FATIGUE TESTING OF QUASI-UD AND CROSS-PLY REINFORCED COMPOSITES: THE RECENT ACHIEVEMENTS OF TEST SPECIMEN GENERATION

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Keywords: fatigue test methods, specimen design, UD laminate, S-N curve

Abstract

Tension–tension fatigue testing results, damage development and final failure mode were studied using recently developed dog-bone shaped specimens for a quasi-unidirectional (quasi-UD) glass-fibre reinforced plastic (GFRP) laminate and for a cross-ply laminate reinforced with aramid-fibre reinforcement. The quasi-UD laminate consisted of three non-crimp fabric layers and the cross-ply laminate consisted of six 4H satin weave layers. The laminates were manufactured using a vacuum infusion technique. The study showed that the tension–tension fatigue life of the quasi-UD GFRP laminate and aramid-fibre reinforced cross-ply laminate can be realistically measured using the developed dog-bone specimen. Damage development in the gauge section was observed using photography and thermography for all the specimens. All the glass and aramid-fibre reinforced specimens failed finally in the gauge section. However, the exact location of the damage initiation and accumulation in the thickness direction of the laminate could not be accurately traced. It was observed that the mutual location of each reinforcement fabric in respect to a neighbouring fabric varied, e.g., transversal and axial fibre bundles or stitch loops were located rather randomly in respect to each other.

1. Introduction

Long-term durability is one of the most important issues within the design process of wind turbine blades. The fatigue properties of the laminates in the blade structure need to be known although testing is a burdensome and time-consuming process. The standard rectangular test specimens of unidirectional (UD) glass-fibre reinforced plastics (GFRP) laminates perform poorly in tension–tension fatigue testing because the specimens tend to fail at the end tabs [1–5]. Consequently, the true fatigue life is underestimated. Thus, proper comparisons between different high-performance composite systems, for example, comparison between different UD fabric architectures on fatigue behaviour cannot be made.

Recently, advanced dog-bone shaped test specimens have been generated to solve the problems of traditional specimens (e.g. ISO 527-5) in the tension–tension fatigue testing of UD and quasi-UD GFRP laminates [1]. The advanced specimens possess smooth shear stress distributions and very low stress concentration factors (SCFs) in the tab area, as illustrated in Fig 1. The dog-bone shaped test specimens have been found to decrease the specimen tab failures and to increase the measured fatigue life for the UD and quasi-UD non-crimp fabric (NCF) reinforced laminates. The specimens delay damage in the tabbed area, concentrate the fatigue damage along the specimen gauge length and allow

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observing the damage type and accumulation. The performance of the specimens has been validated using a two-laboratory test campaign [1] (see Fig. 2).

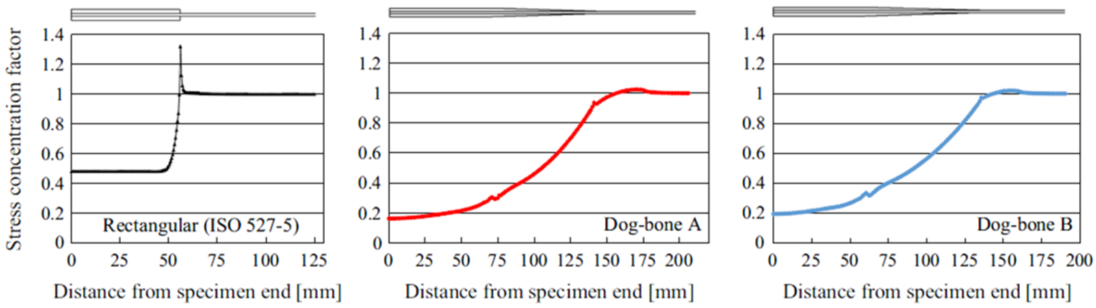

Figure 1. SCFs along the rectangular and dog-bone specimens, based on a finite element analysis [1].

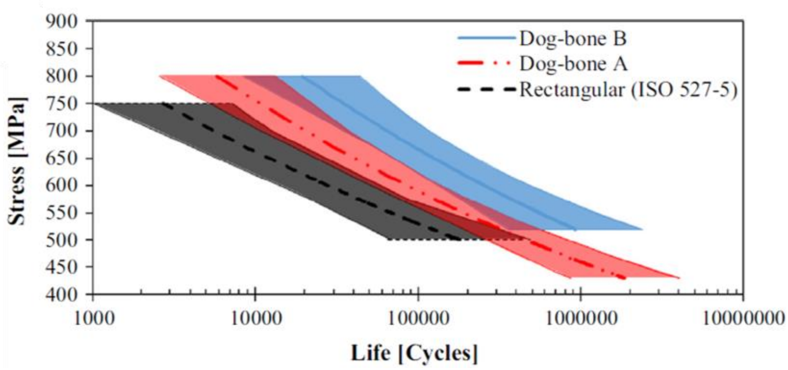

Figure 2. S-N curves with corresponding 95% confidence bands for the UD laminate, measured with the rectangular test specimen, the earlier developed test specimen (dog-bone A) and the recently developed test specimen (dog-bone B) [1].

The quasi-UD laminates used in Ref. [1] consisted of two NCF layers. In this study, we will widen the validation of the recently developed dog-bone specimen design (so-called dog-bone B) by demonstrating its performance in the tension–tension fatigue testing of a quasi-UD GFRP laminate reinforced with three stitched NCF layers and an aramid-fibre reinforced cross-ply laminate. The damage development in the gauge section during the fatigue tests will be studied using photography and thermography. The failure mode of the specimens will also be studied in detail.

2. Materials and methods

2.1. Materials

A quasi-UD NCF supplied by Ahlstrom Glassfibre Oy was used in the quasi-UD laminate. It consisted of continuous high modulus glass roving in the 0° direction and continuous, stabilizing E-glass yarns in the 90° direction. The total areal weight of the fabric was 1001 g/m^2: 946 g/m^2 of glass in the 0° direction, 40 g/m^2 of glass in the 90° direction and 15 g/m^2 of synthetic polyester stitch thread. The fabric was stitched with a tricot stitch pattern using high stitch tension. The nominal diameter of the glass fibres was 17 µm. EPIKOTE RIMR135 epoxy resin and RIMH137 hardener (supplied by Momentive) were used as a resin system. A mixing ratio of 100:30 parts by weight was used.

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HexForce 20914T reinforcement with 4H satin weave was used for the cross-ply aramid-fibre reinforced laminate. The total areal weight of the reinforcement was 175 g/m^2 with areal weight distribution of 50% in the 0° direction and 50% in the 90° direction. The nominal diameter of the aramid fibres was ≈11 µm. Araldite epoxy resin and Aradur hardener (supplied by Huntsman) were used as matrix material with a mixing ratio of 100:38 by weight.

2.2. Laminate manufacture

The quasi-UD laminate for the study was manufactured using vacuum infusion, as described in Ref. [6]. The fabrics were cut into 450 × 500 mm^2 pieces and placed on a glass mould with a stacking sequence of $[0°]_3$. A slightly unsymmetrical lay-up was used in the laminate, meaning that the stabilizing 90° yarns were always placed on the bottom side. A perforated plastic film and distribution medium were placed on the fabrics and they were covered by a plastic bag. During resin impregnation 0.9 bar vacuum pressure was used and it was decreased to 0.3 bar vacuum pressure when the fabrics were fully wetted. After the impregnation of the laminate it was cured in the mould for 24 hours at room temperature under vacuum pressure of 0.3 bar. The cured laminate was released from the mould and post-cured in an oven for 10 hours at 80 °C, as proposed by the resin manufacturer.

The cross-ply reinforced (aramid) laminate with a stacking sequence of $[0°]_6$ was manufactured by using the vacuum infusion technique described above, except that the vacuum pressure was a constant 0.5 bar during the infusion. The cross-ply laminate was cured in the mould after impregnation under vacuum pressure of 0.3 bar for 24 hours at room temperature. The cured laminate was finally released from the mould and post-cured in an oven for 15 hours at 60 °C.

2.3. Specimen manufacture

All the test specimens (see Fig. 3 for the dimensions) were manufactured for quasi-static and fatigue tests, as described in Ref. [1]. The end tabs for the specimens were manufactured from cross-ply GFRP laminate and bonded using structural epoxy adhesive (DP190, 3M). A thin scrim cloth layer was used in a bond line to control the adhesive thickness. The dog-bone shaped specimens made of the quasi-UD laminate were CNC-machined and the specimens made of the aramid-fibre reinforced cross-ply laminate were water-jet cut. Tab tapers were ground next to the gauge section area using a belt-grinding machine. Composite end-tab junctions were smoothed with sandpaper.

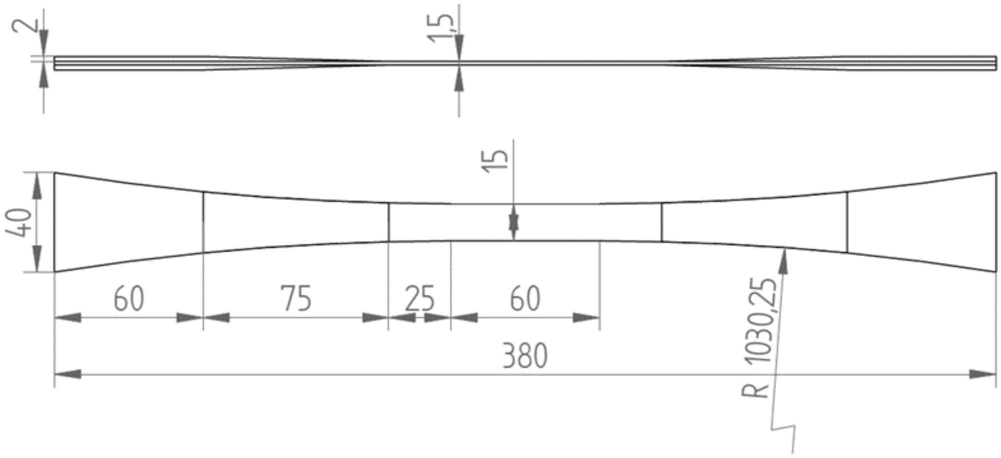

Figure 3. The dimensions (in millimetres) of the dog-bone specimens [1] used in the testing.

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2.4. Fibre volume fraction

The fibre weight fraction was determined from the quasi-UD laminate by using the resin burn-off technique. Two test samples were taken from the laminate. The test samples were weighed before burning and burned in an oven, the temperature of which was slowly increased to 700 °C. Fibre and resin densities of 2.61 g/cm3 and 1.15 g/ cm3, respectively, were used for calculating fibre volume fractions

The fibre volume fraction for the aramid-fibre reinforced cross-ply laminate was estimated using the following equation:

$$V_f = A_w \cdot n / (q_f \cdot h) \quad (1)$$

where A_w is the areal weight of one reinforcement layer, n is the number of layers, q_f is the density of the fibre (1440 kg/m^3) and h is the average thickness of the laminate (1.50 mm).

2.5. Tensile tests

An initial tensile modulus of the specimens was measured prior to fatigue loading for all the specimens. The thickness and width of the specimens' gauge section were measured at three cross-sections and the average values were used to calculate the cross-sectional area. The loading rate of 7 kN/min was used for all the specimens. The test was stopped when a predefined stress level was achieved in the specimen's gauge section. The tests were performed on a servo-hydraulic Dartec testing machine with a load cell of ±100 kN. The strain was measured continuously by an extensometer with a 50 mm gauge length. The tensile modulus was calculated for each specimen based on the slope of the strain-stress curve between the points of 0.001 and 0.003 m/m.

2.6. Tension–tension fatigue tests

A constant-load amplitude, sinusoidal wave-form, uniaxial tension–tension fatigue test with the stress ratio R = 0.1 was performed for each specimen directly after the quasi-static tensile test at the same load level (stress) that had been applied in the quasi-static test. The tests were performed in the load control mode using a Dartec 100 kN testing machine with digital control (Elite Suite, MTS). The tests were stopped when the specimens completely separated into two parts. A test frequency of 4 Hz was used in the tests to avoid an excessive rise in the specimen temperature.

Fatigue test results were analysed by plotting S-N fatigue data on a conventional linear-logarithmic graph. To analyse the fatigue data, the relationship between applied maximum stress and the number of cycles to failure was used with a power-law regression model (Basquin 1910) equation:

$$N = C \cdot S^m \quad (2)$$

where S is the maximum applied stress, C is an intercept parameter, N is the measured fatigue life (cycles to failure) and m is the slope of the S-N curve. Eq. (2) yields a linear S-N curve on a log–log graph. The least-squares method was used according to the ASTM E 739 standard to obtain parameters C and m. The number of cycles to failure was used as a dependent variable and maximum stress as an independent variable [7]. The coefficient of determination, R^2, was also determined for each data set to show how well an S-N curve fits the regression model.

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2.7. Digital imaging

Damage accumulation was monitored in the gauge section during the quasi-static and fatigue tests by photographing. For the quasi-UD GFRP laminate, the matrix cracks, fibre breakages and voids were easily detected by digital photography with auxiliary light. The glass fibres could not be seen while the stitch threads remained visible. For the aramid-fibre reinforced cross-ply laminate, matrix cracks or fibre/matrix debonds were also detected by the photography. Digital images were taken with a Canon SX30 IS digital camera during the fatigue tests.

2.8. Thermography

During the fatigue tests, the specimens were investigated by means of thermal imaging to monitor possible heat generation in the specimens' gauge section. Thermal images were taken with a Fluke Ti32 infrared thermal imaging camera during the fatigue tests at 1000, 5000 and 10 000 cycles and later usually within intervals of 10 000 cycles.

3. Results

3.1. Tensile moduli and the fibre volume fraction

The average tensile moduli and fibre volume fractions of the test laminates are shown in Table 1. The results indicate that the standard deviations of the measured values were small for both laminates.

Table 1. The measured tensile moduli and fibre volume fractions of the test laminates (average ± standard deviation)

Laminate	Fibre type	Number of layers	Initial modulus (GPa)	Fibre volume fraction (%)
Quasi-UD	glass	3	46.63 ± 1.56	58.9 ± 0.15
Cross-ply	aramid	6	28.11 ± 0.57	48.75

3.2. Observed damages and failure mode

Digital images taken during fatigue tests showed that damages initiated and accumulated in the gauge section. Transversal matrix cracks in the 90° bundles, and fibre and matrix debonds in axial bundles initiated and accumulated, also some fibres broke in the gauge section for the quasi-UD laminate (see Fig. 4). It seemed that for the quasi-UD laminate some of the damages occurred in different fabric layers in the thickness direction because the sharpness of the damages varied. However, the exact location of the damages in the thickness direction of the laminate was difficult to estimate. It was also observed that the mutual location of transversal and axial fibre bundles, as well as each stich loop in each fabric, varied in respect to each other. Finally, the specimens failed in the gauge section (see Fig. 4).

For the aramid-fibre reinforced cross-ply laminate, transversal matrix cracks in the 90° yarns, and fibre and matrix debonds in axial bundles were also observed. However, they were much more difficult to observe compared to the glass-fibre reinforced laminates since the aramid fibres are not as transparent (see Fig. 5). Finally, the specimens failed in a sudden and local manner in the gauge section.

A temperature increase was also observed with all the specimens throughout the gauge section, as shown in Figs. 6a and 6b. Peaked, locally high temperatures were only observed for quasi-UD

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laminates in the areas of severe debond concentrations or broken fibre areas, as shown in Fig. 6a. In the aramid-fibre reinforced cross-ply laminate, two regions with a slightly higher temperature seemed to form along the gauge section.

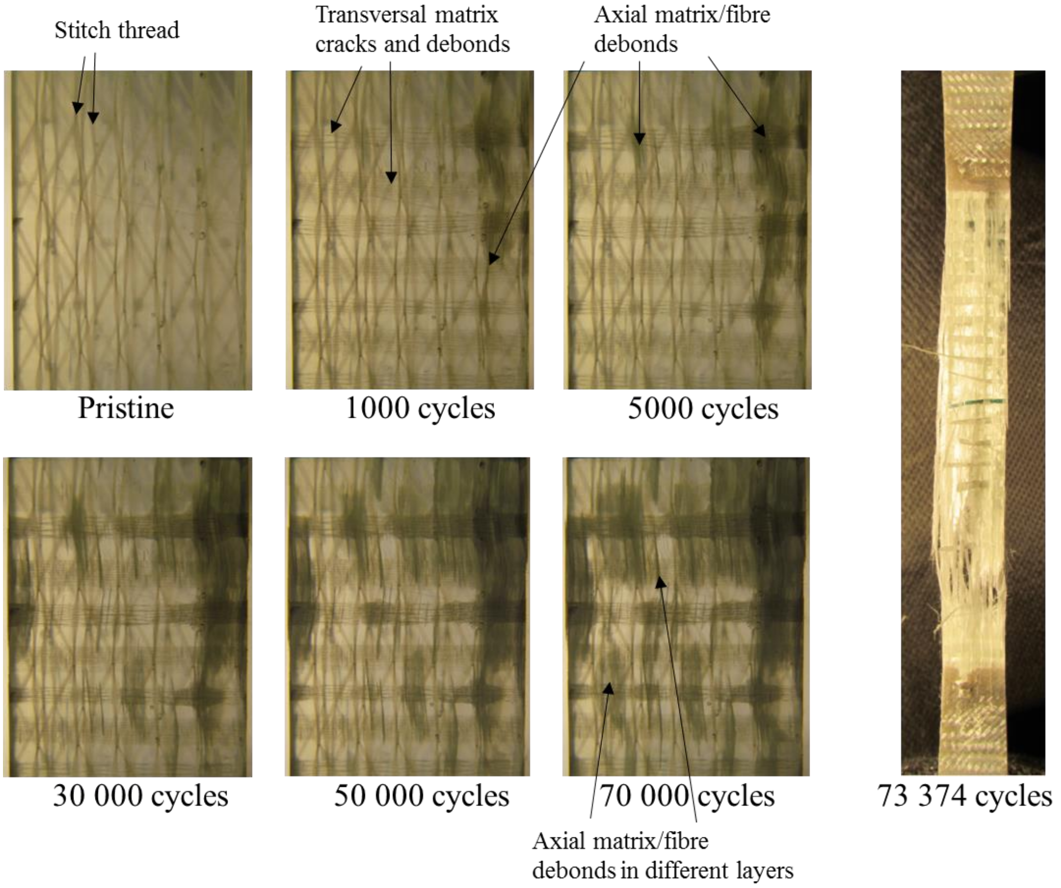

Figure 4. Digital images of the quasi-UD GFRP laminate under the maximum stress of 600 MPa during the fatigue tests.

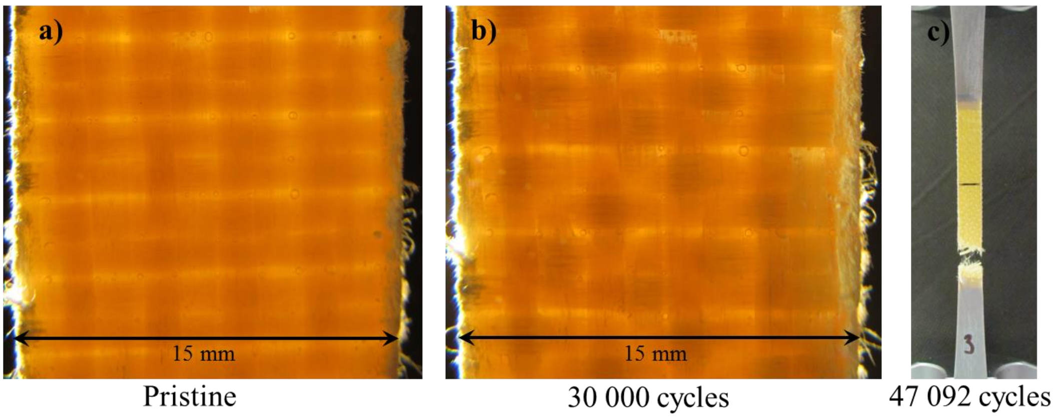

Figure 5. Digital images of the cross-ply aramid-fibre reinforced laminate under the maximum stress of 425 MPa during the fatigue tests.

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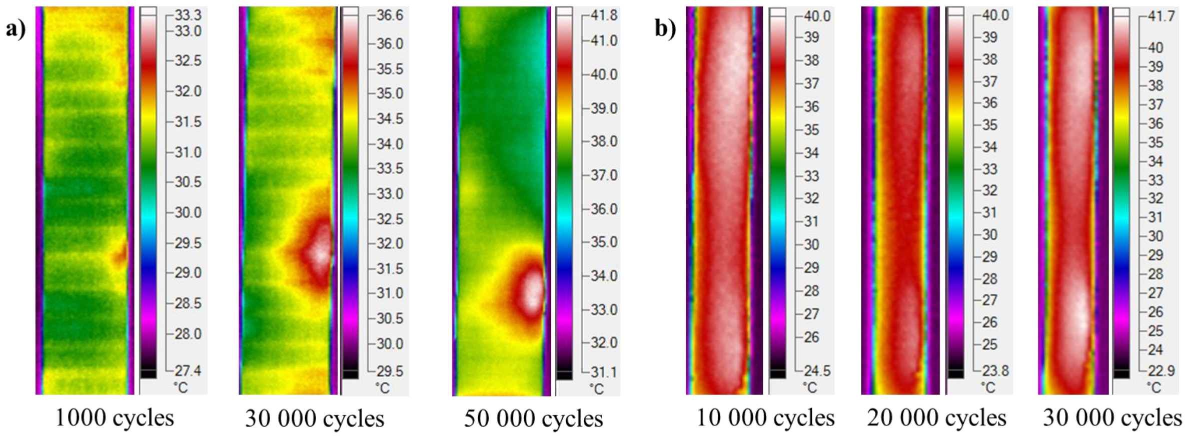

Figure 6. Thermal images during the fatigue tests for a) the quasi-UD GFRP laminate under the maximum stress of 600 MPa and b) the cross-ply aramid-fibre reinforced laminate at the maximum stress of 425 MPa.

3.3. Measured fatigue lives

Fatigue data with a fitted S-N curve for the quasi-UD GFRP laminate is presented in Fig. 7a. The results show a small scatter (R^2 > 0.89) for the quasi-UD laminate, meaning that the power regression accurately fitted the fatigue data. The slope parameter *m* value of -9.88 was calculated for the quasi-UD GFRP laminate.

Fatigue data with an S-N curve for the cross-ply laminate reinforced with aramid fabrics is presented in Fig. 7b. The results again show a very small scatter (R^2 > 0.94), meaning that the power regression accurately fitted the fatigue data. The slope parameter *m* value of -26.9 was calculated for the cross-ply laminate.

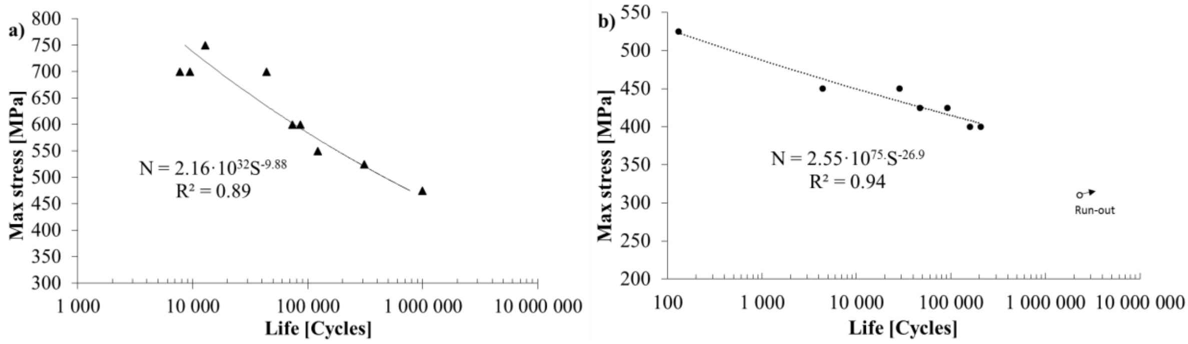

Figure 7. Fatigue test data for the a) quasi-UD GFRP laminate and b) aramid-fibre reinforced cross-ply laminate used in this study.

4. Conclusions

This paper presents recent results on the applicability of advanced dog-bone specimens in the experimental tensile fatigue testing of quasi-UD GFRP laminates reinforced with stitched NCFs and cross-ply laminates reinforced with aramid-fibre reinforcements. The quasi-UD laminate consisted of

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three NCF layers and the cross-ply laminate consisted of six 4H satin weave layers. The laminates were manufactured using a vacuum infusion technique. The investigation showed that the tension–tension fatigue life of the quasi-UD GFRP laminate and aramid-fibre-reinforced cross-ply laminate can be realistically measured using the recently developed dog-bone specimens. All the specimens experienced damages in the gauge section and failed finally in the gauge section. Also, it was observed that peak temperatures were generated at the points of damage concentration for the quasi-UD laminate. However, the determination of the exact location of the damage initiation in the thickness direction of the laminates requires further studies. It seemed that some of the damaging occurred only in certain fabric layers in the thickness direction. Also, it was observed that the mutual location of each fabric with respect to the neighbouring fabric varied, e.g., transversal and axial fibre bundles or stitch loops located rather randomly with respect to each other. Clearly, a more fundamental investigation on the effect of the exact positioning of the fabrics with respect to each other may reveal possible difference in the internal structure of the laminates and damage development phenomenon during the fatigue tests.

Acknowledgments

This work was funded by the Finnish Funding Agency for Technology and Innovation (TEKES) through the FIMECC Light and Hybrids project. Kevra Oy (Finland) is acknowledged for their collaboration in the research.

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