP textile layers was draped onto the pin arrays in a symmetrical manner on the top and bottom side of the insert. CFRP specimen panels were produced via a liquid resin infusion process.

The final SLS specimens were cut out of the CFRP specimen-panels by waterjet cutting. Before waterjet cutting GFRP tabs were bonded onto both ends of the CFRP specimen-panels. This ensured both a symmetric clamping of the SLS joint specimens within the test system and an axially aligned joining interface. The final joint specimens had a width of 25 mm and a joining area of 750 mm^2 (Fig. 2).

Co-cured specimens with equal geometry, but without metal inserts, were chosen as reference. To produce these specimens, the textiles for the two CFRP panels were put in the metal mould, infused with resin and cured simultaneously at 180 °C. The two CFRP panels were thus bonded by the cured resin.

2.2. Test methods

Fatigue tests were carried out on a servo-hydraulic test machine, type MTS 322 (MTS Systems Corp., Minneapolis, USA), with a 250 kN (±0.1%) load range. The frequency of the fatigue tests was fixed to 10 Hz in order to prevent hysteretic heating in the CFRP laps. The stress ratio, amounted to $R = 0.1$ for all tests. The tests were run until failure of the SLS specimens occurred. S–N curves were analysed based on ASTM E 739-98 [35]. For statistical interpretation of the results, the range of scatter related to number of cycles to failure, T_N, was calculated via Eq. (1).

$$T_N = \frac{N_{10\%}}{N_{90\%}} \quad (1)$$

where $N_{10\%}$ is the 10% failure probability and $N_{90\%}$ is the 90% failure probability related to the number of cycles.

All tests were carried out at a laboratory atmosphere of 23 ± 1 °C room temperature and 50 ± 10% relative humidity. Specimens were preconditioned at laboratory conditions for at least 24 h.

The DIC system Aramis (GOM GmbH, Braunschweig, Germany) was used to get information about local strains and displacements on the specimen's lateral surface. It was used to get information about damage initiation and growth in the joint section of the SLS specimens. Shear strains were measured using DIC. It was not feasible to calculate average shear strains from DIC, as strains showed a pronounced gradient in the bonding/reinforcement line. Therefore, two points were tracked at ±3 mm from the joint