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Fatigue delamination growth - Is UD testing enough?

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Abstract

Full scale composite structures typically consist of multi-directional lay-ups. However, fatigue delamination growth experiments are usually conducted on test coupons with a unidirectional lay-up. This raises the question how to transfer results gathered from such coupons to understand and predict fatigue delamination growth in full scale structures. Is testing unidirectional coupons sufficient, or is further data needed to take the fibre orientation change across a delaminating interface into account?

The present work investigated the effect of fibre orientation on fatigue driven mode I delamination growth in a carbon fibre reinforced polymer composite. Specimens with a 0//0, a 0//45, and a 0//90 interface were tested. It was found that the fibre orientation affected the delamination growth rate, as it changed the nature and strength of toughening mechanisms such as fibre bridging and crack migration. Of the tested interfaces, the 0//0 interface exhibited the fastest delamination growth rates for a given fatigue load and pre-crack length, but further investigation is necessary to confirm that a 0//0 interface will indeed reliably provide 'worst case' delamination growth data.

Keywords: CFRP; Crack migration; Double Cantilever Beam test; Fibre bridging; Fibre orientation;

1. Introduction

Fibre reinforced polymer composites are seeing increasing use as structural materials, in particular for applications where structural weight should be kept as low as possible, such as aerospace or wind energy. Early composite structural designs usually contained large safety factors to deal with issues such as potential manufacturing defects and environmental influences. Consequently, the in-service loading is sufficiently low that fatigue issues are avoided. However, as our control over material quality improves, and designers seek to use more of composites' strength potential, this situation is changing, and fatigue of composites is becoming an issue in service. As a result, the need to understand and predict fatigue of composite materials is gaining more and more attention (Vassilopoulos, 2020).

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Nomenclature

a	Crack length (mm)
b	Specimen width (mm)
C	Compliance (mm/N)
d	Displacement (mm)
G	Strain energy release rate (N/mm)
h	Specimen thickness (mm)
N	Number of cycles (-)
m	Slope of a/h versus $C^{1/3}$ plot
P	Force (N)

Fatigue in composite materials is a complex phenomenon, involving the interplay of different damage mechanisms, including matrix cracking, fibre-matrix disbonding, delamination, and fibre failure. In an effort to reduce this complexity, researchers have developed test methods that attempt to isolate the different damage modes, so they can be studied independently. In particular, fatigue driven delamination growth has received a lot of attention, because this is usually considered to be the most severe damage mode and likely also because it is the damage mode that can most easily be detected during experiments.

Formal fatigue delamination growth test standards are still under development (Brunner et al., 2021; Stelzer et al., 2014; Brunner et al., 2009). Nevertheless, the research community has settled on a de facto standard approach for these kinds of tests, basing specimen geometries and test rigs on quasi-static test standards. While details of the test procedure and data analysis vary between researchers, specimen geometries and load application are usually the same. For mode I delamination growth, often the double cantilever beam (DCB) specimen is used, based on ASTM D5528 (ASTM International, 2013) or ISO 15024 (International Organization for Standardization, 2001). The pertinent question is how to transfer results from such experiments to understand and predict the behaviour of full-scale structures.

There are various differences between full-scale structures and the standard test coupons used by researchers. This work focusses on one point in particular: the composite lay-up. Standard DCB specimens consist of a unidirectional (UD) lay-up, with all fibres aligned along the long axis of the specimen. The delamination occurs at the mid-plane of the specimen, between two plies with the same fibre orientation. On the other hand, full scale structures typically make use of a multi-directional (MD) lay-up, with different fibre orientations in different plies. Furthermore, delaminations are more likely to occur at interfaces between two plies with dissimilar fibre orientations (Hitchen and Kemp, 1995; Fuoss et al., 1998). Nevertheless, as will be discussed below, only a few researchers have so far reported investigations of fatigue delamination growth in a multi-directional interface.

Therefore this work set out to answer the question: Is it sufficient to only test fatigue delamination growth in unidirectional interfaces? Or should we also test delamination multi-directional interfaces? To this end, fatigue delamination growth tests were performed on DCB specimens with different lay-ups, producing delamination growth curves for a variety of fibre angle combinations at the interfaces. The results indicate that the fibre orientation at the interface can indeed significantly affect the delamination growth and requires further study.

2. Background

Under quasi-static loading it has already been established that the fibre orientation affects the fracture toughness. Results have been reported for different interfaces, including both $0//\alpha$ interfaces and anti-symmetric interfaces. A comprehensive overview has recently been provided in the introduction of Blondeau et al. (2019). In summary, the initial fracture toughness appears to be independent of the ply orientation, but the propagation or R-curve behaviour often does depend on the fibre orientation.

The likely reason for this is that the delamination initiation is mainly dominated by the resin properties (which are not affected by the fibre orientation), while the R-curve behaviour is governed by phenomena such as fibre bridging, which do depend on the fibre orientation (Bin Mohamed Rehan et al., 2017). Furthermore, multi-directional laminates exhibit phenomena such as crack migration, which can increase the (apparent) fracture toughness[1]. The nature of the crack migration has been observed to depend on the fibre orientation. For example, Pichler et al. (2020) investigated an antisymmetric ±45° interface and found that the crack progressively migrated away from the initial delaminating interface. On the other hand, in a $[90/0_{10}/90]_S$ layup, Mollenhauer et al. (2018), observed an oscillatory behaviour, where the crack migrated up and down between the 0//90 and 90//0 interfaces on either side of the initially delaminating 90//90 interface. Compared to quasi-static delamination, fatigue driven delamination growth in multi-directional interfaces has received less study. Works in the literature include those of the group of Banks-Sills (Chocron and Banks-Sills, 2019; Banks-Sills et al., 2019) who studied delamination growth between a 0° UD ply and a ±45° weave, Peng et al. (2012), Zhao et al. (2016) and Gong et al. (2020) who studied a +45//-45 interface, Yao et al. (2014, 2017) who studied a +45//+45 interface, and Singh and Greenhalgh (1998) who compared 0//0 and 0//90 interfaces.

Singh and Greenhalgh report a higher fracture toughness for the 0//90 interface due to a secondary cracking mechanism. Peng et al. (2012) noted that when normalising by the quasi-static fracture toughness, the normalised fatigue thresholds for a +45//-45, a 0//5, and a 90//90 interface were more or less the same. However, they did not compare the crack growth behaviour at loads above the fatigue threshold. Yao et al. (2017) found that the fatigue threshold (not normalised in this case) was higher for the 45//45 interface than for a 0//0 interface, as was the quasi-static R-curve. The remaining authors did not provide a comparison between the multi-directional interface they investigated and a 0//0 interface, making it difficult to draw any conclusions on the effect of the fibre orientation.

In summary, we could expect that also in fatigue different fibre orientations will lead to differences in fibre bridging and crack migration. This would then affect crack growth rates.

Regarding fibre bridging in fatigue, Yao et al. (2016) found that the amount of fibre bridging depends on the crack length. As the crack length increases, a fibre bridging zone develops and grows ahead of the crack tip. The progressive growth of this zone causes a reduction of the fatigue delamination growth rate (at a given applied load cycle in terms of strain energy release rate). This effectively causes the Paris curve (crack growth rate vs maximum strain energy release rate, or strain energy release rate range) to shift to the right. Additionally, the increase of crack length, and thus fibre bridging over the course of a single test will also affect the slope of the Paris curve (Alderliesten, 2018). This process does not continue indefinitely however. At some point a further increase of the crack length will not cause a further shift of the Paris curve, indicating a saturation of the fibre bridging (Yao et al., 2016).

3. Methodology

3.1. Specimens

Double cantilever beam specimens were manufactured from Deltapreg M30SC/DT120-200-36 unidirectional carbonfibre / epoxy prepreg, for which previous fatigue data is publicly available (Alderliesten and Yao, 2017). The prepreg was laid up into different plates with the lay-ups specified in Table 1 and a 0.01 mm PTFE crack starter film at the laminate mid-plane. Per the manufacturer's recommendation, the plates were cured in an autoclave for 90 minutes at 120 °C and 6 bar (0.6 MPa), with a 700 minute post cure at 40 °C. After curing, specimens were cut from the plates using a diamond saw. To connect the specimens to the load frame, aluminium load blocks were bonded to the specimens using 3M Scotch-Weld EC-2216 B/A epoxy adhesive.

The specimen design followed ASTM D5528, with the exception of the lay-up. The specimen dimensions were 200 x 25 mm, with a nominal thickness of 5.2 mm (nominal ply thickness 0.16 mm). Rather than the unidirectional lay-up specified by ASTM D5528, specimens with a number of different lay-ups were produced. Due to space limitations this paper will discuss only three of the lay-ups tested, as shown in Table 1. For more details and results of the other four lay-ups tested (with delaminating interfaces: 45//45, 90//90, +45//-45 and 30//-60), see van der Panne (2022). The data for all seven tested lay-ups is also publicly available via `https://dataverse.nl/dataverse/FibreOrientationFatigueDelam`.

[1] One can debate whether it's still appropriate to speak of a fracture toughness value when crack migration occurs, as now multiple interfaces are involved in the cracking process. The key point for the present discussion is that it requires more energy to propagate the crack.

Table 1. The different lay-ups used in this research. The double backslash (//) marks the location of the PTFE insert.

Interface	Lay-up
0//0	$[0_{16}//0_{16}]$
0//45	$[0_{16}//45/0_{15}]$
0//90	$[0_{16}//90/0_{15}]$

3.2. Testing and data analysis

The test procedure was based on a (currently unpublished) draft protocol under development within ESIS TC4. Two separate fatigue tests were conducted per specimen, one with a short initial crack length and one with a long initial crack length.

Fatigue tests were performed on an MTS hydraulic fatigue testing machine, with a 1 kN capacity load cell. The cross-head displacement was measured by the testing machine, and two cameras (one per side of the specimen) were used to measure the crack lengths, in order to capture growth of delamination in case the delamination front was not perpendicular to the specimen sides. To assist in this a piece of graph paper with 1 mm graduations was adhered to the side of the specimens.

The specimens were initially loaded quasi-statically in displacement control at a rate of 1 mm/min. As soon as crack propagation was observed, the loading was halted and the obtained cross-head displacement was used as the maximum displacement value (d_{max}) for the fatigue test. The minimum displacement was set to $d_{min} = 0.1d_{max}$. The fatigue cycles for this first test were applied at a frequency of 5 Hz. Because the test was conducted in displacement control, the crack growth rate decreased as the crack grew. Once the crack growth rate had reached a sufficiently low level (approx. 10^{-6}mm/cycle) the test was halted. This was typically after 150-200 kcycles.

To prepare the second fatigue test, the same specimen was again loaded quasi-statically. In this case, the crack was allowed to propagate, to obtain a ‘long’ initial crack. After a sufficient amount of crack extension had been obtained, the loading was halted and the final displacement value was used as the maximum displacement for a second fatigue test, again with $d_{min} = 0.1d_{max}$. Allowing for this quasi-static crack growth is a deviation from the draft protocol, but was chosen in order to have a greater difference between the short and long initial crack lengths, allowing a first insight into the fibre bridging behaviour with fewer tests.

For the 0//0 specimens, the crack was quasi-statically grown to >100 mm, which, based on the data from Yao et al. (2016) was expected to give saturation of the fibre bridging. However, it was also found that this long crack length required a reduction of the test frequency to 2-2.5 Hz, as the fatigue machine was not able to maintain 5 Hz at the higher displacements required for these long crack tests. Therefore for the 0//45 and 0//90 specimens it was decided to use a shorter crack extension (to 75-85 mm) for the second test, and increase the test frequency to as close to 5 Hz as possible. This allowed the second test for the 0//45 and 0//90 specimens to be conducted at 3-5 Hz, depending on the specific test (see van der Panne (2022) for the details).

At regular intervals, the specimen was held at the maximum load and to acquire an image for the crack length measurement. Following the draft protocol, an image was acquired every 100 cycles during the first 5,000 cycles of the test. For the range from 5,000 to 20,000 cycles, an image was acquired every 500 cycles. After 20,000 cycles, an image was acquired every 1,000 cycles.

From the measured force, displacement, and crack length, the strain energy release rate was calculated using the modified compliance calibration method described in ASTM D5528 (ASTM International, 2013):

$$G = \frac{2P^2C^{2/3}}{2mbh} \tag{1}$$

with G the strain energy release rate, P the force, C the compliance, m the slope of the best fit line through the a/h versus $C^{1/3}$ data, b the specimen width and h the specimen thickness.

The crack growth rate da/dN was determined from the crack length measurements following the 7-point incremental polynomial method described in ASTM E647 (ASTM International, 2015).

4. Results

In total two specimens were tested for each interface investigated, with two tests per interface. Figures 1a-c show the crack growth rate curves for each interface. The initial cack length a_0 for each interface is also shown.

For the 0//0 tests (Figure 1a) the crack growth rate curves for the short crack tests showed a shift to the right, correlating to the increase of pre-crack length, whereas the curves for the long crack tests overlapped. For the 0//45 tests (Figure 1b) the curves for the short crack tests overlapped those of the 0//0 tests. On the other hand, the curves for the long crack tests were shifted significantly to the right compared to the 0//0 tests, even though the pre-crack length for the 0//45 tests was much shorter. For the 0//90 tests (Figure 1c), the curves for the short crack tests fall on the right hand side of the range of the 0//0 and 0//45 tests, but the pre-crack lengths were also longer. The curves for the long crack tests fall in between the 0//0 and 0//45 curves.

Comparing the crack lengths on both sides of the specimens, for the 0//45 tests these differed by less than 2 mm for three out of the four tests, and for about 4-5 mm for one of the long crack tests. The crack length differences remained roughly constant during the test. C-scan images also showed a front more or less straight and perpendicular to the crack front (see van der Panne (2022)). For the 0//90 tests a difference of 4-5 mm was noticed for the short crack tests and one of the long crack tests. The other long crack test showed a different of 7-9 mm. C-scan images showed that the front was not perpendicular to the edge of the specimen, but under an angle (again see van der Panne (2022) for more details).

After the fatigue tests were completed, the two specimens arms were pulled apart by applying a monotonicly increasing displacement until failure of the specimen, in order to observe the fracture surfaces. During this process the fibre bridging behaviour was clearly visible. Representative examples are shown in Figures 1d-f.

5. Discussion

The behaviour of the 0//0 experiments (Figure 1a) is in line with the results of Yao et al. (2016): at short initial crack lengths, an increase of the initial crack length results in more fibre bridging and thus a shift to the right of the crack growth rate curve. At long initial crack lengths saturation of the fibre bridging occurs and thus there is no further shift of the curves, even though the initial crack length is increased from 106 mm to 114 mm. The existence of fibre bridging could also be visually confirmed (Figure 1d).

For the 0//45 experiments we can see that the crack growth curves at short initial crack lengths lie on top of the 0//0 curves (Figure 1b). However, at long crack lengths the curves are shifted far to the right compared to the 0//0 curves, even though the initial crack lengths were significantly shorter (72 and 88 mm vs 106 and 114 mm). This is reminiscent of what has been reported in literature for the quasi-static case (see section 2), where the delamination initiation does not depend on the fibre orientation, but the propagation behaviour does. Similarly, based on the results shown in Figure 1b, we can hypothesise fibre bridging needs to be developed and therefore mainly plays a role at longer initial crack lengths. If this fibre bridging then has a stronger effect due to the fibre orientation, it could cause a further shifting of the crack growth curve. Indeed, a visual comparison of the fibre bridging behaviour of the 0//45 interfaces (Figure 1e) and the 0//0 interfaces (Figure 1d) shows a difference in fibre bridging behaviour. For the 0//0 interfaces we see many individual bridging fibres, whereas in the 0//45 interfaces bundles of bridging fibres can be distinguished. One could even argue that these bundles represent a case of crack migration, rather than simple fibre bridging. In any case, Figure 1b makes it clear that this phenomenon had a stronger slowing effect on the crack growth rate than the fibre bridging that occurred for the 0//0 specimens.

For the 0//90 specimens the crack growth rate curves for the short crack lengths overlapped with the 0//0 and 0//45 curves (Figure 1c), though more towards the right side. At the same time the pre-crack length for the 0//90 specimens was also longer than for both 0//45 specimens and one of the 0//0 specimens. This again suggests that the crack growth rate at low initial crack lengths, where not much fibre bridging has yet developed, is less affected by the fibre orientation. The crack growth rate curves for the long initial crack lengths fall in between the 0//0 and 0//45 curves, even though the initial crack lengths for the 0//90 curves were longer than those for the 0//45 curves. A possible explanation of this is offered by the fibre bridging behaviour. For the 90//90 specimens, an oscillatory migration behaviour was observed (Figure 1f), similar to that reported by Mollenhauer et al. (2018). This created bundles of bridging fibres, similar to the 0//45 interface (Figure 1e), but aligned in the 90° direction, whereas for the

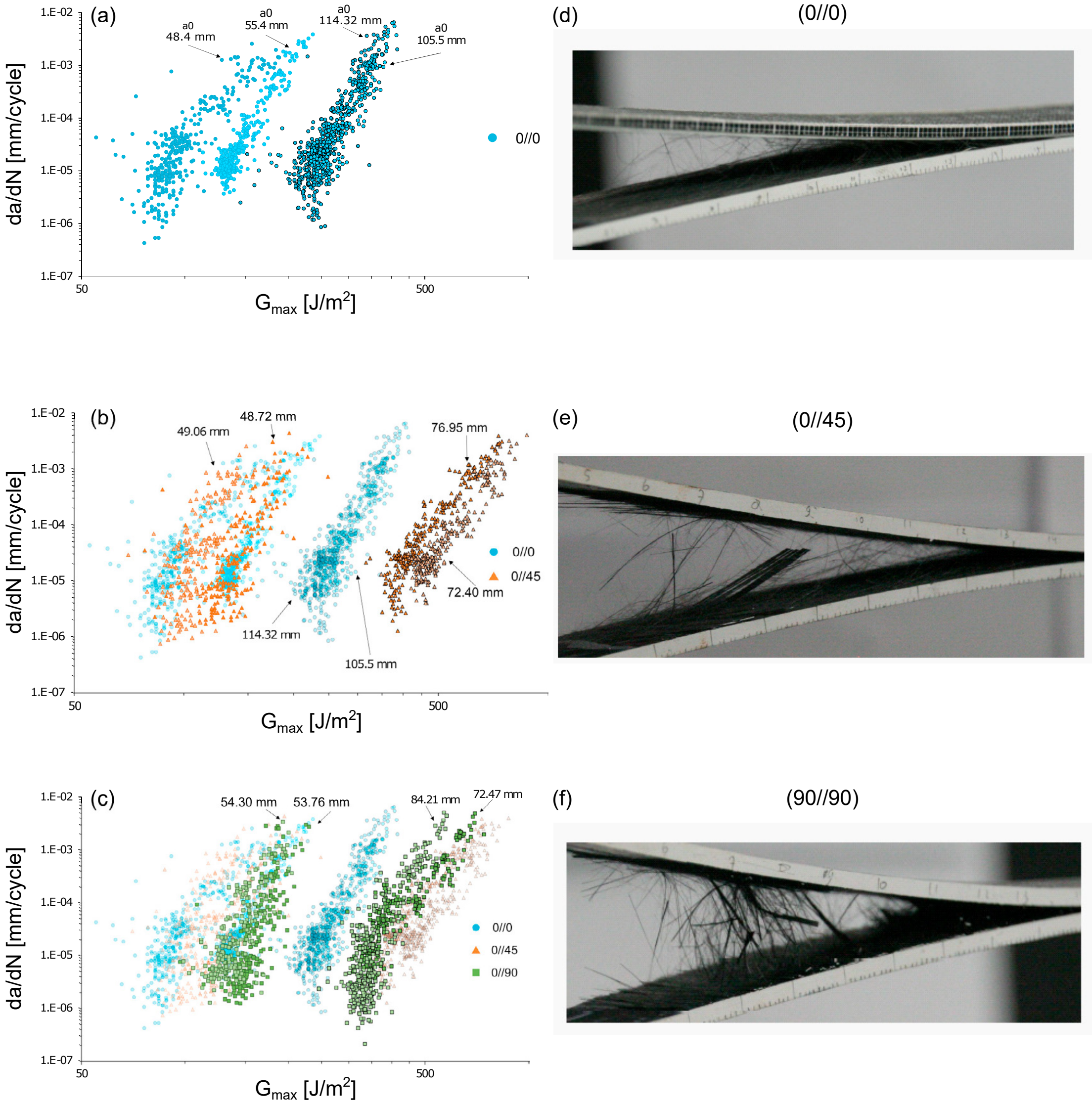

Fig. 1. Results of the delamination growth tests; there were two specimens per interface, and two tests per specimen. Panels (a)-(c) show the Paris crack growth rate curves for the three different interfaces. The initial crack length a_0 (measured from the load application point) is shown for each test. Panels (d)-(f) show typical examples of the fibre bridging in each interface. These images were acquired during a quasi-static opening of the crack after the second fatigue test.

0//45 interface the bundles were aligned in the 45° direction. The length of these bundles is in both cases limited by the width of the specimen. This means that in the 0//45 specimens, longer bundles can develop, which may explain the stronger slowing of the crack growth rate for the 0//45 specimens. In full scale structures this width effect may not be present, which would then also change the fibre bridging behaviour.

The presented results imply that the fibre orientation has a strong effect on the fibre bridging. In order to be able to investigate more interfaces, for the present research the choice was made to only investigate a 'short' and a 'long' initial crack for each interface and to grow the crack quasi-statically between these tests. For a detailed characterisation of the fibre bridging, e.g. to reconstruct the 'zero-bridging' curve (Alderliesten, 2018), quasi-static crack growth should be avoided, and Paris curves should be generated for more than just two initial crack lengths. Having more data points would also allow us to investigate whether fibre orientation affects when saturation of the fibre bridging occurs.

The presented results also imply that testing multiple different fibre orientations, and possibly different widths, is necessary to fully understand delamination growth. For practical applications this is not desirable. One option is to only test a small number of interfaces and then try to interpolate for other interface angles, for example by employing an approach similar to those discussed by Jones et al. (2021). However, the change of crack migration behaviour at different fibre orientations might prevent this from working. Alternatively, one could conduct planar delamination growth tests, where the fibre orientation with respect to the delamination varies around the circumference of the delamination. Another option would be to only perform tests on an interface that will give 'worst-case' crack growth results, i.e. with the least amount of fibre bridging. Of the interfaces presented in this paper, the 0//0 interface clearly presented the worst case, especially at long pre-crack lengths. However it is not certain this indeed represents the absolute worst case. For example a 0//5 interface might prevent nesting, and thus suppress fibre bridging, which at the same time also blocking the delamination migration behaviours seen in the 0//45 and 0//90 specimens. Further research is needed to establish what is the worst-case delamination growth scenario.

6. Conclusions

In the present research, fatigue driven delamination growth was investigated using double cantilever beam specimens with a 0//0, a 0//45, and a 0//90 delaminating interface. The results show that:

- The fibre orientation affects the nature and strength of the fibre bridging and crack migration phenomena and consequently the resulting delamination growth rate at a given fatigue load;
- The delamination growth rate is more sensitive to the fibre orientation for longer initial crack lengths; possibly this is related to the crack extension needed to develop the fibre bridging zone;
- Of the tested interfaces, the 0//0 interface produced the fastest crack growth rates, especially for long initial crack lengths.

It is clear that further investigation of the effect of fibre orientation on delamination growth under fatigue loading is required. Relying solely on unidirectional coupons to understand and predict the behaviour of full-scale structures is likely not sufficient, unless worst-case data is used, which could result in over conservative designs.

To prevent the neccesity of testing many different lay-ups, it would be preferable to develop our understanding of the underlying physics governing fatigue delamination growth. This would then allow us to a predict the delamination growth rate for an arbitrary combination of fibre angles at the interface, based on only limited material data.

Data access statement

The data underlying this research will be made publicly available via: https://dataverse.nl/dataverse/FibreOrientationFatigueDelam. If needed, a copy of the data can also be requested directly from the corresponding author via e-mail: j.a.pascoe@tudelft.nl

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