

## FATIGUE BEHAVIOUR OF LAMINATED CARBON FIBRE REINFORCED POLYMER STRAPS FOR BRIDGE SUSPENDERS

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### Abstract

This paper focuses on the fretting fatigue behaviour of pin-loaded carbon fibre reinforced polymer (CFRP) straps studied as models for suspenders of arch bridges. Eight straps were subjected to an ultimate tensile strength test. In total, 26 straps were subjected to a fretting fatigue test, of which ten did not fail. An S-N curve was generated for a load ratio of 0.1 and a frequency of 10 Hz, showing a fatigue limit stress of the straps around the matrix fatigue limit, corresponding to 46% of the straps' ultimate tensile strength ( $\sigma_{UTS}$ ). The fatigue limit was defined as 3 million load cycles ( $N = 3 \times 10^6$ ), but tests were even conducted up to  $N = 11.09 \times 10^6$ . Catastrophic failure of the straps was initiated in their vertex areas. Investigations on the residual strength and stiffness properties of straps tested around the fatigue limit stress (for  $N \geq 1 \times 10^6$ ) showed little influence of the fatigue loading on these properties. Quasi static Finite Element Analyses (FEA) were conducted. The results obtained from the FEA are consistent with the experiments and demonstrate a fibre parallel stress concentration in the vertex area of factor 1.3.

### 1. Introduction

By weighing six times less than comparable steel riggings, rigging systems made from CFRP have recently become more and more important in the sailing and construction industry [1], where they are starting to replace steel ropes that are prone to environmental influences such as salt water, which can cause stress corrosion. However, CFRPs are not unaffected by environmental influences either and in applications such as suspenders used for half-through arch bridges [2], dynamic fatigue is highly relevant as well. In the present study, the fretting, which is caused by the relative movement between the outer surface of the contacting pin and the inner surface of the strap, further increases the material degradation [3–5]. Compared to isotropic materials such as metals, ceramics or polymers, the damage modes and crack propagation are much more complex in CFRPs and depend on a variety of factors. Nevertheless, Reifsnider [6] characterized the fatigue behaviour of multiaxial fibre reinforced composites (FRPs) in a general way and divided it into three stages. In the first stage, the damage develops at a very rapid rate within the first 10%–15% of the laminate's life. In this stage, the major damage mode is matrix cracking in the laminae with the most off-axis fibre orientation. This intralaminar matrix cracking between the fibres reaches a uniform saturation spacing at the end of stage I, called characteristic damage state (CDS). In stage II, comprising 70%–80% of the fatigue life, damage is still initiated and the already existing damages continue to grow, but at a much slower rate, until the laminate is severely damaged and then enters stage III, where the damage process is accelerated again until final failure of the laminate.

In the case of purely unidirectional (UD) CFRP laminates, the situation is different, since no off-axis plies are present. However, since carbon fibres show excellent fatigue behaviour [7], the matrix and its interaction with the fibres remains the limiting factor in the composite's fatigue life [8-10]. Based on this idea, Talreja [11] introduced a fatigue life diagram in which he suggests that the fatigue life of a unidirectionally reinforced polymer is governed by the composite's quasi-static fracture strain and the matrix' fatigue limit strain. With the matrix fatigue limit strain being at  $\varepsilon_{mf} = 0.6\%$  for epoxy resins [12], no damage progression takes place in the composite below this strain level, given the carbon fibres' insensitiveness to fatigue.

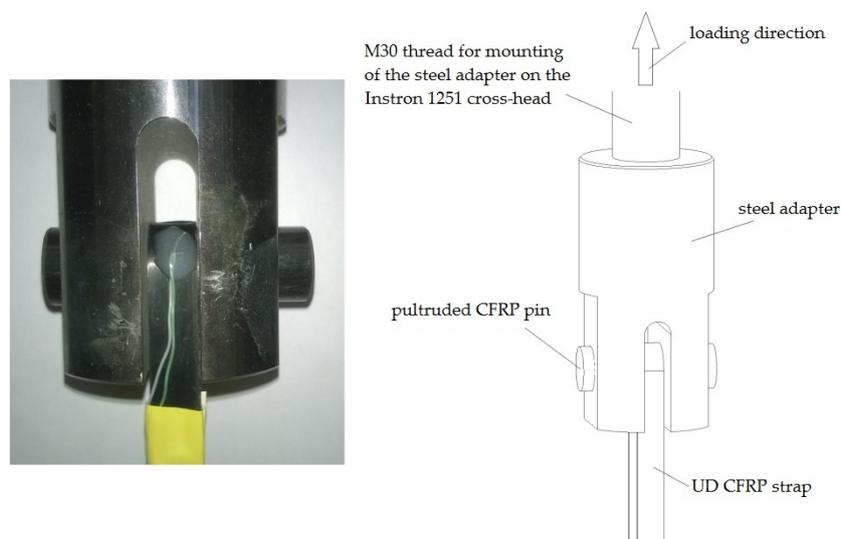
This assumption of course only holds if no fretting of the unidirectional CFRP laminate is present or if the fretting stops at some point. Schulte et al. [3-5] could show how an increased normal contact force leads to a more pronounced decrease in fatigue strength and that the influence of the contact force increases if the contacting ply is oriented in the primary loading direction. This is also the case in the examined pin-loaded CFRP straps, and the goal of this study was to investigate the fretting fatigue behaviour of these straps in contact with a pultruded CFRP pin in order to improve the durability of existing CFRP riggings.

## 2. Materials and Manufacturing

The materials used for the production of the out of autoclave (OOA) carbon fibre/epoxy (CF-EP) prepreg were a XB3515/Aradur<sup>®</sup> 5021 matrix system by Huntsman (Huntsman Advanced Materials GmbH, Basel, Switzerland) and intermediate modulus IMS60 carbon fibres by Toho Tenax<sup>®</sup> (Toho Tenax Europe GmbH, Wuppertal, Germany) with a reported Young's modulus of 290 GPa and tensile strength of 5'600 MPa. The  $12 \pm 1$  mm and  $9 \pm 1$  mm wide prepreg tapes were produced by Carbo-Link AG in Fehraltorf, Switzerland and reported to have a  $V_f$  of  $62\% \pm 2\%$ . The laminate's average experimental tensile strength was  $2'567 \pm 58$  MPa with a longitudinal (fibre parallel) elastic modulus  $E_{11}$  of  $168 \pm 6.6$  GPa and an average ultimate tensile strain  $\varepsilon_{11u}$  of  $1.52\% \pm 0.23\%$ . Investigations on the laminate quality of the hand laminated straps revealed an average  $V_f$  of 66% and a void content of less than 1%. The pultruded T300 CF-EP pins used for the loading of the straps had a  $V_f$  of 60-65%. The CFRP straps had a thickness  $t$  of 1 mm, a shaft length  $L$  of 250 mm, a width  $w$  of 12 mm or 9.7 mm, depending on the prepreg tape used, and an inner radius  $r$  of 10 mm.

## 3. Experimental Setup

The ultimate tensile strength ( $\sigma_{UTS}$ ) and fretting fatigue tests on the straps were conducted on a servo-hydraulic test machine (type 1251, Instron<sup>®</sup>, High Wycombe, Buckinghamshire, UK). The tensile strength tests were performed under displacement-control at a cross-head speed of 2 mm/min. The fatigue tests were performed under load-control at a frequency of 10 Hz and a load ratio  $R$  of 0.1. Figure 1 illustrates the mounting of the strap and pin in the testing machine. The pultruded CFRP pin is placed in a fork-like steel adapter that is screwed to the cross-head of the testing machine. The picture also shows the type K thermocouple that was glued to the strap in order to monitor the temperature development on the outside of the strap in the critical (vertex) area. Even though Barron et al. [13] found that fibre-dominated orientations exert smaller frequency effects on their fatigue behaviour than matrix-dominated orientations, higher test frequencies lower the dynamic properties of a composite structure due to hysteretic heating [13] and hence lead to more conservative results. Whenever narrow straps were tested, thin copper washers were placed on both sides of the strap to ensure the lateral support of the strap, which is reported to reduce stress concentrations [14].



**Figure 1.** Mounting of the pins and straps in the testing machine.

## 4. Experimental Results and Discussion

### 4.1 Quasi-Static Behaviour

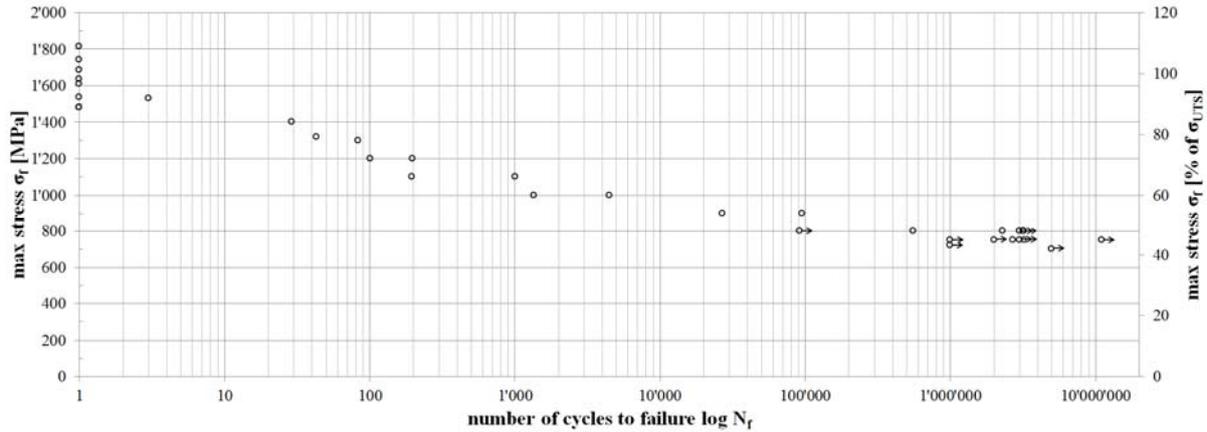
Before the fretting fatigue tests were conducted, five to eight straps were tested for their ultimate tensile strength. The results of the quasi-static tensile tests performed on the wide (12 mm) and narrow (9.7 mm) straps are shown in Table 1. Two different types of straps were tested since the 12 mm wide straps required a lateral machining of the straps in order to fit into the adapter. The 9.7 mm straps, on the contrary, did not require this kind of invasive post-processing which was suspected to negatively influence the mechanical performance of the straps. As can be seen from Table 1, the narrow straps showed a slightly higher  $\sigma_{UTS}$ . The elastic modulus on the other hand was slightly below that of the wide straps. Since the results for  $E_{11}$  and  $\sigma_{UTS}$  of the wide and narrow straps are within the larger of the two respective standard deviations, an influence of the lateral machining of the strap on  $E_{11}$  or  $\sigma_{UTS}$  was not found. However, all measurements on the narrow straps showed a significantly lower standard deviation, which is tentatively attributed to the machining, inducing larger scatter due to the respective defects.

### 4.2 Fretting Fatigue

Figure 2 shows the S–N curve obtained from the fretting fatigue testing of 12 mm wide pin-loaded straps. A strap was defined to have reached the fatigue limit once it endured more than 3 million load cycles. Straps tested without failure have an arrow attached to their data point in Figure 2, indicating that further load cycles could have been endured. In order to confirm this, one strap was tested for 11'089'000 load cycles at the fatigue limit stress (750 MPa) without failure.

**Table 1.** Average quasi-static tensile strength and stiffness of wide (12 mm) and narrow (9.7 mm) straps. The fibre parallel elastic modulus  $E_{11}$  (GPa) was measured with strain gauges ( $E_{11\_SG}$ ) and a linear encoder ( $E_{11\_LE}$ ). The composite strains at failure  $\varepsilon_{cf}$  (%) were measured with the strain gauges.

Strap	$\sigma_{UTS}$ (MPa)	$E_{11\_SG}$ (GPa)	$E_{11\_LE}$ (GPa)	$\varepsilon_{cf}$ (%)
wide	1'624±121	177.8±8.6	175.8±12.1	0.99±0.04
narrow	1'714±55	174.4±1.1	166.2±6.2	1.00±0.05



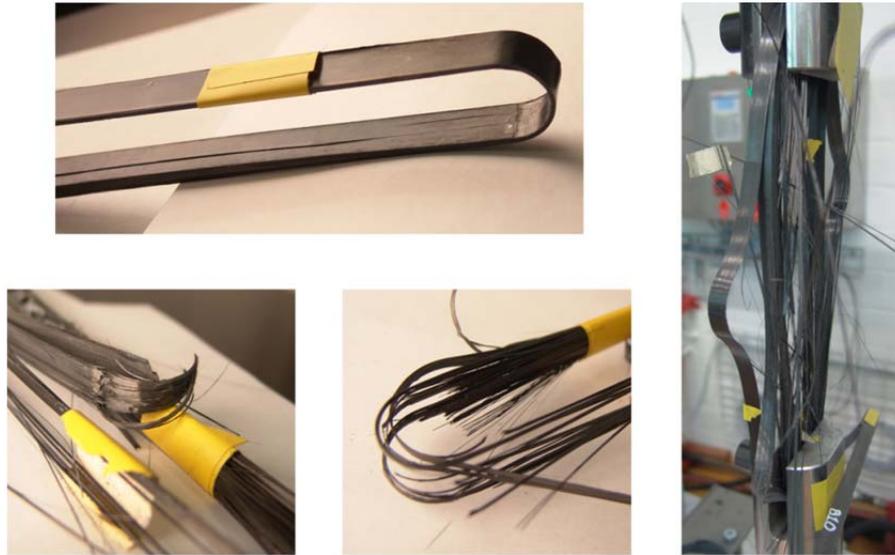
**Figure 2.** S-N curve of the 12 mm wide straps, listing the stress at failure ( $\sigma_f$ ) as a function of endured load cycles at failure ( $N_f$ ).

The residual mechanical properties of straps tested without failure after 1, 2, 3 and 11 million load cycles around the fatigue limit stress were tested in quasi-static tensile tests until failure. The test setup was the same as for the virgin straps. Table 2 lists the results of these measurements.

**Table 2.** Average residual strength and stiffness properties of wide straps after 1, 2, 3 and 11 million load cycles at an upper stress level ( $\sigma_u$ ) of 720–750 MPa. The fibre parallel elastic modulus  $E_{11}$  was calculated from linear encoder measurements ( $E_{11\_LE}$ ).

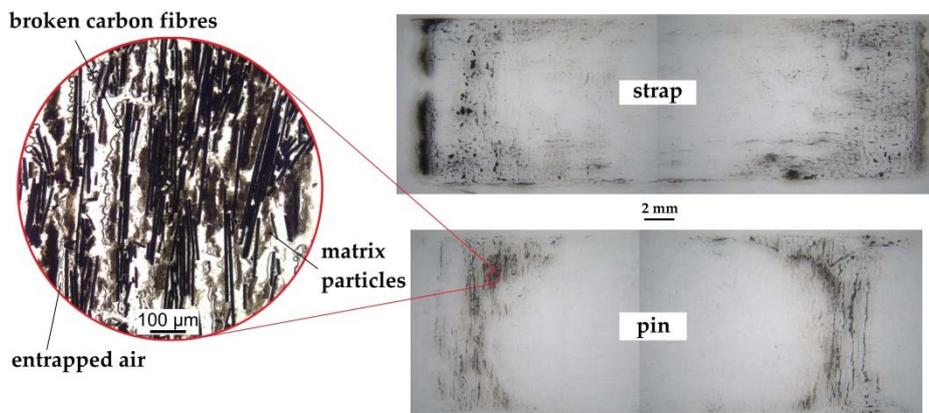
Strap	$\sigma_{UTS}$ (MPa)	$E_{11\_LE}$ (GPa)
wide	1'620±65	165.9±4.0

Comparing the residual stiffness's of straps tested for  $N \geq 1 \times 10^6$  to the stiffness of an average virgin strap reveals a slight stiffness reduction over time of up to 10%. The ultimate tensile strength of the straps on the other hand is hardly affected by the fretting fatigue loading. Furthermore, the standard deviation is much lower in the fatigue tested straps and first signs of (further) damage occur only after the straps have reached approximately 80% of their ultimate tensile strength. In virgin straps, first signs of damage were observed just above 50% of their ultimate tensile strength. The damage modes of all fretting fatigue tested CFRP straps were similar. First, visible damage always occurred in the form of delamination of the inner- and outermost layers in the shaft with the overlapping plies. The delaminations started at the free ends of the tape and propagated along the shaft until they stopped in the vertex area, see Figure 3, top. Another damage mode was longitudinal matrix cracking. This damage mode also occurred solely in the inner- and outermost plies and did not propagate over the vertex area of the strap either (Fig. 3). However, the failure of all straps was initiated in the vertex areas where clear signs of broken fibres were present (Fig. 3) leading to fibre bursting in one or both shafts. In some straps, the bursting of the innermost plies was accompanied by delamination of the outermost ply (Fig. 3, right). This additional delamination predominantly occurred in quasi-static loading until failure of straps that were previously fatigued around the fatigue limit, but was also observed in straps tested at much higher stress levels. Hence, no clear evidence for the correlation between damage mode and stress level was found.



**Figure 3.** Damage modes in different fretting fatigue loaded straps.

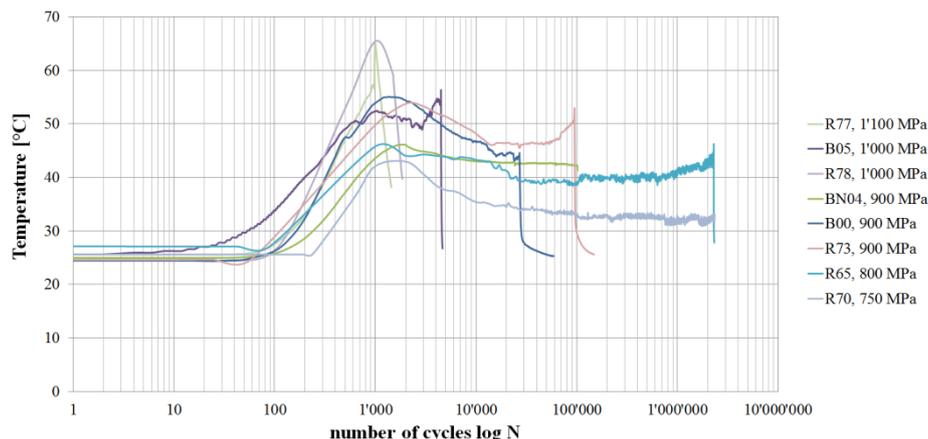
The fretting behaviour of the pin-strap contact surface was investigated by placing a transparent adhesive tape on both surfaces just after testing. After pulling the tape off the surfaces, most of the fretting products remained on the tape. These tapes were placed on a sheet of paper and investigated under an optical microscope (ZEISS Axioplan in reflected-light mode). Figure 4 shows two representative pictures from a strap and a pin. Clearly visible are the carbon fibre particle accumulations just outside the vertex area of the strap. In accordance with the literature [4,15–17] the main damage mode observed on the strap (sliding of the contacting surface in fibre direction) was fibre thinning, resulting in small carbon particles. The fretting products on the pin on the other hand consist mostly of short, broken and pulled-out carbon fibres with parts of neat resin still attached to the fibres. This is also reported to be typical for sliding perpendicular to the fibres [15-19]. Clear signs of a homogeneous graphite particle film covering the contact area that might act as a lubricant were not detected. However, the graphite particle aggregations just outside the vertex areas of the strap suggest a particle transport from the fretting areas to the free surfaces of the shaft. This would require that the particles do build, at some point, an intermediate film between the pin and the strap which would contribute to a reduction of the coefficient of friction.



**Figure 4.** Fretting products of a strap after  $3 \times 10^4$  load cycles (top) and a pin after  $N = 10^6$  (bottom). Both images show fretting products from tests conducted at a load level of 720 MPa.

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The temperature measurements on the outside of the straps given in Figure 5 show a significant initial temperature increase with a peak within the first  $10^4$  load cycles. After this peak, the temperature decreases and levels out before increasing again prior to failure of the strap. This behaviour suggests a running-in process where the contacting surfaces are smoothed. According to the datasheet of the matrix, the glass transition temperature ( $T_g$ ) of the matrix is between 140 and 145 °C if cured for 1 h at 120 °C followed by 2 h at 140 °C. Since the laminate tested in this study was cured at 140 °C for 2.5 h, the  $T_g$  can be assumed to be in the same temperature range. Hence, the high test frequency and the resulting measured maximum temperatures around 65 °C can be considered non-critical.



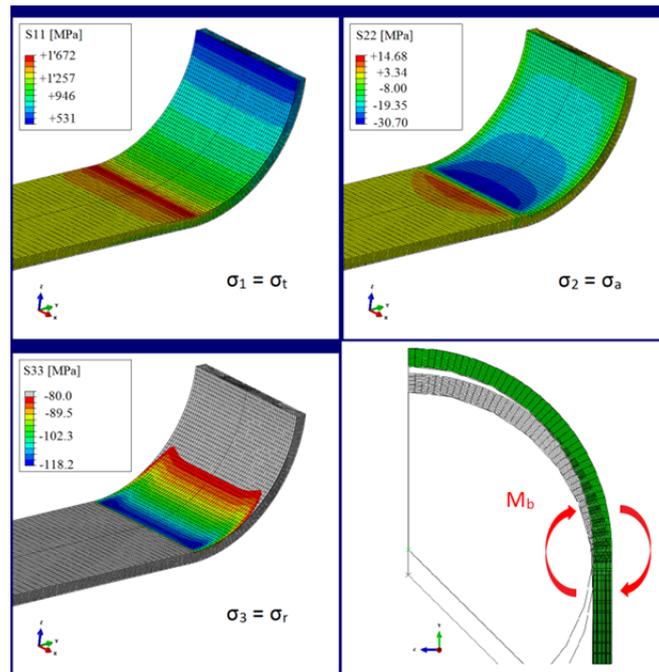
**Figure 5.** Temperature curves of fretting fatigue tested CFRP straps. Curves shown for straps tested at an upper load level between 750 and 1'100 MPa.

## 5. Numerical Modelling

The analytical model presented in [14] predicts a fibre parallel stress concentration in the vertex area of pin-loaded straps of 1.1 for the investigated geometry, lateral support and material properties. This is far below the values measured in this study and in order to investigate this mismatch, a FEA of the pin-strap contact problem under quasi-static tensile loading was conducted in the commercial FEA Software Abaqus/Standard 6.14 (Dassault Systèmes Simulia Corp., Providence, RI, USA).

With the help of the FEA, the influence of the coefficient of friction ( $cof$ ), the upper tensile load, the pin diameter and the strap thickness on the stress distribution in the strap and the relative slip between pin and strap could be investigated. The pictures in Figure 6 show the resulting stresses in the vertex area of a 12 mm wide and 1 mm thick strap with an inner radius of 10 mm that was subjected to a pin displacement of 1.05 mm (1'250 MPa shaft-stress). The displacement of the pin causes a bending moment in the vertex area of the strap (bottom right picture) and the resultant significant stress concentrations in fibre direction ( $\sigma_1 = \sigma_i$ ) become clearly visible in the top left picture. Furthermore, the profile of the normal stresses in the strap ( $\sigma_3 = \sigma_r$ , bottom left) is similar to the wear pattern observed under the microscope, shown in Figure 4.

The obtained results of an increasing stress concentration of  $\sigma_1$  with decreasing inner radius and/or increasing strap thickness are consistent with the literature [14]. However, with the help of the FEA it could be shown how the analytical model presented in [14] underestimates the stress concentrations in the innermost plies. This is due to the fact that it does not consider secondary effects such as the bending moment in the vertex area.



**Figure 6.** Stress distribution in the vertex area of a 12 mm wide and 1 mm thick strap in contact with an analytical rigid pin ( $cof = 0.5$ ).

## 6. Summary

The fretting fatigue behaviour of pin-loaded CFRP straps under tensile loading was presented in this study. The investigated straps had been subjected to ultimate tensile strength and fretting fatigue tests up to  $11 \times 10^6$  load cycles. Ultimate tensile strength tests of the laminate were performed to determine the laminate's mechanical properties needed for the FEA. Eight 12 mm and five 9.7 mm wide straps were tested in quasi-static tensile loading until failure and the results were compared to coupon tests and FEA. A total number of 26 straps, all 12 mm wide, were subjected to fretting fatigue loading at a load ratio  $R$  of 0.1 and a frequency  $f$  of 10 Hz and the results were used to generate an S–N curve. The following conclusions can be drawn on the basis of the study described in this paper:

- The pin-loaded CFRP straps showed a fatigue limit stress of 750 MPa, which corresponds to approximately 46% of their ultimate tensile strength. The fatigue limit was defined to be reached once a strap endured more than  $3 \times 10^6$  load cycles, and one strap was tested for  $11.09 \times 10^6$  load cycles to confirm this.
- The experimentally determined fatigue limit corresponds to the matrix fatigue limit strain of 0.6%, which is reported in the literature [11, 12] to be the ultimate lower bound for a UD fibre reinforced composite fatigue limit.
- The ultimate tensile strength of the straps is significantly reduced by stress concentrations in the vertex area. In the investigated case of a 1 mm thick strap with an inner radius of 10 mm, the fibre parallel stress concentration factor in the innermost plies of the strap was 1.3.
- The stress concentrations in the vertex area of the strap depend on the coefficient of friction, the applied load and the pin and strap geometry, as was shown in previous studies [14].
- The influence of the lateral machining of the straps on their stiffness and ultimate tensile strength could not be shown. However, measurements on straps that were laterally machined showed a higher standard deviation of stiffness and strength.
- Clear signs of a graphite film acting as lubricant between pin and strap were not found. However, the carbon fibre particle accumulations just outside the vertex area of the inner strap surface require a transport of these particles from the fretting areas to the outside. This in turn

means that a particle film is present at some point and contributes to a reduction of the coefficient of friction.

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