INTERLAMINAR FATIGUE CRACK GROWTH IN CARBON FIBER REINFORCED COMPOSITES

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Keywords: delamination fatigue, mode I, mode II

1 Introduction
Characterizing interlaminar fatigue delamination in carbon fiber-reinforced polymer-matrix (CFRP) composites is important due to rising use of these materials in primary structures [1]. In many applications CFRP composite elements are subject to cyclic or intermittent loads which can initiate and promote delaminations even if initial defects cannot be detected with nondestructive testing [2]. For designing CFRP structures understanding fatigue delamination initiation and growth is hence crucial [2–4]. Published standards, test results and research in cyclic fatigue delamination are summarized in, e.g., [5, 6].

Recent round robin test analysis [6, 7] for developing test procedures for cyclic delamination growth combined with improved understanding of relevant effects [2, 8] have highlighted a number of issues. The question of “threshold behavior” of fatigue delamination growth in composites which is essential for fracture mechanics based design approaches [4] does seem to play a central role in several aspects. A threshold is the observation of decreasing average delamination growth rate da/dN (from delamination length a per fatigue cycle number N) at constant applied load Gmax (e.g., shown in Fig. 1). Selected examples of the analysis and interpretation of fatigue crack growth will be illustrated by experimental data and discussed. The aim of the paper is to point out open questions and alternative interpretation of data in order to stimulate further discussion and research. The focus is on fatigue delamination growth in CFRP composites under mode I and mode II loading.

2 Experimental
With the exception of a standard test method for fatigue delamination growth onset under mode I (tensile opening) load issued by the American Society for Testing and Materials (ASTM) [9], there are no standardized test methods for fatigue delamination growth in CFRP composites available yet. Both, Technical Committee 4 on Polymers, Composites and Adhesives of the European Structural Integrity Society (ESIS) and Subcommittee D30.06 on interlaminar properties of composites of ASTM have started round robin testing towards development of a mode I fatigue delamination growth standard. These are essentially based on the existing quasi-static test procedures [10–12] which are then adapted for fatigue loading. Preliminary results for mode I fatigue [6, 13] and for mode II fatigue [14] have been published.

The fatigue delamination growth test procedures for the round robin tests specify so-called Double Cantilever Beam (DCB) specimen for mode I and End-Loaded Split (ELS) or End-Notch Flexure (ENF) specimen for mode II [6, 13, 14]. Fatigue loading shall typically start from a precrack obtained from quasi-static mode I and mode II loading, respectively, followed by cyclic fatigue loading under the respective mode using displacement control and a R-ratio (ratio between minimum and maximum displacement) of 0.1. Test frequency shall be as high as possible, but not exceed 10 Hz, unless specimens are monitored for temperature rise. Delamination growth shall be monitored visually with the aid of a travelling microscope, and loading can be stopped for that. Corresponding maximum load and displacement values and one cycle of machine load and displacement values every 500 to 1'000 cycles shall also be recorded. The test shall be run until a delamination length increment da/dN of 10⁻⁶ mm per cycle is reached. For determining the so-called threshold (see Fig. 1), the test duration may be increased.

The incremental polynomial method for computing da/dN as described in appendix X1.2 of [15] can be
used for analysis of CFRP composites fatigue data, even though the standard applies to fatigue testing of metals. A parabola is fitted to \((2n+1)\) successive data points (for equation see appendix X1.2 of [15]). Recommended values for \(n\) comprise 1 to 4, resulting in 3- to 9-point fitting. 7-point fitting, for example, has been shown to yield reduced scatter in mode I fatigue data from CFRP composites [6].

Three types of CFRP composites have been used in the ESIS round robin tests, one thermoplastic poly-ether-ether-ketone (PEEK) matrix polymer and two thermoset epoxy polymers (Rigidite R5276 and Cycom 977-2). The carbon fibers were AS4 (from Hexcel) for the CFRP-PEEK, G30-600 12k for the R5276 and IM7 for the 977-2 CFRP epoxy laminates. Additional measurements were carried out on a CFRP-epoxy with a R5259 matrix resin reinforced with G30-600 12k carbon fibers. Specimens for mode I and mode II fatigue testing were about 145 mm long, 20 mm wide and 3 mm (CFRP-PEEK) and 4 mm (CFRP-epoxy) thick, respectively. The starter crack was a laminated thin polymer film at half-thickness of the beam. A 20 micrometer thick poly-tetra-fluoro-ethylene (PTFE) was used for CFRP-PEEK, G30-R5259 and G30-R5276 CFRP-epoxy, and a 10 micrometer thick poly-tetra-fluoro-ethylene-hexa-fluoro-propylene (FEP) film for IM7/977-2 CFRP-epoxy. For mode I tests, specimens had two [11] and for mode II ELS one aluminum load block [12]. ENF specimens used a specimen restraint that had shown to be necessary to prevent shifting during the tests [14].

3 Mode I Fatigue Delamination Growth

As long as the scope of the mode I fatigue crack growth test is to determine the linear part, i.e., “region II”, of the \(da/dN\) versus \(G_{\text{max}}\) curve (the so-called “Paris plot”), the procedure developed and tested in the round robins so far, seems to work well. There is some scatter between specimens tested in one laboratory as well as additional scatter in comparing results from different laboratories obtained for the same CFRP composite. The slopes of these curves, in principle, could be used for design of composite structures. However, beside the scatter noted above, the slopes of these curves frequently turn out to be rather steep, i.e., showing a large change in \(da/dN\) (sometimes more than one decade) even for a small change in applied load \((G_{\text{max}})\). One example for this is shown in Fig. 2 with mode I fatigue data from one laboratory. Fig. 3 shows mode I fatigue data from five laboratories and if a typical design rule with a safety margin of two standard deviations from the mean value is applied (private communication from Prof. A.J. Kinloch, Imperial College London), the allowable \(G_{\text{max}}\) at a rate of \(10^6\) mm/cycle in this case amounts to less than 50 J/m².

A recent, unpublished analysis of round robin data for mode I fatigue performed by ESIS TC4 has yielded indications that scatter in the slope of the crack propagation in the \(da/dN\) versus \(G_{\text{max}}\) plot may in part depend on the “experience” of the operator. The correlation coefficient \(R^2\) of fits to the visually determined data points for each specimen for different laboratories resulted in two classes if an arbitrary value of \(R^2=0.95\) was set. One class of laboratories typically had 1 or 2 specimens, the other typically 4 or 5 specimens with \(R^2<0.95\). This (inversely) correlated with the number of round robins the laboratories had previously performed, i.e., there seems to be a “learning curve” when performing such tests according to a written procedure. This obviously poses a challenge for drafting a standard fatigue test procedure.

In the same analysis, the effect of different methods for calculating \(da/dN\) was investigated as well. A comparison of m-point parabola fitting \((m=3, 5\) and 7) according to [15] yielded decreasing scatter with increasing \(m\) essentially for all data. While the parabola fitting will reduce scatter, it may also mask a possible curvature in the data at low values of \(G_{\text{max}}\) that would indicate threshold behavior. Therefore,
other types of fitting or statistical analysis may have to be explored that would indicate possible changes in slope. One approach could, therefore, be to fit part of the data (e.g., the initial 40, 60, 80%) and then to compare an extrapolation of these fits with the remaining data extending into the low $G_{\text{max}}$ regime.

4 Mode II Fatigue Delamination Growth

Since it has been shown that the resolution of the load cell used for the load measurement (under displacement control) can yield significant scatter in the resulting delamination length increase per cycle, $da/dN$, and the corresponding value of $G_{\text{max}}$, it is worthwhile to ask whether an analogous behavior is observed for tests performed under mode II fatigue loading. Fig. 4 shows the evolution of the load trace in a mode II test and the corresponding crack length, calculated from pairs of load and displacement values. Similar to mode I tests under displacement control, the scatter in load signal increases with increasing number of cycles and, at the same time, decreasing load. This scatter in load results in increasing scatter in crack lengths calculated from compliance with increasing number of cycles (see Fig. 4). In two of the authors’ laboratories, the scatter in load amounted between a few tenths of Newton to about 1 N for mode I, i.e., between about 1 to 3% (at loads of 30-50 N) and between about 1 N to 3 N for mode II, i.e., between about 1 to 2.5% (at loads of 100 to 300 N). It may seem somewhat surprising that a scatter of less than 3% in the load has a significant effect on the delamination length calculated from machine compliance (Fig. 4). This effect, however, becomes even more important in the evaluation of the delamination growth rate, $da/dN$, as shown in Fig. 5. It can be noted here that a similar and, again, significant amount of scatter is observed in the Paris plot for mode I fatigue loading. When the crack growth rate under mode II fatigue loading, $da/dN$, is determined from calculated crack lengths via 7-point fitting [15] without previously filtering the data, large scatter bands are obtained in the Paris plot (see Fig. 5). One approach to reduce this scatter is to eliminate all data points which do not correspond to a certain delamination length increase, $\Delta a$. Fig. 5 on the one hand shows the influence of the magnitude of $\Delta a$ and on the other, the influence of two different incremental polynomial methods, in this case 7- and 9-point fitting, on scatter in $da/dN$. In the case of 9-point fitting and elimination of data that does not meet a crack length increment of minimum 0.05 mm an apparent mode II threshold is received. This type of threshold, however, does not appear for the other fitting approaches, including 9-point fitting requiring larger values of $\Delta a$. Therefore, and also since there is no clear plateau visible in the evolution of crack growth rate $da/dN$, as shown in Fig. 5.
length versus number of cycles in Fig. 4, this is considered an apparent threshold, essentially an artifact from data analysis. Of course, this will have to be confirmed by analyzing additional data sets, including round robin data from other laboratories.

5 Mode I versus Mode II Fatigue Delamination Growth

It has been argued that for composite design, it is important to use “conservative”, i.e., the lowest quasi-static delamination resistance values for the material under consideration for achieving “safe” designs [16]. Early, e.g., [17] and later research, e.g., [18] indicate that quasi-static mode I loading provides conservative data compared with quasi-static loading under other modes or mode combinations. Unidirectional laminates also seem to provide conservative values over non-unidirectional or angle-ply composite laminates [5, 16, 17]. For higher rates, no significant changes are expected up to intermediate loading rates around one meter per second [19–21] and somewhat lower values than quasi-static mode II have been reported for mode II fracture toughness under impact speed loads (up to 20 m/s) [21]. So far, there is no indication that quasi-static mode I delamination tests performed on unidirectional CFRP will not provide a conservative value compared with other loading modes or composites with other fiber orientation [21]. However, for fatigue loading under mode II, fatigue crack growth data for a thermoplastic CFRP (AS4/PEEK) [22] show that mode II yields higher delamination rates da/dN for comparable applied load (expressed as either ΔG_{II} or G_{II,max}) than mode I for sufficiently low applied loads. Also, the data show a lower slope (less steep) for mode II compared with mode I. This has recently been confirmed by tests at one of the authors’ laboratories (see Fig. 6). Even though the data shown in Fig. 6 are for single specimens and repeating the test may yield significant scatter (as shown by unpublished round robin data for mode I fatigue obtained in ESIS TC4), it is unlikely that this “dominant” (higher da/dN at given G_{max}) mode II over mode I behavior can be explained by scatter only and would yield dominant mode I fatigue if larger numbers of specimens were analyzed. For CFRP composites with epoxy matrix, recent mode II fatigue crack growth data for IM7/977-2 laminates also seem to indicate a lower slope for mode II than mode I as a function of G_{max} in the da/dN versus G_{max} plot [23]. For comparable G_{max}, the mode I data for IM7/977-2 still yield higher da/dN over the range of G_{max} that was investigated. However, if the difference in slope between the two modes (I and II) extends unchanged into the regime with lower G_{max}, there may be a
cross-over point where mode II yields higher $da/dN$ values at sufficiently low values of $G_{max}$ (estimated to be around 120 J/m² for IM7/977-2, see Fig. 7). Implications of this for fracture mechanics based composite designs are obvious. Basing composite design on mode I fatigue data only may not be always possible, since a design study on high-performance composite flexbeams explicitly noted the lack of mode II fatigue data [24].

![Fig. 6](image)

**Fig. 6.** Mode I and mode II Paris plots of a thermoplastic CFRP composite (AS4/PEEK).

![Fig. 7](image)

**Fig. 7.** Average mode I (dashed blue line) and mode II (dashed black line) fatigue delamination of a CFRP epoxy composite (IM7/977-2) suggesting a possible “cross-over” from dominant mode I to mode II. Blue and black vertical lines indicate quasi-static values for mode I and mode II, respectively [25]; Figure adapted from [23]).

6 Possible Analogies to Fatigue Crack Growth in Metals

Since fracture mechanics was first developed for metals it is worthwhile to investigate whether effects observed for that class of materials also apply to CFRP composites. Recently, mode I and mode II fatigue data for metals used in aerospace applications (different aluminum alloys) were analyzed together with data for high performance CFRP based on the so-called Hartman-Schijve equation [2] (see Fig. 8). It could be shown that metal data followed a linear behavior in a double logarithmic plot of crack extension “$da$” per number of cycles $N$, i.e., $da/dN$ versus $\Delta K/\Delta K_{th}$, the difference between the applied stress intensity factor $K$ and the associated threshold. The resulting power law relationship yielded an exponent of around 2 (within a margin of about 10 percent) for all data that were analyzed. A suitably modified Hartman-Schijve equation for CFRP composites, using the energy release rate $G$ rather than the stress intensity factor $K$ yielded a similar power law, again with an exponent around 2, again within a margin of about 10%. It can be noted that the assumption of a threshold value ($K_{th}$ or $G_{th}$) is an important part of this approach. The analogy or similarity in the power law describing the fatigue crack growth for different classes of materials (metals and composites) with the Hartman-Schijve equation may, in principle, imply possible analogies in the behavior, specifically at low values of $\Delta K$ and $\Delta G$, respectively.

On the other hand, as also pointed out in [2], there remains the question whether the fatigue threshold for small or short cracks (e.g., millimeter or sub-millimeter size) in composite materials or structural elements becomes “very small”. This would constitute a composite analogy to the so-called “short crack” problem for metals (see, e.g., [26, 27]) where anomalous behavior under fatigue loading was observed for cracks extending for, e.g., 10 micrometer, compared to “longer” cracks of several millimeter length and more. Guidelines for defining and distinguishing “small” and “short” cracks in metals are shown, e.g., in Table X3.1 of [15] and experimental procedures for measuring short crack growth in metals are outlined in Appendix X3 of the same document [15]. Implementing similar short cracks of a few micrometers at a defined location in the CFRP composite fatigue test specimens is difficult. Starter
cracks for CFRP composites are usually manufactured by inserting thin, polymer films (thickness less than 13 micrometer is recommended [10–12]) extending over the full width of the specimen and 40 to 60 millimeters from the load-line along the beam at the mid-thickness of the laminates. Frequently, composite laminates, and specifically CFRP epoxy composites, already contain micro-pores or micro-cracks from manufacturing, e.g., caused by relaxation of residual stresses. These, as well as specifically manufactured micro-cracks for investigating short crack growth in CFRP composites are further quite likely subject to a complex, multi-axial stress field on the micro-scale even if the globally applied fatigue load is mode I or mode II. Fatigue loading a CFRP composite specimen without defined macroscopic starter crack (e.g., from laminated thin polymer films) may, therefore, initiate crack growth from several short cracks already present after manufacturing at different locations simultaneously. Small or short cracks in composites could, e.g., be defined as below or comparable to the fracture process zone size, i.e., up to a few millimeter at most [28], if the criterion of plastic zone size for small cracks in metals from Appendix X3 of [15] is adapted analogously for composites. Therefore, the only information on the behavior of small and short cracks in composites could currently be drawn from testing structural elements or components and comparing the observed fatigue crack growth behavior with models based on Paris type law and associated threshold or the Hartman-Schijve approach. Instances in which failure in a high-performance CFRP composite component may have been due to short cracks developing rapidly to critical size under fatigue loading are presented and discussed in [29–32].

One question that arises from this study is how to account for the differences observed in tests performed on nominally identical materials at different laboratories, see Fig. 3. To this end we examined the ability of the Hartman-Schijve equation to address this problem. The particular equation studied was (see [2] for more details),

\[
\frac{da}{dN} = D \left( \frac{\sqrt{\Delta K_{\text{max}}^2 - \sqrt{G_{\text{th}}}}}{1 - \sqrt{\Delta K_{\text{max}}^2}} \right)^\beta
\]

where in each case we used \( \beta = 2.3, A = 372 \text{ J/m}^2 \), and \( D = 2.2 \times 10^{-7} \). The values of \( \sqrt{G_{\text{th}}} \) were varied in the fitting to investigate if this could reflect differences in the \( da/dN \) versus \( G \) test data. The resulting measured and predicted curves for selected specimens from two laboratories are shown in Fig. 9.

From this study it appears that, in the data presented in Fig. 3 for tests performed at two of the authors’ laboratories, the differences in the measured \( da/dN \) versus \( G \) relationships can, as a first approximation, be represented by equation (1) by changing the values of \( G_{\text{th}} \) to those listed in Table 1 while keeping all of other parameters constant. As shown in Fig. 9 the “predicted” curves obtained from varying \( G_{\text{th}} \) with all other parameters in equation (1) kept constant do not exactly fit the experimental data over the whole range of \( da/dN \) and \( G_{\text{max}} \), respectively. However, considering the large value range of the double-logarithmic data presentation and the variation of one single parameter (\( G_{\text{th}} \), the fits yielding the predicted curves agree well with the experimental data.

This procedure raises a question as to the uniqueness of the threshold (if it exists). In any case, the values of \( G_{\text{th}} \) in Table 1 are relatively small and on the order of (apparent) threshold values deduced from the Paris plot, if appropriate safety factors (e.g., twice the standard deviation) are taken into account. All this will also have to be investigated in more detail. As such the question of the applicability of the Adjusted Compliance Ratio (ACR) [15] is also worthy of investigation.

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![Figure 8](image-url)  
**Fig. 8.** Hartman-Schijve power law for CFRP Mode II delamination in several composites, adapted from [2].
Further, performing delamination growth tests at low displacement resolutions of the load measurements in the composite materials due to the steep gradients from literature indicates that the question whether such thresholds really exist and if so, how they can be determined experimentally, are crucial and of importance. Detailed analysis of selected mode I fatigue crack propagation data from ESIS TC4 round robin tests and from literature indicates that an apparent, threshold-like behavior can be mimicked by limited resolution of the load measurements in displacement-controlled fatigue tests at da/dN values as high as $10^5$ to $10^6$ mm/cycle. Polynomial smoothing applied to the data analogous to the procedure for metals fatigue (ASTM E 647) does not seem to reduce the scatter sufficiently for eliminating this apparent threshold in all cases. Further, performing delamination growth tests at low delamination rates da/dN, e.g., $10^7$ to $10^8$ mm/cycle, will require high numbers of cycles to achieve measurable delamination growth (e.g., 5 million cycles at $10^8$ mm/cycle for 50 micrometer growth). Therefore, verification of the existence of a threshold with virtually no delamination growth will require correspondingly longer test durations.

Other data analysis using a modified Hartman-Schijve equation for presentation of fatigue crack propagation data for FRP composites under mode I and mode II loads seems to suggest formal analogies with fatigue crack propagation in metals. As shown with preliminary data analysis, the Hartman-Schijve equation using fixed parameters $\beta$ and $D$ (see equation (1) above for details) and variable threshold values for each specimen (Table 1) also yields nicely fitting predictions of fatigue crack growth. This, however, then raises the question whether fatigue thresholds are unique material properties or not and whether a variant of the Adjusted Compliance Ratio (ACR) approach should be investigated for delamination growth.

Whether the formal analogy between metals and CFRP composites in the Hartman-Schijve approach implies the existence of possibly anomalous crack propagation behavior in CFRP (or all FRP) composites similar to short crack behavior in metals or metal alloys, is not clear. At present, evidence for investigating this question quite likely will have to come from structural fatigue tests or from composite structural applications under real fatigue load spectra, since a direct experimental verification on laboratory scale specimens does seem difficult, due to, among others, e.g., cracks and other defects already present in the material after manufacturing and the difficulty of implementing suitable, well defined starter cracks for testing.

The question whether conservative fracture toughness values can be obtained from unidirectional test specimens under fatigue mode I loading only may also have to be investigated, since at low $G_{\text{max}}$ values, mode II fatigue propagation may dominate over mode I. In applications, the load is frequently mixed mode and combined with residual stresses from manufacturing, the local stress field on the microscopic scale, where cracks initiate and start to propagate, will result in a complex stress state which is difficult to reproduce in laboratory-size test specimens.

Experimentally, at present, a safe approach for fracture mechanics based FRP composite structural design would have to be based on laboratory fatigue tests on structural elements considering the load.

7 Summary and Outlook

Since fracture mechanics based CFRP composite design approaches tend to using threshold values for the composite materials due to the steep gradients typically observed for mode I and mode II fatigue propagation in region II of the Paris plots (i.e., double logarithmic presentations of da/dN versus $G_{\text{max}}$) the question whether such thresholds really exist and if so, how they can be determined experimentally, are crucial and of importance. Detailed analysis of selected mode I fatigue crack propagation data from ESIS TC4 round robin tests and from literature indicates that an apparent, threshold-like behavior can be mimicked by limited resolution of the load measurements in displacement-controlled fatigue tests at da/dN values as high as $10^5$ to $10^6$ mm/cycle. Polynomial smoothing applied to the data analogous to the procedure for metals fatigue (ASTM E 647) does not seem to reduce the scatter sufficiently for eliminating this apparent threshold in all cases. Further, performing delamination growth tests at low delamination rates da/dN, e.g., $10^7$ to $10^8$ mm/cycle, will require high numbers of cycles to achieve measurable delamination growth (e.g., 5 million cycles at $10^8$ mm/cycle for 50 micrometer growth). Therefore, verification of the existence of a threshold with virtually no delamination growth will require correspondingly longer test durations.

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Experimentally, at present, a safe approach for fracture mechanics based FRP composite structural design would have to be based on laboratory fatigue tests on structural elements considering the load.
spectra from the intended application and implementing a sufficient safety factor in the number of cycles tested, while simultaneously monitoring delamination crack propagation or damage accumulation. Use of a “no growth” approach with respect to cracks in CFRP composites design requires the existence of a threshold and/or the absence of anomalous short crack behavior. Even if a threshold can be shown to exist at some value of $G_{\text{max}}$, defining a safe value taking the inherent scatter in the experimental data into account could then result in very low values (possibly a few tens of J/m$^2$ or even lower) which effectively may exclude structural designs using that approach.

In any case, fatigue crack propagation in CFRP composites will have to be further investigated. This will require additional data from round robin tests under mode I and mode II loading from different laboratories for comparative data analysis. ESIS TC4 will start new round robin activities this year with a different type of CFRP laminate. Threshold behavior will be one of the focal points in tests and data analysis.

Acknowledgment

Mode II fatigue data obtained by Dr. G. Dell’Anno (Cranfield University, UK) and discussions with members of ESIS TC4 as well as numerous comments and suggestions by Prof. A.J. Kinloch (Imperial College London, UK) on the topics of this manuscript are gratefully acknowledged.

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