Development of a novel testing device for fabric reinforced carbon fibre composites under cyclic biaxial load applications

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Abstract. In this paper, a novel testing device has been developed and adopted to a planar-biaxial servo hydraulic testing machine to examine the multiaxial fatigue behaviour of woven CFRP under superimposed interlaminar cyclic shear and static or cyclic through-thickness compression stresses.

1. Introduction

Woven-fabric composites gain an increasing usage in modern advanced applications of carbon fibre reinforced plastics (CFRP), because of their inherit advantages [1]. Generic applications are fan blades, bolted joint, drive shafts and furthermore, where multiaxial stress states are likely common. Characteristic load applications are in-plane tensile or out-of-plane shear stress superimposed with through-thickness-compressive stresses ($\sigma_1/\sigma_3$ - or $\tau_{13}/\sigma_3$-state of stresses). Particular interlaminar shear stresses can cause delamination leading to degradation and fatigue of the composite material.

In order to initiate such failure critical stress-states, like $\tau_{13}/\sigma_3$-state of stress, in a carbon fibre reinforced thermoset, a novel specimen and testing device has been iteratively developed and adapted to a planar-biaxial servo hydraulic testing machine, to ensure a homogenous stress distribution [2]. In multiaxial quasi-static tests (for example by [3, 4, 5, 6]), it has been experimentally proven that through thickness compression increases the interlaminar shear strength. Many failure criteria proposed in literature can describe this phenomenological and empirical evidence either by a maximum failure strain criterion, such as NU-Theory [7], Sun [8] or Christensen et. al. [9], or by an invariant based failure criterion, such as Cuntze [10].

The influences of the interface waviness and nesting of fabric reinforcements on the mode I and II energy release rates have been investigated in [11, 12, 13], but there is a lack of a reliable understanding of the delamination propagation during fatigue load applications especially with superimposed through-thickness compression [1]. Currently, there are plenty of biaxial testing devices for cyclic analysis, which can be distinguished in tests using a single loading system,
where the biaxial stress ratios are determined by the specimens’ geometry or the loading fixture configuration, and tests using two or more independent loading systems. But apparently these testing methods rely on in-plane characteristics of CFRP, except for the hydraulic bulge test, but an inhomogenous stress gradient in thickness direction of the specimen makes it challenging to estimate the stress distribution [14].

Consequently the described testing method for $\tau_{13}/\sigma_{3}$-stress states has been adapted to cyclic load applications, to describe the influence of through-thickness compression on the delamination propagation of CFRP. Although the proposed stamp-geometry, to initiate the through-thickness compression stresses, has been designed to minimize premature failure in the contact area, it could be observed that premature failure occurs at the outer-notches, when $\tau_{13}/\sigma_{3}$-stresses exceed the ratio of 1:2. Hence a wider contact surface has been chosen to assure the same stress conditions at the notches’ corners. Unfortunately in cyclic load applications the frictional and wear behaviour of the CFRP has to be emphasised and hence it is challenging to predict the shear forces in the shear plane.

In this paper a testing device and a method to assess the stresses in an experimental approach are presented. Furthermore step-wise load increase tests were carried out to determine the influence of through-thickness compression on the interlaminar shear fatigue behaviour.

2. Experimental details

2.1. Planar biaxial testing system

The tests were carried out on a servo hydraulic planar biaxial system Instron 8800 (cf. Figure 1). This system has four actors, which are orthogonally aligned (x- and y-axes). Each actor can reach forces up to 250 kN. In this setup, a high speed camera (mvBlueCOUGAR-XD) has been incorporated and aligned on the region of interest respectively the hole notch pattern for image acquisition (cf. Figure 2). In a post-scripting process the images have been assessed by the Digital Image Correlation (DIC) software ARAMIS v6.1.1-8 for strain measurements. The camera has a native resolution of 2048 × 2048 pixels, which corresponds to a spatial resolution of 11 × 11 µm per pixel on the focused area.

Figure 1. Servo hydraulic Planar biaxial testing system Instron 8800 with the axes x and y.

Figure 2. Illustration of the test setup with the high speed camera mvBlueCougar-XD.

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Table 1. Selected material properties (a) elastic constants (b) strength of the orthotropic fabric reinforced polymer CF-EP - determined with standard test methods.

(a) elastic constants

|        |        |        |
|--------|--------|--------|
| $E_1$  | 69.4 GPa | $G_{12}$ | 4.95 GPa |
| $E_2$  | 69.4 GPa* | $G_{13}$ | 3.40 GPa |
| $E_3$  | 11.5 GPa | $G_{23}$ | 3.40 GPa* |
| $\nu_{12}$ | 0.080 | $\nu_{13}$ | 0.015 |
| $\nu_{23}$ | 0.015* |        |        |

(b) strength

|        |        |
|--------|--------|
| $R_1^+$ | 911 MPa |
| $R_2^+$ | 911 MPa* |
| $R_3^-$ | 907 MPa |
| $R_1$  | 185 MPa |
| $R_2$  | 35 MPa  |
| $R_3$  | 35 MPa* |

* symmetry assumed

2.2. Material and samples

The material used in this investigation is a carbon fibre reinforced thermoset, compounded from a textile plain weave fabric (ECC-style 450, areal density: 200 g/m²), processed out of TENAX-E® HTMA 3K rovings, and an aerospace epoxy thermoset (RTM6) in a resin transfer moulding process. After consolidation of a 10 mm thick plate with an estimated fibre volume fraction of 60% and a density of 1.52 g/cm³, the specimens were cut out and the hole notch pattern has been added by drilling and milling.

According to the symmetrical rapport of a plain weave fabric and neglecting the influence of the weaving process, it can be assumed that the in-plane elastic and strength properties are identical in the material coordinate of the 1- and 2-axes. The through-thickness direction (material coordinate system: 3-axis) of this orthotropic material differs in its elastic and strength properties (cf. Table 1).

The geometry of the specimens, as illustrated in Figure 3, has been numerically and experimentally designed on the basis of the double lap shear [2, 15]. Due to the force redirection in the hole notch area, interlaminar shear stresses $\tau_{13}$ are initiated in the CFRP.

![Figure 3](image)

**Figure 3.** (a) Drawing of the specimen with hole-notch-combination. (b) Picture of the sample in the testing area with visible layers and two main shear areas (red).

2.3. Testing device

In comparison to the quasi-static test setup it has been decided for a fixation (cf. Figure 4) instead of a wedge clamping, because of the easier manufacturing process of the specimens and the low expected forces [2]. Additionally the noval test setup is able to apply either tensional or compressional forces in x- respectively 1-direction. To compensate any misalignment of the fixtures a dove tail for fixation is incorporated.

A further evolutionary step was to increase the stamps’ contact surface to avoid premature failure at the outer notches, as mentioned before. Hence, equal stress states at the notches could be achieved. As in the former setup radii were added on the sides of the stamps to decrease...
Figure 4. Illustration of the test setup with fixations and stamp alignment.

Figure 5. Illustration of the test setup and its schematic force fluxes for (a) uniaxial and (b) biaxial testing.

the Hertzian contact pressure and to avoid premature failure in that region. Both compression stamps and fixations were milled out of hardened 42CrMo4 steel without any surface treatment like diamond like coating as used in [2]. Nevertheless, on the one hand the exceptional higher force demand in y-direction compared to the solution proposed in [2] and on the other hand the previously indefinable effect on the stress distribution due to friction are challenging.

Without the use of the stamps in uniaxial shear testing, the axial force $F_x$ is completely conducted over the shear planes, what results in a shear force $F_S$ (cf. Figure 5 (a)). In biaxial testing, the axial force $F_x$ is the sum of the shear force $F_S$ and the friction forces $F_I$ and $F_{II}$ (cf. Figure 5 (b)). The force $F_I$ results in a bending moment of the stamps, while $F_{II}$ is reconducted through the stamps in the specimen. Without any reliable characterisation of the tribological system it is defying to estimate the shear stresses causing delamination by measuring the reaction forces. In this paper a second attempt is presented to obtain the forces by a strain-measuring method.

2.4. Sample testing
Varying tensile loads $F_x$ and constant or cyclic pressure loads $F_y$ were applied on the specimens. Also different phase shifts $\phi$ between $F_x$ and $F_y$ were examined (cf. Figure 6). The initial loads
(cf. Table 2) were set to different levels in order to reduce testing time. After every $10^5$ cycles, the loads were step-wise increased by 10%. The first cycle of each level had a frequency that was defined by a constant force change rate of 2 kN/s (cf. Figure 7). All other cycles on that level were performed with a sinus shaped function and a frequency of 5 Hz.

### Table 2. Initial test load parameters for the specimens and amount of load increasement (subscripts: »a« amplitude, »m« mean force).

| Specimen | Initial load | Increase after $10^5$ cycles |
|----------|--------------|-----------------------------|
|          | $F_{x,m}$  | $F_{x,a}$  | $F_{y,m}$  | $F_{y,a}$  | $\phi$ | $\Delta F_{x,m}$ | $\Delta F_{x,a}$ | $\Delta F_{y,m}$ | $\Delta F_{y,a}$ |
| 1        | 0.55        | 0.45        | 0         | 0          | 0     | 10            | 10             | 0              | 0              |
| 2        | 3.19        | 2.61        | 30        | 0          | -90   | 10            | 0              | 0              | 0              |
| 3        | 0.83        | 0.68        | 10        | 0          | 0     | 10            | 10             | 0              | 0              |
| 4        | 2.18        | 1.78        | 30        | 0          | 0     | 10            | 10             | 0              | 0              |
| 5        | 2.92        | 2.39        | 2.92      | 2.39       | 180   | 10            | 10             | 10             | 10             |
| 6        | 3.19        | 2.61        | 3.19      | 2.61       | 90    | 10            | 10             | 10             | 10             |
| 7        | 3.19        | 2.61        | 3.19      | 2.61       | -90   | 10            | 10             | 10             | 10             |
| 8        | 3.19        | 2.61        | 30        | 2.61       | 90    | 10            | 0              | 0              | 0              |

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**Figure 6.** Exemplary illustration of tensile and compressive forces for both in-phase and out-of-phase loading per one cycle.

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### 2.5. Measurement of strains and stresses in the shear areas

To evaluate the deformation and to calculate the stresses by a linear-elastic material model in the main shear areas on the surface, the acquired images were assessed by a DIC software. Before the test, one side of the sample was prepared with white paint and graphite spray to produce a unique randomly distributed gray-scale pattern with high contrast. The shear force $F_S$ was calculated by the strain in 1-direction $\varepsilon_1$ in the area of the notches and the elastic behaviour of the material (cf. Figure 8). Also the average strain of the through-thickness compression $\varepsilon_3$ was measured between the notches and the hole by this method.

### 2.6. Simulation of the pressure distribution in the shear areas

For the understanding of the pressure distribution in the shear areas of the specimen by applied stamps, finite element analysis (FEA) has been used. For the specimens mesh hexahedron elements with a mean element length of 0.5 mm and a higher mesh density in the shear areas
3. Results and discussion

FEA of applied compressive forces $F_y$ showed a much better pressure distribution in the shear planes with the stamps in comparison to [2]. In the area of the hole and the notches, the $\sigma_3$ stress was inhomogeneous. In some positions, e.g. at the hole and at the notches, even tensile stresses in 3-direction were detected (cf. Figure 9 (b)). Higher compressive forces showed a more homogeneous pressure distribution in the area between the hole and the notches.

Figure 9. (a) FEA mesh in the shear area with the chosen line for pressure evaluation in 3-direction from hole ($l = 0 \text{ mm}$) to notch ($l = 8.5 \text{ mm}$, red line).
(b) Stress distribution in 3-direction $\sigma_3$ in the shear area along the red line of figure 9 (a) at different compressive forces $F_y$.

Because of the lower pressure or tensile stresses in 3-direction, crack initiation occurred in the area of the notches or of the hole (cf. Figure 10); the notch tip was not the position of crack initiation.

Fatigue crack growth was detected along the shear planes between the fabric layers (cf. Figure 11). The crack growth is connected with a reduction of the shear areas, what results in higher shear stresses and higher shear angles, if the same shear load $F_S$ is applied. Furthermore, it was possible to determine the delamination propagation qualitatively by the strain-field assessment of $\varepsilon_1$ from DIC analysis.
Unwanted delamination on the other side of the notches was prevented through the compression of the stamps. The friction between the sample and the fixations was high enough to apply tensile forces $F_x$ on the sample up to 10 kN.

Only two samples failed directly after load increase. Again, failure occurred through shear on the shear planes. The maximum possible stresses estimated from DIC are shown in Figure 12 and are compared with static results. Here maximum cyclic delamination failure stress is below the static strength in dependence of the interlaminar pressure. Interlaminar pressure increases the shear failure level. Specimens with phase shifts of $\pm 90^\circ$ failed below all other specimens. Even if the layers in the shear areas were not connected anymore and were delaminated, the friction between the layers had to be overcome to notice a failure and a separation of the specimen.
4. Conclusions

◦ Failure didn’t occur directly after load increase in seven of nine specimens.
◦ The stresses in the shear areas could be estimated in a indirect way by obtaining the strain via DIC and a determination of the stresses with an linear elastic material behaviour.
◦ The maximum forces of shear fatigue failure were significantly lower than the static failure results.
◦ Phase shifts $\phi$ of $\pm 90^\circ$ resulted in fatigue failure at even lower shear stress amplitude levels.
◦ Crack initiation occurred in the area of the notches and hole, because of the low pressure (or even tensile stress components) in 3-direction.
◦ Crack growth was detectable. The localisation of the crack tip on the surface under compression was possible with help of DIC.
◦ Through-thickness compression affects the delamination propagation and the fatigue behaviour positively.

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