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Characterizing Fatigue Delamination Growth in Multidirectional CFRP Laminates [†]

Davide Biagini ¹, Francisco Monticeli ¹, Yasmine Mosleh ² and John-Alan Pascoe ^{1,*}

¹ Department of Aerospace Structures and Materials, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2926 HS Delft, The Netherlands; d.biagini-1@tudelft.nl (D.B.); f.m.monticeli@tudelft.nl (F.M.)

² Department of Engineering Structures, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands; y.mosleh@tudelft.nl

* Correspondence: j.a.pascoe@tudelft.nl

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Abstract

Despite the popularity of multidirectional laminates in many fatigue-prone design applications, there is still little understanding of how the adjacent plies' fibre orientation affects interfacial crack (delamination) fatigue propagation. To expand our knowledge on this matter, we present a systematic experimental investigation of the delamination growth behaviour for different interfaces and under different opening modes. In mode I, off-axis plies (as in 90//0 and 45//0 interfaces) increase the effects of fibre bridging, shifting the Paris curves to higher strain energy release rates (SERR), and thus making the 0//0 results (highly) conservative. Instead, in the presence of mixed mode, the Paris curves of 0//0 interfaces were not conservative in case of low SERR and low crack growth rates. These effects need to be accounted for when predicting the fatigue behaviour of a multidirectional laminate.

Keywords: delamination growth; damage tolerance; fatigue; mixed mode; mode I; mode II; CFRP; fibre orientation

1. Introduction

The use of fibre-reinforced polymer (FRP) composites for aerospace structures is now well established. The first commercial airliner to incorporate more than 50% composites by mass, the Boeing 787, is well into its second decade of service. In the wind energy sector, FRP composites have been the material of choice for turbine blades for quite some time. Composites are also gaining ground in other sectors, such as maritime and automotive. Therefore, at this point, one can justifiably speak of the first generation of composite structures that are in operation.

For this first generation of composite structures, fatigue failure was not a main design driver. That composites can be prone to fatigue has been understood since their introduction as engineering materials [1], and guidelines on fatigue testing and analysis were included in early design handbooks such as the MIL-HDKB-17 [2]. This handbook however notes:

“It is important to note that, for the majority of current aircraft composite structures, fatigue capability does not become a limiting factor if all static strength concerns have been thoroughly and successfully addressed. Exceptions to this are high-cycle components such as those found in helicopter dynamic systems” [2].



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This is true in part due to the conservative knockdown factors applied in first-generation composite designs. These were used to account for aspects such as manufacturing tolerances, limited analysis capability, and environmental influence on mechanical properties. As a result of this conservative approach, load levels in first-generation composite structures, especially during normal operations, indeed typically stay well below the fatigue limit. However, as manufacturing quality and analysis capabilities have improved, there is a desire to increase allowable load levels to make more optimal use of the material. In this case, the occurrence of fatigue may become more relevant. A better understanding of fatigue propagation can also be required to support life extension programmes, or to evaluate the impact of unanticipated damage findings in service [3].

The need for more advanced fatigue analysis has been recognised by the community, and, for example, the Composite Materials Handbook 17 (CMH-17) [4], the successor to MIL-HDBK-17, contains more extensive methods for fatigue analysis. However, due to the limited ability to predict fatigue behaviour of composites, these methods are still heavily reliant on empirical data, which is costly and time-consuming to generate. Thus, there is a clear need for fatigue analysis methods that require less experimental data input. Developing such methods was a key objective of the D-STANDART project.

The present paper presents results from one aspect of the D-STANDART project, which was the investigation of the influence of fibre orientation on fatigue-driven delamination growth. The delamination growth behaviour was characterised for IM7/8552 carbon fibre/epoxy pre-preg for three different interface fibre orientations, under pure mode I, pure mode II, and 50/50 mixed-mode I/II loading.

2. Importance of Understanding the Fibre Orientation Effect

For certifying aircraft structures, typically, the building block approach [5,6] is followed, as illustrated in Figure 1. In this approach, at first, a large number of coupon tests are performed to characterise the material behaviour. Then more and more structural complexity is added to the tests, making the specimens increasingly specific to the product being developed. Finally, a full-scale test of the entire aircraft structure caps the pyramid.

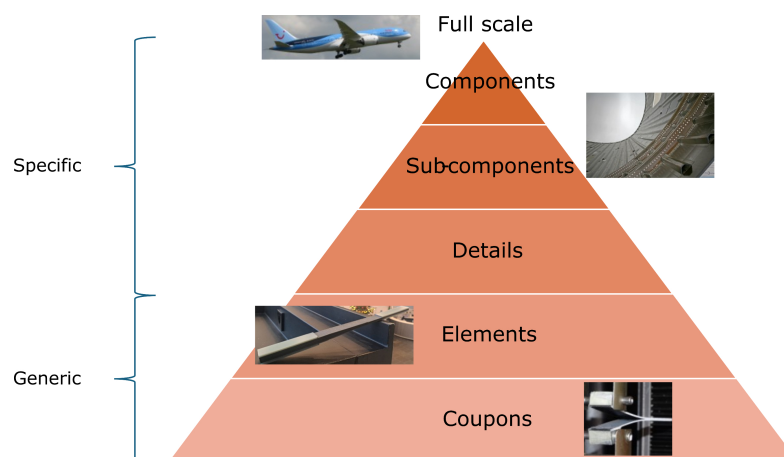


Figure 1. The test pyramid used in aircraft structure certification.

However, for composite materials this approach can form quite a testing burden, due to the complexity of the material behaviour. It is well established that in the fatigue of composites, several mechanisms play a role, including intralaminar matrix cracking, interlaminar delamination, fibre–matrix disbonding, and fibre fracture. These mechanisms are typically distributed throughout the material and can interact with each other. Which particular mechanisms occur at a specific stage of the fatigue degradation process will depend on the applied loading and the laminate lay-up.

This lay-up dependence makes it very difficult to transfer results from coupon testing on one lay-up to predict the behaviour of a different lay-up. This was, for example, shown in the blind prediction challenge conducted by the US Airforce Research Lab [7]. For this reason, CMH-17 [4] advises that fatigue testing should be performed on the same laminate as used in the final structure. This implies that if a structure contains multiple different lay-ups (as would typically be desirable for an optimal design), then the test pyramid would have to be repeated for each new lay-up used in the design. The practical consequence of this is that designers are limited to selecting from a small number of qualified lay-ups in their design, severely curtailing the design freedom that composite materials promise. More advanced techniques like steered fibre paths or variable stiffness laminates are completely out of reach, as these designs would effectively result in having tens or hundreds of different lay-ups distributed throughout the structure, which would then have to be individually characterised.

To move forward, we need to have a way of producing reliable fatigue predictions based on tests on only a small set of lay-ups. For this, we need to understand the effect of fibre orientation on the damage propagation, so that the effect of different lay-ups can be accounted for through modelling rather than empirical data. In particular, attention should be given to delamination growth, given its importance as a damage mechanism [8], and the dependence of its growth on the fibre orientations adjacent to the delaminating interface.

The effect of fibre orientation on quasi-static delamination growth has seen quite some investigation, as reviewed by Blondeau et al. [9]. However, the investigation of the effect of fibre orientation on the fatigue propagation has been more limited. Recent works include those of Banks-Sills et al. [10], Gong et al. [11] and van der Panne and Pascoe [12], but a systematic investigation of delamination growth for different interfaces and opening modes was still lacking. The aim of this work was therefore to provide such an investigation.

3. Materials and Methods

Delamination growth experiments were conducted on carbon fibre/epoxy composites with three different interface configurations, using adapted quasi-static testing standards.

3.1. Specimens

Specimens were manufactured from IM7/8552 carbon fibre/epoxy pre-preg (Hexcel) by hand lay-up, with debulking after the first ply and then every four plies. The laminates were cured in an autoclave following the manufacturer's recommended cure cycle. A 12.7 μm thick Polytetrafluoroethylene (PTFE) insert was placed at the mid-plane of the laminate to act as a crack initiator. For most specimens the stacking sequence was $[0_{11}, 0 // \theta, 0_{11}]$, where $//$ indicates the location of the delaminating interface and $\theta = 0, 45$, or 90 . In some specimens with the $0 // 90$ interface, splitting was observed after curing the ply. To mitigate this issue, for the specimens used for mode II testing, the lay-up $[90_2, 0_9, 90 // 0_{10}, 90_2]$ was used instead. Nominal specimen dimensions were $160 \times 25 \times 3 \text{ mm}^3$ for the DCB specimens and $160 \times 20 \times 3 \text{ mm}^3$ for the ELS and MMB specimens.

3.2. Experiments

3.2.1. Mode I—DCB

The DCB tests were based on ASTM D5528-13 [13]. Fatigue tests were performed under displacement control with a frequency of 2.5 Hz and a load ratio $R = 0.1$. A camera aimed at the side of the specimen was used to record the crack length. The Compliance Calibration method provided in the standard [13] was used to reduce the data and calculate the strain energy release rate (SERR). Multiple fatigue tests were performed on each specimen to create Paris curves with different pre-crack lengths.

3.2.2. Mode II—ELS

The ELS tests were based on ISO 15114 [14]. A manual mode I pre-crack of 2–5 mm was applied. After this, the specimens were loaded in displacement control at 70% of critical displacement with a frequency of 2.5 Hz and a load ratio $R = 0.1$. To populate the full Paris curves, different load levels were applied. The calibrated beam theory (CBT) approach from the standard [14] was used to estimate the equivalent crack length, flexural modulus and clamp correction factor and to calculate the strain energy release rate.

3.2.3. Mixed Mode—MMB

Mixed mode loading was applied using the load rig specified in ASTM D6671 [15]. Cyclic loading was applied under displacement control with a frequency of 2.5 Hz and $R = 0.1$. For this work only one mode mixity was used, viz. 50% mode I, 50% mode II (i.e., $G_I = G_{II}$). Data reduction and calculation of the SERR followed the methods specified in the standard, also considering the weight of the lever [15].

4. Results

This section will present the Paris curves for the different loading modes. A more detailed fractographic analysis will be presented in an upcoming journal paper.

4.1. Mode I

The Paris curves for mode I loading are shown in Figure 2. Results are shown for different pre-crack lengths. As has been seen in previous investigations [16], when the pre-crack length is increased, the Paris curve shifts to the right, indicating a higher resistance to delamination growth due to fibre bridging. As the crack grows, a large bridging zone is created, resulting in more toughening. For the 0//0 results (blue circles) a saturation effect can be seen, where curves for subsequent pre-crack lengths overlap. This indicates that the fibre bridging zone has been fully developed, and further growth of the crack does not result in increased toughening.

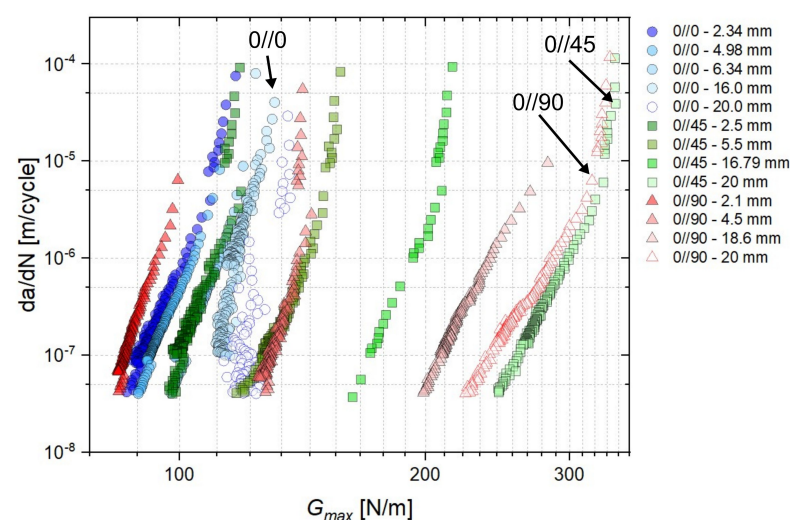


Figure 2. Paris curves for mode I loading.

For short pre-crack lengths, the Paris curves for the different interfaces overlap (especially considering the amount of scatter typically seen in fatigue tests). However, for longer pre-crack lengths, a substantial difference can be seen, with the shift to the right being much larger for the 0//45 and 0//90 interfaces compared to the 0//0. Based on

the current dataset, it can also not be confirmed whether the 0//45 and 0//90 results are already saturated, or whether a further shift would occur for even longer crack lengths.

The differences in toughening behaviour can be explained by comparing the different fibre bridging/migration behaviours, as shown in Figure 3. For the 0//0 interface, the classical fibre bridging behaviour is seen (Figure 3a) where individual fibres bridge both crack flanks. In contrast, for the 0//45 interface (Figure 3b), not only individual fibre bridges can be observed, but also concentrated bundles of fibres. For the 0//90 interface, bridging fibre bundles can also be observed, but these are now aligned with the specimen width (i.e., 90° direction) and produce a cross-wise pull-out pattern. This cross-wise pull-out has been previously reported for both fatigue [12] and quasi-static [17] loading.

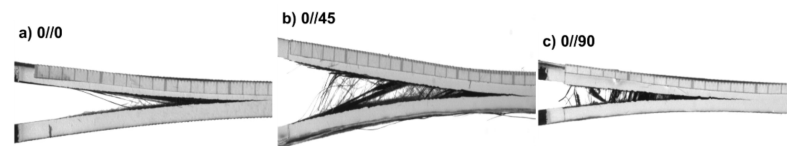


Figure 3. Specimen side-views showing differences in fibre bridging and related behaviours for the different interfaces under mode I crack opening.

It can be debated as to what extent the behaviours shown in Figure 3b,c still qualify as fibre bridging. Especially for the 0//90 case, the term oscillatory migration [17] may be more appropriate. For the current discussion, the key point is that these mechanisms all have a toughening effect that is dependent on the crack length. In summary, we can say that at short crack lengths there is a limited effect of fibre orientation, but at longer crack lengths the 0//45 and 0//90 interfaces will exhibit much slower crack growth for a given applied load, when compared to 0//0. From a design point of view, the 0//0 Paris curve could therefore be considered to be the conservative case, avoiding the need to also characterise other interfaces. However, the resulting conservatism is quite significant. In a developed bridging condition (20 mm pre-crack), for comparable da/dN values, considering only 0//0 interfaces leads to an underestimation of G values for a given crack growth rate of more than 100% in the 0//45 and 0//90 configurations.

4.2. Mixed Mode

The Paris curves for mixed mode loading are shown in Figure 4. Although the 0//90 and 0//45 curves appear to exhibit a fatigue threshold, it should be kept in mind that this is an artefact of the test set-up, caused by the crack approaching the clamp area. Therefore, for a conservative design approach, it should be assumed that the log-linear behaviour continues towards lower SERR ranges. Also, for mixed mode loading, a clear fibre orientation effect can be observed. Unlike for the mode I case, for mixed mode loading the fibre orientation effect is also present for short pre-crack lengths. The difference in delamination growth rates in this case cannot be attributed to macroscopically visible fibre bridging or migration effects. Instead the differences may be caused by micromechanical differences in the delamination growth mechanisms.

At higher SERR values, the 0//45 and 0//90 interfaces exhibit slower delamination growth than the 0//0 interface. However, because the slope of the 0//0 Paris curves are much steeper than those of the 0//45 and 0//90 interfaces, at low SERR ranges, the 0//0 interface actually exhibits slower delamination growth. This range is especially relevant given the current practice of ‘no-growth’ design, where the aim is to keep stress levels in the structure below the fatigue threshold. In this case, the 0//0 data may not be conservative.

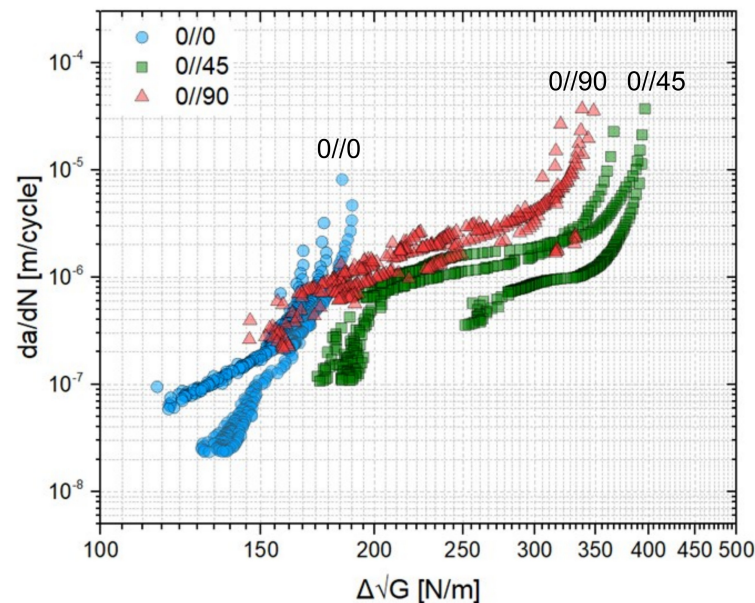


Figure 4. Paris curves for mixed mode I/II (50/50) loading.

4.3. Mode II

The Paris curves for mode II loading are shown in Figure 5. Once again we see a clear effect of fibre orientation. Here it should be noted that significant plastic deformation was seen in the 0//90 specimens after the test. This plastic deformation has two effects: (1) the plastic deformation is not accounted for in the calculation of the SERR, leading to an overestimation of the SERR; (2) the softening of the specimen due to the plasticity leads to an overestimation of the crack growth rate (which is measured indirectly via the compliance). As a result, the position of the 0//90 Paris curves is not reliable.

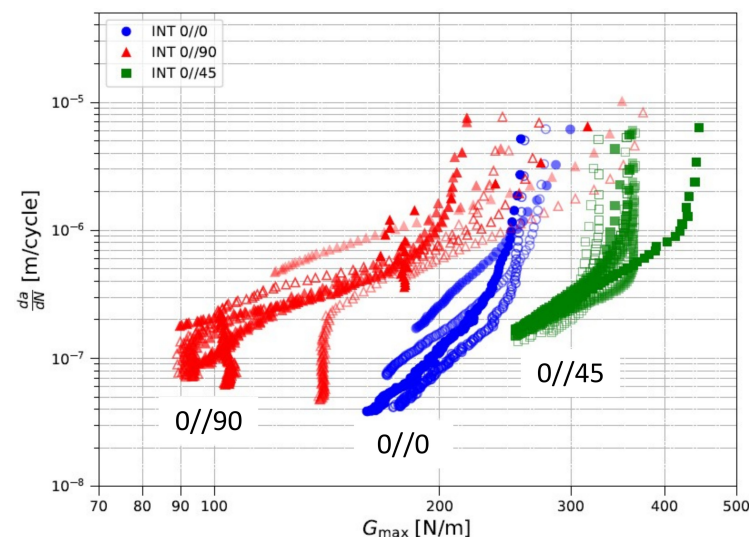


Figure 5. Mode II Paris curves. The quantitative values of the 0//90 interface data are unreliable.

From the current dataset we can therefore conclude that the 0//0 interface exhibits faster delamination growth behaviour than the 0//45 interface, but it is not clear whether 0//0 is the most conservative case. Recent work by Tu [18], using an adjusted lay-up for the 0//90 case, suggests that the difference between 0//45 and 0//90 and even 0//0 may be quite limited if delamination migration is prevented.

5. Discussion

The presented results clearly show that the fibre orientation affects the delamination growth rate for both pure and mixed-mode loading. This effect, therefore, needs to be accounted for when predicting the fatigue behaviour of a multidirectional laminate.

For mode I, the present results suggest that a 0//0 interface provides a conservative Paris curve. However, it should be noted that even for the 0//0 interface, fibre bridging was present. It is possible that an interface with a small offset (e.g., 0//5) would suppress the fibre bridging but also block delamination migration and thus exhibit faster delamination growth than a 0//0 interface. Further investigation into such interfaces is therefore warranted. Additionally, this possibility highlights the importance of correcting fatigue delamination growth characterisation data for the presence of fibre bridging.

For mixed mode at low SERR ranges (especially applicable for no-growth design), the 0//0 Paris curve may not provide the most conservative data.

It should be noted that for the asymmetric lay-ups used for the 0//45 and 0//90 interfaces, the loading mode at the interface will not be pure mode I (DCB) or II (ELS). Although a numerical analysis with the virtual crack closure technique (VCCT) indicates the amount of mode-mixity is limited, it could be worthwhile to explore more advanced analysis methods, such as suggested in Ref. [19], in future work.

Additionally, a clearly different influence of fibre orientation was observed between pure mode I, mixed-mode, and pure mode II. The manner in which the transition from mode I-dominated to mode II-dominated behaviour occurs remains unclear. For this reason, intermediate mode mixities should also be tested. Additionally, for mode II, further work is needed to design a suitable specimen lay-up for the 0//90 case.

6. Conclusions

The fibre orientation of the plies adjacent to a delaminating interface has a clear effect on the delamination growth behaviour in fatigue. This effect needs to be better understood in order to be able to predict the behaviour of arbitrary laminates, based on a limited set of test data. Changes in fibre orientation can generate new damage mechanisms, such as delamination migration/oscillation, which can significantly alter macroscale fracture behaviour. For mode I, 0//0 data is considered a conservative case with respect to 0//45 and 0//90, but this is not true for mixed-mode loading at low SERR ranges. Therefore, designers need to take care that they use fatigue data that matches the lay-up used in their design. Further work is needed to better understand the fibre orientation effect and how to include this in predictive models in the future.

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Abbreviations

The following abbreviations are used in this manuscript:

CBT	Calibrated Beam Theory
CMH	Composite Materials Handbook
DCB	Double Cantilever Beam
ELS	End Loaded Split
FRP	Fibre Reinforced Polymer
MMB	Mixed Mode Bending
PTFE	Polytetrafluoroethylene
SERR	Strain Energy Release Rate

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