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Experimental study of Z-pin fatigue; understanding of mode I and II coupon behaviour

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Abstract

Insertion of carbon fibre reinforced polymer rods (Z-pins), is an effective method for the through-thickness reinforcement (TTR) of laminated composites. Whilst Z-pins are primarily used to mitigate delamination under quasi-static loading and/or impact events, the effectiveness of TTR following long-term exposure to cyclic loads still needs to be properly understood. This paper aims to fill the aforementioned knowledge gap by addressing the effect of fatigue on the Z-pins themselves, both in mode I and mode II regimes. The fatigue tests considered here are carried out on single Z-pin coupons, as well as Double-Cantilever-Beam (DCB) and End-Loaded-Split (ELS) specimens. The results indicate that, for relatively small cyclic displacements, Z-pins tolerate fatigue well, exhibiting good residual performance post-fatigue. However, increasing the amplitude of the fatigue loads damages the Z-pins and, hence, it tends to reduce the TTR residual ability to mitigate delamination under further quasi-static or impact loading

Keywords: A. 3-Dimensional reinforcement; B. Delamination; B. Fatigue; D. Mechanical testing

1. Introduction

Despite their excellent mechanical properties in in-plane direction prepreg-based laminated carbon fibre-reinforced composites are prone to delaminate under out-of-plane loading. Z-pinning is a 3D-reinforcement technology that involves the insertion of high stiffness and/or high strength rods into the composite before curing. It has been shown to significantly improve the through-thickness properties of CFRPs for various testing conditions, including mode I, mode II and mixed mode I/II fracture under quasi-static, fatigue, impact and high-velocity loading in monolithic composites or joints [1] - [24]. While not being able to completely suppress crack initiation, Z-pins were shown to significantly delay crack propagation. Compared to other 3D-reinforcement technologies, Z-pinning requires a fairly labour-intensive manufacturing process, which is the topic of current research [1, 25, 26]. However, to date it is the only 3D-reinforcement method applicable

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to pre-pregs. A good overview of the mechanisms controlling Z-pin effectiveness and the influence of Z-pins on composite in-plane and out-of-plane properties is given by Mouritz [27].

Z-pins allow the selective reinforcement of a composite structure. This entails varying Z-pin volume content, size and material locally to achieve the maximal energy dissipation during Z-pin failure or pull-out. A further design property was described by Yasaei *et al.* [37], who tested numerous single Z-pin specimens at varying loading angles (deviating from the Z-pin axis), effectively modifying the mixed-mode ratio. They determined a transition zone, *i.e.* a range of loading angles/mixed mode ratios, in which the Z-pins failed in both pull-out and rupture. At angles outside the transition zone the Z-pins would always fail in either pull-out or rupture.

Depending on laminate stacking sequence, ruptured Z-pins were reported to reach only a third or a fifth of the energy dissipation observed for pulled-out Z-Pins. Hence, avoiding Z-pin rupture using knowledge of the transition zone can improve structural design. A mixture of Z-pin pull-out and rupture for Z-pins being loaded under mixed mode loading conditions due to Z-pin misalignment was also reported in [28].

Z-pins are typically used in structures that are likely to experience impact throughout their lifetime or that are required to keep operating in a damaged state. Over its service life, a Z-pinned structure can be assumed to be in operation for a significant amount of time, during which Z-pins are required to maintain their effectiveness. Moreover, even after an impact event has occurred, a safety relevant structure may continue to be in service for a short while, requiring the Z-pins to slow down damage propagation.

During both service life and operation after an impact event, it is likely that the component will see a significant amount of cyclic loading, either through vibration or other loading mechanisms. Hence, the influence of Z-pins on the fatigue performance of a composite is of great interest.

Z-pins have been shown to significantly decrease fatigue crack growth for both mode I and mode II by Cartié *et al.* [20] as well as Pegorin, Pingkarawat and Mouritz [10, 21, 22, 24]. The latter team found further that Z-pins increased the fatigue delamination onset stress, as well as the critical strain energy release rate corresponding to unstable crack propagation in both loading cases. Hence, fatigue crack initiation could actually be inhibited by Z-pin reinforcement, differently to what is reported for the quasi-static behaviour. Overall Z-pin failure mechanisms are the same as under quasi-static loading conditions. No effect of the applied fatigue displacements (average displacement, δ_0 and amplitude, $\delta\Delta$) could be discerned for mode I. For mode II loading conditions, Z-pins performed best at very high or very low stress intensity ranges.

These previous studies have focussed mainly on the degradation of a structure due to crack propagation during fatigue. However, to thoroughly assess fatigue or post-fatigue performance, and develop predictive analytical or numerical tools, the effect of fatigue on the Z-pins needs to be investigated as well. The first investigation of this topic was published by Zhang *et al.* [38], who cycled Z-pin arrays before and after debonding in mode I, showing a clear decrease of

Z-pin/laminate friction under cyclic loading. Recently, Warzok *et al.* [39] presented an experimental micro-scale study on the fatigue degradation of individual **carbon fibre** Z-pins under mode I and mode II. Although a moderate degradation of Z-pin performance during fatigue was reported, the post-fatigue behaviour did not differ from baseline tests for small **displacement amplitudes** (0.05 mm) in mode I. In contrast, a substantial degradation of fatigue and post-fatigue properties was observed for large amplitudes (0.8 mm). However, no Z-pin rupture in mode I was observed. For mode II loading, a low threshold of applicable maximum fatigue displacement was found, above which the Z-pins would fail within a few cycles. Fatigue loading below the observed threshold did not result in a reduction of post-fatigue properties.

All of the results discussed above indicate a beneficial effect of Z-pins on the fatigue performance of composites, allowing a more efficient design of impacted and fatigued structures. Especially the results of Warzok *et al.* [39] indicate a fairly high level of robustness against mode I loading.

However, with regard to the transition zone from pull-out in mode I to pin rupture in mode II reported by Yasaee *et al.* [37], this study aims at transferring the definition of the transition zone to fatigue loading scenarios, to establish if this too is unaffected by fatigue loading, as the mixed-mode case is likely to be commonly observed in realistic loading scenarios. Further, in order to generate more data on realistic loading scenarios, the testing approach of [39] is applied to meso-scale level specimens to provide further insight regarding the scaling of Z-pin performance. Several load cases and laminate configurations were considered for the specimens.

This study focuses on carbon fibre Z-pin solely. Results for metallic Z-pins are very likely to differ. A zero-dominated laminate is employed here. Previous findings [37] indicate that findings for non-UD laminates are be similar. However, for UD laminates results are expected to vary significantly.

2. Specimen Manufacture & Experimental Setup

Two types of experiments were conducted for this study: micro-scale tests to assess the failure mode of individual carbon Z-pins under fatigue loading conditions in relation to the applied loading angle; and meso-scale tests to assess the fatigue degradation of Z-pins on a larger scale. Both tests focus on the Z-pin response. The laminate, in which the Z-pins are embedded, serves as carrier material and to provide different loading and boundary conditions. Similar to the results published in [39], the mid plane interface is artificially pre-cracked with an FEP fluoropolymer film. Hence, all reaction forces exhibited by the specimens can be either linked to the Z-pin reinforcement or the specimen stiffness.

The specimens for micro-scale testing are shown in Figure 1. The nominal in-plane dimension is 20 mm by 20 mm. 6 mm and 8 mm thick specimens were tested. According to Pegorin *et al.* [21], the Z-pin foundation stiffness is significantly increased in thicker specimens and it affects the pull-out behaviour. Thus, the thinner specimens were expected to exhibit Z-pin pull-out at larger

loading angles. The specimen main characteristics are:

- Laminates made from IM7/8552 prepreg (Hexcel, UK)
- 48 or 64 0.125 mm thick plies, for a total thickness of 6 or 8 mm
- In-plane dimension: 20 mm by 20 mm
- Zero-dominated (ZD) layup with two symmetric sublaminates
 - Stacking sequence: $[(45/0/-45/0)_{3s}/ * /(-45/0/45/0)_{3s}]$ or $[(45/0/-45/0)_{4s}/ * /(-45/0/45/0)_{4s}]$
 - 0.016 mm FEP fluoropolymer film in midplane (*)
- T300 carbon/BMI $\varnothing 0.28$ mm Z-pins

In order to prevent interpenetration and thus interlocking of the prepreg fibres, a nonsymmetric stacking sequence with a 90° orientation change of the $\pm 45^\circ$ plies at the mid-plane was utilised. Inserting the FEP film ensures that only the individual pin response was measured in the experiments. Different specimens were reinforced with either a single, six or nine Z-pins. This is to separate the effects of reaction forces during deformation from the different loading/boundary conditions provided. The misalignment of each Z-pin was measured using the surface position on either side of the specimen.

Figure 1: Multiple Z-pin specimens with (a) 6 (MP6) and (b) 9 (MP9) Z-pins per specimen for investigating the effect of embedded Z-pin length.

For micro-scale testing purposes, the specimens were glued onto the same jigs previously utilised for mode I testing [39] using cyanoacrylat adhesive. To achieve different loading angles, the jig was tilted in 5° steps within the testing machine gripping device. The loading angle α is determined from Z-pin misalignment, ζ and jig tilting ϕ according to

$$\alpha = \sqrt{(\phi + \zeta_{13})^2 + \zeta_{23}^2} \quad (1)$$

with ζ_{13} being the Z-pin misalignment in the specimen rotation plane and ζ_{23} the Z-pin misalignment perpendicular to the specimen rotation plane (Figure 2). To identify the transition zone, specimens were loaded such that Z-pin pull-out and rupture were observed within one specimen. The mixed mode angle was then varied until one specimen showed only one failure mode for all Z-pins within it.

Figure 2: (a) Angle labelling conventions for Z-pin misalignment calculations and (b) determination of α .

The meso-scale specimen dimensions, Z-pin pattern, material orientation and loading conditions are shown in Figure 3. With the exception of a small section at the end, the artificial pre-crack extends through the full specimen. For mode I testing, DCB specimens were employed. The test setup allows the development of an extensive bridging zone, thus altering the Z-pin loading conditions along the specimen. For mode II testing ELS specimens were used, whose fixture allows good control of the specimen displacement. Compared to ENF specimens, the crack can extend through the whole specimen, again allowing for a wider variety of Z-pin loading conditions in one specimen. The specimen thickness was kept at 8 mm for easier comparison back to the micro-scale tests results presented in [39]. For the same reason, the stacking sequence is not altered (including the mid-plane release film). Two different Z-pin patterns were used in the ELS specimens. This is due to the fact that the Z-pin pattern in ELS_1 could not be loaded to full failure because of the low shear displacement at the specimen clamped end.

For load application purposes, piano hinges were glued onto the ELS specimens. Due to bond line peel loading, these are not suited for DCB testing. Instead, a bolted Aluminium fixture is glued onto the specimens. Two component epoxy Araldite 2013 (Huntsman, USA) was employed for bonding. During testing, the specimens were clamped in the rear section, just behind the artificial pre-crack. This is to allow extensive post-fatigue quasi-static residual testing without premature specimen failure by crack growth through the rear section. The specimens were coated with a grey scale speckle pattern on one side to perform optical measurements on the coupon surface. Loaded specimens are shown in Figure 4.

Figure 3: Sketches of the meso scale DCB and ELS specimen designs.

Figure 4: Images of (a) DCB and (b) ELS specimens highlighting the rear fixture.

For all specimen types, T300 carbon/BMI $\varnothing 0.28 \text{ mm}$ Z-pins were used. As in [39], the Z-pins were manually inserted into the heated laminate to reduce misalignment. Silicone rubber plates were placed between the laminate and the caul plates during autoclaving, as the use of metallic plates only has been identified as a further source of pin misalignment [20]. The laminate was

cured in an autoclave following the manufacturer’s recommended cycle. Using the manufacturing method described above, the Z-pin misalignment **was** reduced to an average of 5°. Because of the rubber plates, small pin protrusions are visible after curing on both sides of the composite. These **were** ground down to ensure a proper specimen positioning during testing and better comparison between micro and meso-scale results.

Servo-hydraulic uniaxial Instron 8872 25 kN and Instron MJ 6272 27 kN machines were used for all tests. Tests were conducted with calibrated 1 kN load cells and Instron hydraulic wedge grips.

3. Experimental Procedure

Micro-scale testing **was** undertaken to determine the Z-pin failure mode depending on loading angle and fatigue loading parameters. In the case of the meso-scale specimens the goal was to compare fatigue and post-fatigue specimen performance to the individual Z-pin results presented in [39]. Specimens tested in fatigue were deformed quasi-statically (0.25 mm/min) until the average fatigue displacement, δ_0 is reached. Subsequently, a **displacement amplitude** $\Delta\delta$ is applied to the specimens with a given frequency f and a certain number of loading cycles n . All tests were performed in displacement control.

3.1. Micro Scale testing

Fatigue loading is dynamic by nature. CFRP is known to exhibit a pronounced strain-rate dependency. In a first step, the transition zone was determined quasi-statically (0.25 mm/min) and also with an increased pull-out velocity of 0.1 m/s to facilitate the differentiation between effects caused by the dynamic loading and by the push-in experienced during fatigue. For fatigue testing, only the amplitude of the fatigue loading was varied, **because varying the average fatigue displacement δ_0 in the single Z-pin tests showed little to no difference for a similar displacement amplitude**. This was confirmed by . Following the results of Pegorin *et al.* [21] a specimen thickness of 6 mm and 8 mm was used to capture the influence of foundation stiffness in all micro-scale experiments.

For a misaligned Z-pin, the reaction force to a displacement in the nominal specimen thickness direction is offset, leading to the presence of a component in the dominating alignment direction and noticeable lateral displacement, even for micro-scale specimens during nominal mode I loading. To reach approximately comparable lateral reaction forces in the 6 mm and 8 mm thick specimens, the tests with quasi-static loading used 9 Z-pins in the thinner and 6 Z-pins in the thicker specimens. In contrast, 9 Z-pins were used in both the 6 mm and 8 mm thick specimens during fatigue loading. An overview of the loading conditions and the utilised specimen type is given in Table 1.

Table 1: Overview of the micro-scale fatigue tests.

specimen thickness in mm	number of Z-pins	applied loading	
6	9	quasi-static pull-out	
8	6	quasi-static pull-out	
6	9	dynamic pull-out	
8	6	dynamic pull-out	
fatigue loading			
8	1	$\Delta\delta = 0.8\text{mm}$	$\delta_0 = 1.5\text{mm}, 3\text{mm}$
8	9	$\Delta\delta = 0.8\text{mm}$	$\delta_0 = 1.5\text{mm}$
8	9	$\Delta\delta = 0.1\text{mm}$	$\delta_0 = 1.5\text{mm}$
8	9	$\Delta\delta = 0.05\text{mm}$	$\delta_0 = 1.5\text{mm}$
6	9	$\Delta\delta = 0.8\text{mm}$	$\delta_0 = 1.5\text{mm}$

Similar to the tests presented by Warzok *et al.* [39], the frequency was set to 5 Hz. However specimens were only fatigued for 10^3 cycles, since Z-pin failure was only observed during the gradual ramp-up to full **displacement amplitude** in the beginning. The peak load per cycle decreases after the full amplitude is reached, because the Z-pin surface is worn away. Hence, Z-pin failure due to buckling or bending when sliding back into the laminate is almost always expected to occur in the first cycles. The full **displacement amplitude** was reached at 300 cycles. Tests were monitored using a Canon digital camera (resolution: 1920x1080, 25 frames per second (fps) for dynamic loading, 1 fps for quasi-static loading). Displacements measurements were conducted using Aramis@software (GOM, Germany).

3.2. Meso Scale Testing

Table 2 contains the different fatigue configurations trialled for the meso-scale specimens. Three fatigue loading configurations were chosen for the DCB specimens. DCB_1 and DCB_2 are representative of a slightly and heavily damaged structure respectively, which are still operating and experiencing vibrations. The fatigue loading parameters for DCB_3 are not considered to be realistic for actual structures but were chosen for validation purposes. For the mode II tests, as shown in [39], only small shear displacements can be applied to Z-pins before final failure. Since the bending deformation of the specimen translates into small shear displacements, a fairly large **displacement amplitude** can be applied. Preliminary numerical simulations were run in order to assess the global displacement to Z-pin displacement ratio. With the specimen design chosen, the range of relevant displacements of the individual Z-pins can be covered with just one set of applied fatigue loading displacements in one specimen. According to preliminary finite element results, the critical fatigue displacement of 0.22 mm causing Z-pin failure within a few number of

cycles in the single Z-pin experiments [39] was exceeded in ELS_2 and ELS_{2-1} . Quasi-static reference tests were carried out to set a baseline against which to compare the fatigue loading. After Z-pin failure all ELS-specimens were unloaded and the test was repeated to acquire the specimen stiffness in the absence of through-thickness reinforcement.

Once the average fatigue displacement, δ_0 , was reached quasi-statically, the fatigue displacement was ramped up to maximum amplitude. For all DCB specimens, this build up was extended over the first 10^3 fatigue cycles. This was chosen due to learning from the micro-scale testing. A gradual increase of fatigue displacement was shown to significantly decrease the probability of Z-pin rupture during fatigue loading. Due to the smaller Z-pin displacements, only 10^1 and 10^2 fatigue cycles were needed to reach full displacement amplitude for the ELS specimens. All specimens were cycled with a frequency of 5 Hz. After the desired number of cycles was reached, the specimens were quasi-statically tested to failure. Failure was defined as the complete fracture/pull-out of all Z-pins.

Again, tests were recorded with a Canon digital video camera (resolution: 1920x1080, 25 fps for dynamic loading, 1 fps for quasi-static loading). Full field displacement measurements were conducted using Aramis®software (GOM, Germany).

Table 2: Overview of the meso scale fatigue tests.

denotation	δ_0	$\Delta\delta$	n	No. tests
mode I				
$DCB-ref$	-	-	-	4
DCB_1	0.7 mm	0.2 mm	10^5	3
DCB_2	3.25 mm	0.2 mm	10^5	3
DCB_3	8.15 mm	1.5 mm	10^5	5
mode II				
ELS_1-ref	-	-	-	3
ELS_1	5.2 mm	2.2 mm	10^5	5
ELS_2-ref	-	-	-	3
ELS_2	4.1 mm	1.4 mm	10^5	3
ELS_{2-1}	4.1 mm	1.4 mm	$5 \cdot 10^5$	3

4. Results

4.1. Transition Zone in Dependence of Loading Rate

The Z-pin failure modes under quasi-static and dynamic loading are shown in Figure 5. For quasi-static loading and 8 mm specimen thickness, the transition zone extends from 18° to 30°

mode mixity angle. This is in good agreement with previously reported single Z-pin results from Yasaei [37], who identified the existence of a transition zone from 20° to 26° . As expected, the transition zone shifts to larger mode mixities for a reduced thickness. For 6 mm thickness, the largest loading angles recorded for Z-pin pull-out is 35° ; Z-pin rupture started at 24° . Despite the shift, the range of the transition zone is similar for both test series.

At 0.1 m/s the mode mixity angles for complete Z-pin pull-out and the onset of Z-pin rupture decrease significantly. For 8 mm specimen thickness, the transition zone ranges from 7° to 21° ; for 6 mm thickness from 17° to 30° . The strain rate effect is more obvious for the longer embedded Z-pin lengths. Despite very high loadings rates, Schlueter [18] reported complete Z-pin pull-out for 5 mm thick DCB specimens. Since the transition zone range did not change significantly between the different testing velocities, it can be assumed that a steady-state value will be reached. The minimum loading angle required for consistent Z-pin pull-out is not expected to fall significantly below 6° for any specimen size or loading rate, if pull-out is exhibited in quasi-static loading. The results suggest that this ultimate pull-out threshold will be higher for a smaller Z-pin insertion thickness. However, this needs to be investigated in further detail to gain certainty.

Figure 5: Z-pin pull-out/rupture in dependence on α for two different embedded Z-pin lengths at (a) $4.16 \cdot 10^{-6}$ m/s and (b) 0.1 m/s loading velocity

Z-pins under mixed mode loading conditions were observed to fail in bending, which is accompanied by internal splitting. Figure 6a and 6b show two Z-pins that were tested at 8 mm thickness under quasi-static loading and a mode mixity angle $> 20^\circ$. Although both Z-pins experienced complete pull-out, significant damage can be observed. Due to the increasingly brittle material behaviour, one can conclude that a higher loading rate causes the Z-pin to rupture instead. A ruptured Z-pin is shown in Figure 6c. As to be expected, fracture shows a mixture of mode I (significant pull-out) and mode II (bending failure, internal splitting) failure.

Figure 6: SEM graphs of Z-pins in 8 mm thick specimens and an $\alpha > 20^\circ$ tested quasi-statically: (a,b) Z-pin pull-out from two samples, (c) Z-pin rupture.

4.2. Fatigue Transition Zone

4.2.1. Multiple Z-pins vs. Single Z-pin

For the first tests, specimens reinforced with either nine or a single Z-pins were cycled with a displacement amplitude of 0.8 mm. Failure mode vs loading angle is shown in Figure 7. For single Z-pin specimens (red markers in Figure 7) the likelihood of Z-pin failure depends on the mixed-mode angle. A narrow fatigue transition zone exists, extending from 6° to 7° mixed mode loading angle. The angle at which the shift occurs is much smaller than what was found for quasi-static Z-pin pull-out using either single Z-pins [37] or multiple Z-pins (Section 4.1). Z-pins were observed to fail in buckling or bending. During specimen closure, the Z-pins did not slide into the laminate, but caused a noticeable lateral shift of the upper and lower specimen half within the testing machine 25kN load frame. This effect is considerably enhanced in multi Z-pin specimens (blue markers in Figure 7), leading to Z-pin failure at very low mixed-mode angles of 1° . In a multi Z-pin specimen, a dominant misalignment direction exists, causing all Z-pins to exhibit lateral forces in the same direction during push-in. The effect is highlighted in Figure 8. Hence, Z-pins are not pushed back into the laminate, but bend between the closing specimen halves,

leading to Z-pin failure eventually. Figure 8c shows the lateral displacement in a nominal mode I test of a multi Z-pin specimen. The displacement in the lateral direction is significantly larger than in the nominal loading direction because it depends on "free" Z-pin length *i.e.* total specimen opening displacement. For a stiffer testing setup with horizontal displacement between the two testing machine grips constrained, results for multiple Z-pins are expected to be more similar to single Z-pin results.

Smaller levels of lateral shift can occur without Z-pin failure. If the static friction of the Z-pin/laminate interface is overcome at small displacements, the Z-pin is still able to slide back into the laminate. Due to the rapid degradation of frictional properties during fatiguing, significant lateral displacements do not persist.

Figure 7: Z-pin failure mode for single and multi Z-pin specimens *vs.* α

Figure 8: Lateral displacement during a nominal mode I fatigue test in a multi Z-pin specimen: Specimen at (a) full closure shortly before final failure and (b) full opening & (c) corresponding vertical and horizontal displacement.

The circles mark the time images (a) and (b) were taken.

4.2.2. Amplitude & Fatigue Loading Speed

The influence of displacement amplitude on Z-pin rupture is shown in Figure 9 for multi Z-pin specimens. As discussed, Z-pin failure starts at very low mixed mode angles for a displacement amplitude of 0.8 mm. If the amplitude is reduced to 0.1 mm (green markers), a very clear

transition around a mixed-mode angle of 6° - 7° was found. A further reduction of the displacement amplitude to 0.05 mm resulted in no Z-pin failure for the range of mixed mode angle tested. The displacement rate in the fatigue tests is approximately one tenth lower than in the dynamic pull-out tests. Still, Z-pin rupture starts at lower misalignment angles. Hence, fatigue represents the more disadvantageous loading for Z-pins. As indicated by Figure 8c, specimens failed at small displacements, significantly before the targeted amplitude is reached. This was true for all specimens tested. Since the gradual build up was similar for all tests, the increment of additional displacement is much smaller if an overall smaller amplitude is chosen. Due to the reduction of frictional forces during fatiguing, overall larger displacements can be applied to the Z-pins without failure. Hence, the chosen amplitude is rather an indication of the speed at which the fatigue loading is applied. These results highlight that Z-pins may be less beneficial in heavily damaged structures in which fatigue loading occurs with large displacement amplitudes at high frequencies.

Figure 9: Z-pin failure mode for multi Z-pin specimens *vs.* α in dependence of the applied displacement amplitude $\Delta\delta$.

4.2.3. Specimen Thickness (Embedded Z-pin Length)

Figure 10 shows the likelihood of Z-pin rupture for specimens with 6 mm and 8 mm thickness cycling with 0.8 mm displacement amplitude. As shown previously, Z-pin failure starts at very low mix mode angles for 8 mm specimen thickness. Despite cycling with the same amplitude, a clear transition zone from 5° - 6° mixed mode angle exists for 6 mm thick specimens (yellow markers in Figure 10). Pull-out was observed for larger mixed mode angles in 8 mm than in 6 mm thick specimens. This is attributed to the overall larger scatter at 8 mm specimen thickness. The more damage tolerant specimen behaviour at 6 mm thickness is caused by the more flexible Z-pin foundation (as shown in Section 4.1) and reduced static friction required to be overcome at the displacement amplitude inversion due to the smaller embedded Z-pin length. Since the same number of Z-pins has been used in both specimens, the effect of smaller lateral forces exhibited by the 6 mm thick specimens needs to be considered as well. Similar to the single Z-pin tests, the transition zone rather resembles a transition limit.

Figure 10: Z-pin failure mode for multi Z-pin specimens *vs.* α in dependence of specimen thickness ($\Delta\delta = 0.8$ mm).

4.3. Mesoscale Mode I Results

As described in the previous section the specimens **were** artificially pre-cracked. The experiments showed that the Z-pins were very effective at delaying specimen opening. For simplicity, the term "crack front" will be used in the following. However, it does not refer to a separation of composite material in the crack plane, but to a noticeable (in terms of optical measurements) relative displacement between the upper and lower cantilever. "Crack growth" will accordingly be used to describe the propagation of the newly defined crack front.

4.3.1. Reference Testing

The acquired load-displacement curves of quasi-statically loaded DCB specimens are shown in Figure 11. In contrast to an unreinforced pre-cracked specimen, whose response is only made up by specimen stiffness, the load increase due to Z-pinning is significant. It is caused by both a decrease in free cantilever bending length and the additional resistance forces exhibited by the Z-pins. The load increases steeply until the bridging zone is fully developed, indicated by the first complete Z-pin pull-out. This is highlighted in Figure 12, plotting the Z-pin mode I displacements, δ_{PI} , against global specimen opening **(applied machine displacement)**. The first complete pull-out of Z-pins at around 8 mm specimen opening coincides well with the measured peak load. Although the specimen is pre-cracked, no noticeable opening could be measured optically for the Z-pin rows at the back end of the 3D-reinforced section, until a significant specimen opening was reached. Overall, stable crack growth was observed. However, during the load decrease and the reduction of Z-pin bridging, small amounts of slip-stick behaviour occurred. This is indicated by the "steps" in the orange curve in Figure 11. When the number of Z-pins bridging the gap **was** reduced to just a few, sudden specimen opening was observed in some cases. This is marked by the load drop in the dark blue curve in Figure 11. Although small sections of the Z-pins were observed to still be embedded in the material occasionally, the tests were stopped at openings between 20 mm to 25 mm. A minor number of ruptured Z-pins (≤ 3 per

specimen) were observed. These are believed to be caused by localised Z-pin bending due to the rotating cantilever arms.

Figure 11: Quasi-static load-displacement curves of repeated Z-pinned DCB specimen tests.

Figure 12: Z-pin opening displacements *vs.* global specimen deformation in a quasi-statically tested DCB specimen (dark red curve in Figure 11).

The key properties of the quasi-statically tested DCB specimens are listed in Table 3. Energy dissipation E was taken at an opening displacement of 20 mm. In the single Z-pin tests in [39] energy dissipation was measured at 120 mJ per Z-pin. For complete pull-out of all Z-pins in a DCB specimen, this results in a theoretical energy dissipation of 7.2 J. The elastic energy stored in the specimen was approximated by integrating residual load and displacement at specimen failure and this gave 1.8 J. This results in a total theoretical energy dissipation of 9 J for each DCB specimen, compared to 8.3 J measured experimentally. Given that not all Z-pins were pulled out at $\delta = 20$ mm and some levels of sudden crack growth occurred, the micro and meso mechanical results agree very well.

Table 3: Averaged properties of peak force P , displacement at peak load δ_P and energy dissipation E with standard deviation for quasi-static DCB tests

	P in N	δ_P in mm	E at $\delta = 20$ mm in joule
mean	550	8.7	8.3
std dev	51	0.6	0.8

4.3.2. Fatigue Results

A typical hysteresis curve for DCB_2 is shown in Figure 13, where loads are relative to the average value. Due to the extended build up of the **displacement amplitude** the initial rapid degradation cannot be visualised to a full extent. This is because the effect of load degradation is overlain with increasing reaction forces due to the growing pull-out displacement. The hysteresis shape replicates the findings from [39]. **A distinct non-linearity indicates the change from static to dynamic friction between Z-pin and laminate, which is overlaid by the specimen bending resistance.** For the range of cycles covered the degradation occurs in a power law like fashion. The shift of average loads indicates small levels of crack growth. Hysteresis curves for DCB_1 are virtually identical, however with a smaller contribution of Z-pins towards the total load, due to fewer Z-pins being active.

Figure 13: Hysteresis curves of a DCB_2 specimen.

In contrast, a significant amount of Z-pins ruptured during the gradual build up of the **displacement amplitude** for DCB_3 . Significant crack growth was observed in this stage, often initiated with a sudden jump of the crack front. Due to the fixed amplitude, the applied strain energy release rate decreases with increasing crack length, leading to no obvious crack growth for the remaining number of cycles. For the five specimens tested, between 3 and 31 (out of the total of 60) Z-pins were counted to have ruptured after testing was completed. Overall, micro scale findings that predict significant Z-pin rupture at **displacement amplitudes** above 0.1 mm are confirmed.

The quasi-static pre and post fatigue load-displacement curves are shown in Figure 14. Overall, the results confirm the micro-mechanical observations in [39]. Almost no noticeable difference can be spotted between fatigued and non-fatigued specimens for small displacement amplitudes, despite the slight load drop immediately after restarting the test. The reaction load quickly recovers and no differences in the further results can be noted. Similar to single Z-pin testing, the recovery leads to similar loads for fatigued and reference specimens at the upper fatigue displacement (average displacement plus amplitude), δ_u . Both specimen sets exhibit the previously observed sudden crack propagations after passing the peak load, as well as the sudden specimen opening at the end. In contrast, a substantial degradation can be observed for DCB_3 in the post-fatigue behaviour. This is to some extent caused by the fatigue degradation of the Z-pins (blue and green curves with limited Z-pin rupture) but also by large amounts of Z-pin rupture (red and orange curves). The latter is more severe. While the specimens whose degradation is dominated by fatigue recover into the quasi-static envelope, this is only barely achieved by the specimens experiencing large amounts of Z-pin failure during fatigue. The substantial load drop after restarting the quasi-static deformation can be observed to indicate the level of recovery. Due to the different levels of Z-pin rupture, scatter is significant. The normalised residual peak load, P_{rnorm} , and normalised residual energy dissipation, E_{rnorm} are shown in Table 4. Both are determined by dividing the residual fatigue results to the quasi-static results measured in the displacement range covered by the post-fatigue testing.

Table 4: Residual properties (normalised by non-fatigue results) of peak load (P_{rnorm}) and energy dissipation E_{rnorm} measured in the quasi-static DCB tests after 10^5 cycles.

	P_{rnorm}	std dev	E_{rnorm}	std dev
DCB_1	1.07	0.01	0.99	0.03
DCB_2	1.05	0.05	1.05	0.03
DCB_3	0.68	0.09	0.6	0.08

Figure 15 shows the pre and post-fatigue individual Z-pin displacements in two specimens that were fatigued with an amplitude of 0.2 mm (Figure 15a) and 1.5 mm (Figure 15b). The Z-pin displacements captured in a quasi-static analysis are indicated by the grey dashed lines.

Figure 14: Repeated quasi-static load tests of (a) DCB_1 , (b) DCB_2 and (c) DCB_3 , pre and post fatigue.

Figure 15: Z-pin opening vs global specimen opening in (a) DCB_1 (red curve in Figure 14a) and (b) DCB_3 (light blue curve in Figure 14c)).

No significant fatigued induced opening can be observed for the cycling with the small amplitudes. The post-fatigue does not differ significantly from the quasi-static reference tests. In contrast, a

substantial opening can be observed for DCB_3 , causing pull-out to different levels in all Z-pin rows. Recovery to reference quasi-static Z-pin load is not achieved when reaching the upper fatigue displacement, δ_u , but extends approximately 7 mm further to 15 mm. This is in good correlation with the load levels shown in Figure 14c.

Mode I fatigue testing of Z-pinned composites was previously undertaken by Pingkarawat and Mouritz [4], Pegorin *et al.* [24] and Cartié *et al.* [20]. All found significant reductions in crack rate due to the Z-pins. As shown here, the Z-pins substantially increased load bearing capacity.

Especially when cycling with small amplitudes, high load levels can be maintained over a long period of time, leading to very limited crack propagation. Z-pin fracture was not reported in [4] and [24]. However, the embedded length of the Z-pins was significantly smaller than in this study (3 mm in total). As shown, a reduced Z-pin length leads to a substantially more damage tolerant specimen in terms of mode I fatigue rupture. In contrast, Cartié *et al.* [20] reported significant amounts of Z-pin rupture. The micro-mechanical observations of Warzok *et al.* [39] are confirmed, *i.e.* no post mode I fatigue degradation for small displacement amplitudes and significant post-fatigue degradation for large displacement amplitudes.

4.4. Mesoscale Mode II Results

The overall load-displacement curve for ELS tests is not very informative about the z-pin degradation and so most load-displacement curves in this section will have the load ‘reduced’ by (*i.e.* corrected for) the specimen bending stiffness, to reveal the forces acting on the Z-pins only. Due to the compressive loading force, the two arms of the cantilever are pushed onto each other, preventing opening displacement at the specimen fracture plane. The Z-pins are hence loaded in pure mode II conditions. No specimen opening could be noticed in the optical analyses.

4.4.1. Reference Testing

Figure 16a shows the load-displacement curves from the quasi-static testing of ELS_1 . The curves are reduced by the elastic reaction forces (as measured after Z-pin failure) in Figure 16b. The images show a nearly linear load build up initially. Once the peak load is reached, the Z-pins start to gradually fail, leading to a stepwise convergence of the loads to those arising from the laminate stiffness. Since the load decrease starts with the first failure of Z-pins, it can be concluded that the bridging zone is fully developed at that time and all Z-pins are loaded from the start of specimen deformation. This was confirmed from analysing the local shear displacement at the Z-pin locations, δ_{PII} (Figure 17). A slight increase in slope can be noticed at a displacement of approximately 12 mm, which correlates well with the initiation of Z-pin rupture. Z-pin failure occurs at approximately 0.3 mm local Z-pin shear displacement, which is slightly lower but still in good agreement with the micro-mechanical observations in [39]. Despite the stiff specimen the Z-pins are able to restrain specimen deformation. In contrast to the mode I specimens, the change

of structural behaviour induced by the 3D-reinforcement is significantly smaller. This is due to the effectiveness of carbon-fibre Z-pins under mode II loading conditions being less than in mode I.

Figure 16: Repeated load-displacement curves of $ELS_1 - ref$ specimens tested quasi-statically (a) with and (b) without specimen compliance.

Figure 17: Z-pin shear displacement *vs.* global specimen displacement in a quasi-statically tested $ELS_1 - ref$ specimen.

The quasi-static load-displacement curves of ELS_2 with and without specimen stiffness contribution are presented in Figure 18. Again, the Z-pin bridging zone is fully established from the start of specimen deformation. However, Z-pin failure occurs significantly earlier and less gradually. After small amounts of individual Z-pin failure, several rows fail at once, as indicated by a load drop, which is followed by a more pronounced failure of individual Z-pin rows resulting in a step-like load decrease. In comparison to ELS_1 the peak load is significantly higher. The local Z-pin shear displacement, δ_{PII} , is shown in Figure 19. Again, all Z-pins are loaded from the beginning and are able to noticeably restrain relative displacement between the two cantilever arms of the ELS specimen. This is more pronounced than in ELS_1 , due to the smaller distance between the loading point and the Z-pins. A smooth transition of shear deformation at Z-pin failure can be noticed despite the sudden failure of multiple Z-pins. This may be related to DIC

grey scale pattern resolution. Once the Z-pins fail, a significant increase of shear displacement at the Z-pin locations can be observed in Figure 19. Failure of the individual Z-pin rows occurs at a Z-pin shear displacement of approximately 0.3 mm, confirming results of both micro mechanical testing and ELS_1 . The corresponding specimen displacement of 6 mm is in good agreement with the initiation of failure in the load-displacement curves. The small differences of Z-pin shear displacement for the first five rows are in good agreement with the corresponding load drop and subsequent gradual Z-pin failure.

Figure 18: Repeated load-displacement curves of $ELS_2 - ref$ specimens tested quasi-statically (a) with and (b) without specimen compliance.

Figure 19: Z-pin shear displacement *vs.* global specimen displacement in a quasi-statically tested $ELS_2 - ref$ specimen.

The quantitative results without specimen stiffness are given in Table 5. As predicted by the micro scale results in [39] absorbed energy, E , is similar in both specimens. Multiplying energy absorption per single Z-pin (10.1 mJ) as determined in [39] by the number of Z-pins per specimen predicts a total energy dissipation of 0.61 J per specimen. This is in very good agreement with the results presented in Table 5. Differences in peak load, P , and peak load displacement, δ_P , between ELS_1 and ELS_2 are caused by the different loading rates of the Z-pins due to varying

locations along the specimen length.

Table 5: Averaged properties with standard deviation for quasi-static ELS tests

		P in N	δ_P in mm	E
ELS_1	mean	51	10.8	0.62
	std dev	2.4	1.2	0.04
ELS_2	mean	118	6.2	0.68
	std dev	9.0	0.5	0.05

4.4.2. Fatigue Results

Sudden shifts of the upper and lower cantilever arms or Z-pin rupturing sounds were not noticed during fatigue cycling for any specimen. However, the load trends captured indicate Z-pin failure during fatiguing for ELS_2 and ELS_{2-1} . While the peak load per fatigue cycle, P_F , undergoes only marginal changes for ELS_1 a significant degradation can be observed in ELS_{2-1} . At $n = 10^5$ P_F is reduced to approximately 75% of its initial value. A further reduction of 5% was measured after $5 \cdot 10^5$ cycles. According to reference tests (Figure 18), this reduction corresponds approximately to the contribution of the Z-pin load towards the total load. By the end of fatigue testing, specimen resistance to the applied load is almost solely due to the specimen bending stiffness.

In contrast to single Z-pin testing [39], failure did not occur rapidly in the first few cycles but instead occurred gradually over a large range of cycles. The reason for the change of failure behaviour is related to the gradual change of shear displacement along the specimen length during the failure process, highlighted in Figure 19. It is reasonable to assume that load redistribution in a multi Z-pin array and the reduction of tensile loads due to more pure mode II loading conditions promote gradual instead of sudden failure.

Typical hysteresis curves without Z-pin failure over the range of the fatigue cycling, taken from ELS_1 , are shown in Figure 20. The load is reduced by the initial load at the average fatigue displacement. The meso scale results confirm observations from the single Z-pin testing [39]. A limited contribution of the Z-pins to energy absorption per fatigue cycles is indicated by the small curve area. The shift of Z-pin loading onset at larger displacements with increasing number of cycles, indicated by the non-linearity and the decrease of peak load per cycle, were observed as well.

Figure 20: Hysteresis curves of an ELS_1 specimen.

In contrast, a continuous decrease of the average load during fatigue cycling, indicated by the shift of the hysteresis curves towards lower loads, can be observed for ELS_2 (Figure 21). An increased load reduction rate can be observed for the range of $2 \cdot 10^4$ to 10^5 cycles, and a more gradual load decrease can be observed for the rest of the experiment. With increasing number of fatigue cycles the hysteresis curve area decreases, indicating the reduction of Z-pin contribution to energy dissipation due to fatigue degradation and progressive Z-pin failure.

Figure 21: Hysteresis curves of an ELS_{2-1} specimen.

Pre and post fatigue quasi-static load-displacement curves for ELS_1 with and without specimen stiffness are shown in Figure 22. The results are in excellent agreement with the micro mechanical observations in [39]. After restarting the quasi-static deformation, very low loads are exhibited by the Z-pins. With further deformation, the loads rise and recover the level observed in the quasi-statically tested references at about 10 mm displacement. As in the single Z-pin tests the recovery extends further than the upper fatigue displacement, δ_u . An insignificant reduction of 4% was measured for the peak load. Due to the load drop and subsequent recovery, energy dissipation was determined to decrease by 16% in the fatigued specimens. Similarly, no changes in the local

Z-pin shear displacement curves were noticed.

Figure 22: Repeated quasi-static load tests of ELS_1 specimens, pre- and post-fatigue (a) with and (b) without specimen compliance.

In contrast, a significant reduction of residual properties, that correlates with the applied number of cycles, was found for ELS_2 and ELS_{2-1} (Figure 23). Although specimens exhibit some load recovery, substantial reductions of the peak load by 60% and 70%, respectively, were measured. Contrary to the single Z-pin experiments, where the degradation of residual energy dissipation E was more substantial than the degradation of residual peak load, the reduction of P and E is similar. It is only for a displacement exceeding 10 mm that the load levels of fatigued and reference specimen are similar again. No change of failure displacement could be noticed. The curve shape of the fatigued specimens does not change significantly, though. The loads recover initially and reach the peak load at slightly smaller displacements to that seen in the reference tests. All surviving Z-pins are loaded at once. Due to Z-pin degradation and the decreased number of active Z-pins, the load reached is lower than in the quasi-static reference. Once the peak load is passed, the number of Z-pins bridging the crack is constantly decreasing until the reaction corresponding to the specimen stiffness is reached.

The behaviour can also be observed in the optical analyses. Figure 24 shows the pre and post fatigue Z-pin shear displacements versus global specimen displacement for ELS_{2-1} . A noticeable jump of nearly 0.2 mm Z-pin displacement, indicating crack growth under fatigue, can be observed for all but the last three Z-pin rows. These experience shift in the individual fatigue displacement as well, however to a smaller extent. It is reasonable to assume that all but these three Z-pin rows are at least partially fractured at that point. As indicated by the load-displacement curves, convergence of fatigued and reference specimens is only achieved beyond a displacement of 10 mm. The normalised residual properties for the different configurations are given in Table 6.

Figure 23: Repeated quasi-static load tests of (a) ELS_2 specimens and (b) ELS_{2-1} specimens, pre- and post-fatigue without specimen compliance.

Figure 24: Pre and post fatigue Z-pin shear displacement vs. global specimen displacement in a ELS_{2-1} specimen.

Table 6: Residual properties (normalised by non-fatigue results) measured in the quasi-static ELS tests after 10^5 cycles.

	ELS_1	ELS_2	ELS_{2-1}	ELS_3	ELS_{3-1}
P_{rnom}	0.96	0.39	0.30	0.98	1.02
std dev	0.05	0.1	0.08	0.04	0.05
E_{rnom}	0.87	0.38	0.32	0.71	0.75
std dev	0.05	0.03	0.05	0.07	0.04

Mode II fatigue testing of Z-pinned composites at the meso scale level has so far only been

investigated by Pegorin *et al.* [10, 24]. Similar to this study, gradual Z-pin failure was reported. Effects of Z-pinning were more pronounced for very high or very low stress intensity ranges. As shown for ELS_1 , Z-pins can maintain a stable connection between two composite sections separated by a crack for a long time, thus increasing the effective second moment of area and providing higher stiffness over a relatively small displacement range. For high loading, the ongoing Z-pin failure in ELS_2 was shown to lead to constantly decreasing peak load per cycle, thus highlighting the contribution of Z-pins on the load bearing capacity even for a rather low Z-pin density. However, the effect could not be maintained for a high number of cycles. The significantly lower embedded Z-pin length of 4 mm in [10, 24] is known to result in a substantially more damage-tolerant Z-pin behaviour.

5. Conclusion

A series of studies have been undertaken to better understand the behaviour of laminates reinforced with carbon fibre Z-pins. Constant amplitude fatigue tests at varying Z-pin angles as well as constant amplitude mode I and mode II fatigue tests at coupon scale were conducted. The following conclusions can be drawn:

- Z-pin final failure mode (complete pull-out/rupture) during monotonic loading depends on the loading angle. Increasing loading speed or embedded Z-pin thickness shifts the onset of Z-pin rupture towards smaller angles. However, the range of mixed-mode loading angles in which both failure modes occur (the so-called transition zone), does not change significantly.
- The transition zone concept can be applied to cyclic loading. The onset of Z-pin rupture is shifted towards lower angles by increasing the Z-pin embedded length, displacement amplitude and rate of load application (*i.e.* increased frequency for constant amplitude). In contrast to monotonic loading, the range of the transition zone varies significantly for different parameters.
- Micro-scale testing allows an accurate assessment of Mode I meso-scale fatigue characteristics. Low amplitude, high cycle fatigue loading, leads to no significant reduction of post-fatigue properties. In contrast, large displacement amplitudes were shown to cause a substantial degradation of post-fatigue Z-pin properties, either by wear of the Z-pin surface or Z-pin rupture.
- Likewise, mode II meso-scale and micro-scale fatigue behaviour showed similar characteristics. No noticeable reduction of post-fatigue properties could be observed as long as Z-pins did not fail under cyclic loading. However, for the case of Z-pin shear failure during fatigue, a gradual progression of failure along the fracture plane was observed, whereas Z-pins broke catastrophically in micro-scale experiments. The critical fatigue displacement leading to Z-pin failure could be determined from micro-scale results.

- DIC-data from mode I and mode II meso-scale experiments showed a significantly smaller bridging zone in mode I, with a nearly complete suppression of opening in the rear section of the DCB specimen. In contrast, the complete free bending length of the ELS-specimen was loaded in shear from the start. Still, Z-pins were observed to noticeably reduce the shear displacement.

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