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Comparison of Quasi-static and Cyclic Fatigue Delamination Resistance of Carbon Fiber Reinforced Polymer-Matrix Laminates under Different Mode Loading

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Abstract

Delamination resistance data from different carbon-fiber reinforced polymer-matrix (CFRP) composites are compared for different loading modes, i.e., quasi-static and cyclic fatigue, opening tensile mode I, in-plane shear mode II, and fixed-ratio mixed-mode I/II. For this, data from round robin tests conducted at the authors laboratories will be complemented by selected results from literature. Questions related to delamination resistance of CFRP composites with implications for composite structural design and testing include, e.g., the determination of threshold values in cyclic fatigue, the question of conservative mode (mode I versus mode II), approaches for data analysis, and possible analogies in short crack cyclic fatigue between fracture behavior of structural metal alloys and CFRP. The scatter in Paris-type law data analysis of cyclic fatigue tests and the resulting apparent threshold behavior that has implications for composite structural design will be presented. Load measurement resolution yields the major contribution to scatter in displacement controlled fatigue tests. The analogous displacement resolution for load controlled tests is discussed and limitations in test control and of power law displacement data fitting for analysis are pointed out.

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Keywords: Delamination resistance, Fiber-reinforced composites, Cyclic fatigue test, Paris-law, Composite structures

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1. Introduction

Carbon fiber-reinforced polymer-matrix (CFRP) thermoset and thermoplastic composites are finding wide-spread use in many important industrial sectors (e.g., aerospace, high performance cars, civil engineering structures and mechanical load-bearing components) as well as in sports and leisure equipment. The typical values of interlaminar

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fracture toughness or delamination resistance, and more general, of matrix-dominated properties of CFRP, notably the shear strength, still pose limits to the use of CFRP in high performance structures and elements. An immediate consequence of this is a conservative design approach for CFRP structures and components which does not allow for defect growth, specifically delamination propagation, during service (see, e.g., Martin 2003 for details). Design approaches that take defect distributions and subsequent delamination propagation into account (Martin 2003), require experimental data from quasi-static and cyclic fatigue under the relevant loading modes. Frequently, mode I opening tensile loading is considered to provide a conservative limit for quasi-static and cyclic fatigue tests, but mode II in-plane shear cyclic fatigue can also play a role in some cases, e.g., in design of flexbeams for helicopters, (Murri 2006). However, test methodology and subsequent standardization for cyclic fatigue delamination resistance of CFRP laminates is still under development, in spite of rather long-term research activities on this topic which are summarized, e.g., by Brunner et al. (2008). Recent round robin testing and extensive data analysis by the authors and others has highlighted a number of issues in cyclic fatigue of CFRP composites relating to both, mode I tensile opening and mode II in-plane shear loading, and consequently also for mixed mode I/II loading. A brief summary of these problems together with alternative approaches for data analysis has been presented at a recent conference by Stelzer et al. (2012). Further, a detailed study of mode I cyclic fatigue of CFRP summarizing extensive round robin data obtained within ESIS TC4 has been published by Stelzer et al. (2014) and preliminary data on mode II (using the so-called ELS- and ENF-specimens) and mixed mode I/II cyclic fatigue (using the so-called FRMM test with an inverted ELS-specimen) will be published soon (Brunner 2014). However, in all these investigations, the test approach was based on displacement controlled tests.

Nomenclature

a	delamination length
CFRP	carbon fiber reinforced polymer
DCB	Double Cantilever Beam (standard specimen for quasi-static mode I tensile opening fracture tests)
ELS	End Loaded Split (standard specimen for quasi-static mode II in-plane shear fracture test)
ENF	End Notch Flexure (specimen for quasi-static mode II in-plane shear fracture test)
ESIS	European Structural Integrity Society
FRMM	Fixed-ratio mixed mode I/II test (4:3 mode I to mode II, using, e.g., inverted ELS specimen)
G_{thr}	threshold value (limit of applied load in cyclic fatigue below which no delamination propagation is observed)
G_{IC}, G_{Imax}	Critical fracture toughness or delamination resistance for quasi-static mode I test and applied load for cyclic mode I fatigue test, respectively
G_{IIC}, G_{IImax}	Critical fracture toughness or delamination resistance for quasi-static mode II test and applied load for cyclic mode II fatigue test, respectively
$G_{I/IIC}$, $G_{I/IImax}$	Critical fracture toughness or delamination resistance for quasi-static mixed mode I/II test and applied load for cyclic mixed mode I/II fatigue test, respectively
mode I, II	Basic fracture mode, opening tensile and in-plane shear, respectively
N	cycle number in cyclic fatigue test
PEEK	Poly-ether-ether-ketone (thermoplastic polymer)
R-ratio	ratio between maximum and minimum applied load in cyclic fatigue test

The present paper will, after a summary of cyclic fatigue fracture issues, discusses mode I cyclic fatigue fracture from load-controlled tests using the so-called DCB specimen for a comparison with the data obtained from displacement controlled cyclic mode I fatigue fracture. An earlier study by Brunner et al. (2009) had included selected data from cyclic mode I fatigue fracture tests performed under load-control. The main conclusion was that load control essentially yielded the same results as from displacement control under the same R-ratio. It was then argued that displacement control had the advantage of combining a standardized quasi-static mode I test (e.g., according to ISO 15024 with the DCB-specimen) with a cyclic mode I fatigue fracture test by simply taking the last displacement value from the quasi-static test as starting value for the cyclic fatigue load. This would provide a fairly large range of either delamination growth rate da/dN or cyclic fatigue load (expressed as G_{Imax}) for presenting the data in the so-called Paris-law type approach (i.e., da/dN versus G_{Imax} in double logarithmic scale), if the test was continued to a sufficiently high number of load cycles. Under displacement control, the increasing specimen compliance due to the delamination propagation would reduce the effective applied load and hence the delamination rate da/dN with increasing cycle number. Under load control, the increasing compliance would result in increasing displacement with cycle number. This would accelerate the delamination propagation rate and finally result in failure of the specimen. Depending on the choice of the initial load value this might result in a rather limited range of da/dN or G_{Imax} and hence a limited basis for the Paris-type law analysis which uses the slope of the linear portion of the data (see, e.g., Stelzer et al. 2014 for details). From a technical point of view, depending on the type of test machine, sufficiently accurate and reproducible load control may also be more difficult to implement and maintain throughout the test than displacement control. It can be noted here that there are alternative approaches for presenting cyclic fatigue data beside the Paris-law, selected examples of mixed mode I/II fatigue are discussed by Jones et al. (2014).

2. Selected Results and Discussion

2.1. Issues in cyclic fatigue fracture testing of CFRP

Fig. 1 shows quasi-static and cyclic fatigue fracture data for selected loading modes (see inserts and caption for details) for one type of CFRP thermoset composite made from IM7 fiber and 977-2 type epoxy and for one type of CFRP thermoplastic composite made from AS4 fiber embedded in a poly-ether-ether-ketone (PEEK) matrix. It can be noted that the CFRP thermoplastic composite yields higher quasi-static mode I and mode II fracture toughness and lower delamination rate at any given value of the applied load than the CFRP epoxy.

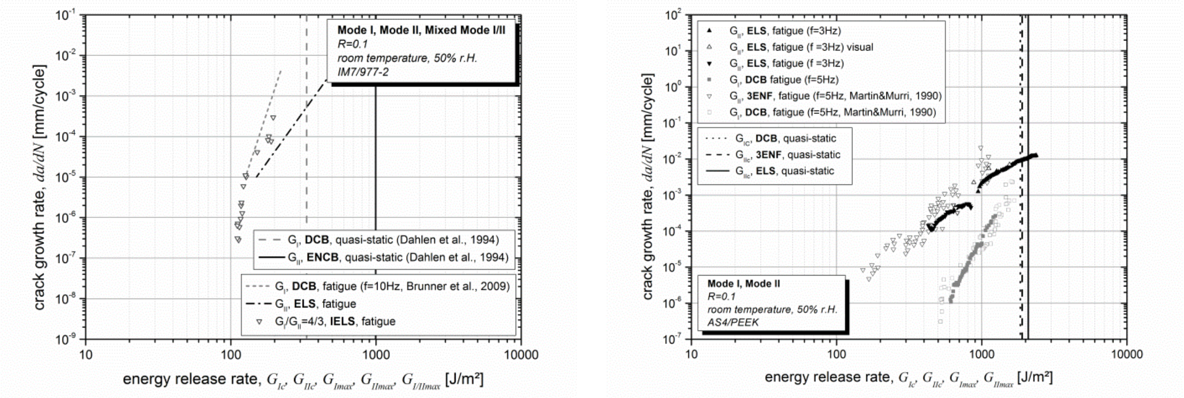

Fig. 1. Quasi-static and cyclic fatigue fracture data for (left) a carbon fiber epoxy (IM7/977-2 from recent ESIS TC4 round robins) and (right) a carbon fiber thermoplastic (AS4/PEEK, from Martin and Murri 1990), showing mode I, mode II and for the carbon fiber epoxy fixed-ratio mixed mode I/II (FRMM) values; vertical solid lines indicate the respective quasi-static values for comparison with the cyclic fatigue fracture data.

These data already point to one question that is relevant for design, even if a conservative "no growth" approach (Martin 2003) is being used. Since mode II cyclic fatigue for AS4/PEEK (Fig. 1) yields higher delamination rates da/dN for any given value of G_{max} (for mode I and mode II, respectively), it is unlikely that mode I cyclic fatigue fracture data can be considered to represent a conservative, i.e., lowest limit for CFRP composite design and it can be hypothesized that this would also be the case for the so-called threshold value (limiting applied load G_{max} for the respective mode below which no delamination propagation is observed which is the quantity used in the no growth design). For the CFRP epoxy composite shown in Fig. 1, mode II cyclic fatigue yields lower delamination rates down to G_{max} values around 100 J/m^2, but if the data are extrapolated to lower values of G_{max}, there might be a cross-over from mode I (DCB specimen) to mode II (both for ELS and ENF specimens) as cyclic load case yielding the higher delamination rate. It can be noted that for quasi-static tests, mode I yields a lower value than mode II for both

CFRP composites shown here. The reason for this behavior, i.e., (possibly) different conservative mode depending on quasi-static and cyclic fatigue loads, respectively is not clear at present and hence deserves further investigation. Additional round robin testing is currently under preparation for obtaining more data.

As discussed in detail by Stelzer et al. (2012), the question of how the delamination behaves at low values of applied load, i.e., the assumed existence of a so-called threshold applied load value, G_{thr}, below which no delamination propagation is observed, will also have to be investigated in more detail. The analysis presented by Stelzer et al. (2014) for the case of cyclic fatigue fracture under mode I loading with displacement control indicates that observed threshold behavior may partly or fully be caused by limited resolution of the load measurement and scatter in the data introduced by calculating delamination rate and applied load from the compliance of the DCB specimen. An issue which recently came up is the cyclic fatigue fracture behavior of CFRP composites with "short" cracks. As discussed by Stelzer et al. (2014) there may be an analogy between delamination propagation in metals (for which the short crack phenomenon is well known) and in CFRP composites, for which the respective range of delamination lengths (typically tens to hundreds of micrometers in metals and metal alloys) has not yet been explored. However, because of inhomogeneous morphology and the resulting complex stress state in CFRP composites it is not clear whether the same length scale will be relevant. Again, this deserves further investigation.

2.2. Load control versus displacement control for mode I cyclic fatigue test

The comparison between load and displacement control of cyclic mode I fracture tests will be discussed for a specific type of carbon fiber epoxy composite (G30-500 fiber and epoxy Rigidite 5276) used in recent round robin testing (Stelzer et al. 2014). The tests were carried out on a servo-hydraulic test machine (MTS 858) with a 15 kN load cell calibrated to a load range from 0 to 400 N in a laboratory environment of 23°C and 50% relative humidity. The crack length was measured via visual observation of the crack through a traveling microscope (magnification 40x). Fig.2 shows the crack length and load as a function of cycle number for a test under displacement control with a stress-ratio R of 0.1. The measured load and crack length increment per cycle are decreasing because of the increasing compliance of the specimen. Both figures show data from visual observation (black squares) and crack length data (open red squares) computed via a compliance calibration approach (see Stelzer et al. 2014 for details) from load and displacement records of the test machine (taken every 500 cycles). The scatter in load measurement which has been noted above as yielding an apparent threshold behavior can clearly be seen. A comparison between the figures shows that this scatter is carried over in the calculated crack length yielding significant scatter in computed delamination rate da/dN. The same holds for applied G_{Imax} which is related to load and directly includes scatter. This finally results in significant scatter in both axes of the Paris-law type plot of the data and requires the application of data smoothing or fitting as well as statistical analysis with sufficient safety factors for evaluating data for design.

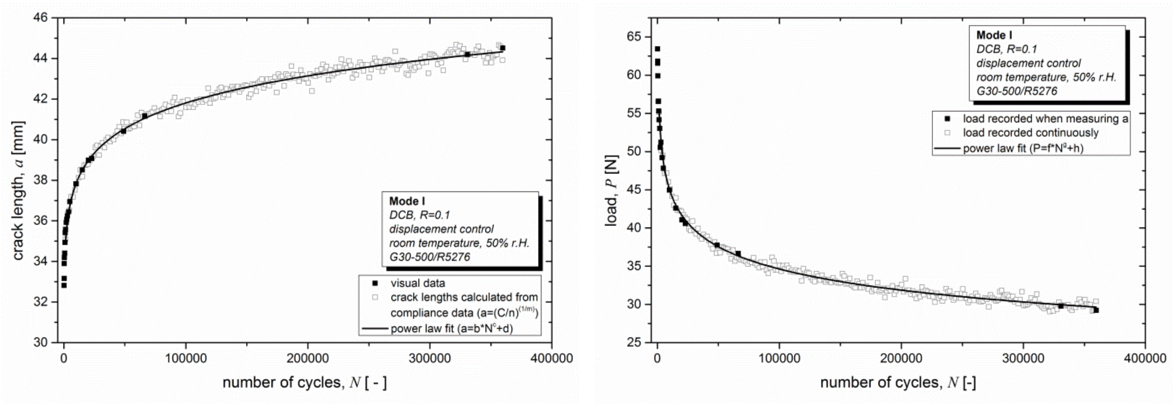

Fig. 2. Carbon fiber thermoset polymer-matrix composite (G30-500 fiber, epoxy Rigidite 5276 matrix) crack length (left) and load (right) versus cycles from displacement controlled cyclic mode I fatigue fracture test.

Fig. 3 shows the corresponding plots of crack length and displacement as a function of cycle number for a load-controlled cyclic mode I fracture fatigue test performed on the same type of test machine and using the same specimen type (G30-500/Rigidite 5276 epoxy CFRP). Now, under load control, the crack propagation is increasing with increasing number of cycles leading to failure of the specimen in the end. The displacement is also increasing at the same time. Fig. 3 also shows that the scatter in load amounts to about ±1 N at typical values around 50 N, i.e., a scatter of about 2-3% up to about 40’000 cycles. Beyond that, the scatter is clearly increasing towards the end of the plot, where the displacement is strongly increasing. This indicates that accurate load control may prove more and more difficult with increasing displacement. Of course, the amount of scatter in the “high cycle” regime will depend to some extent on the type of test machine and its control settings, but nevertheless, the effect will become noticeable in the subsequent analysis (Fig. 4). On the other hand, there are also cases where the delamination propagation did not start within reasonable time due to selection of a value of load which turned out to be too low (see, e.g., Brunner et al. 2009). Such cases are time consuming for testing and analysis. Further, the analysis can then only be performed for data obtained for the same level of load, but not for different, increasing levels applied consecutively, until the initial and average delamination rate allows recording a sufficient number of fatigue cycles.

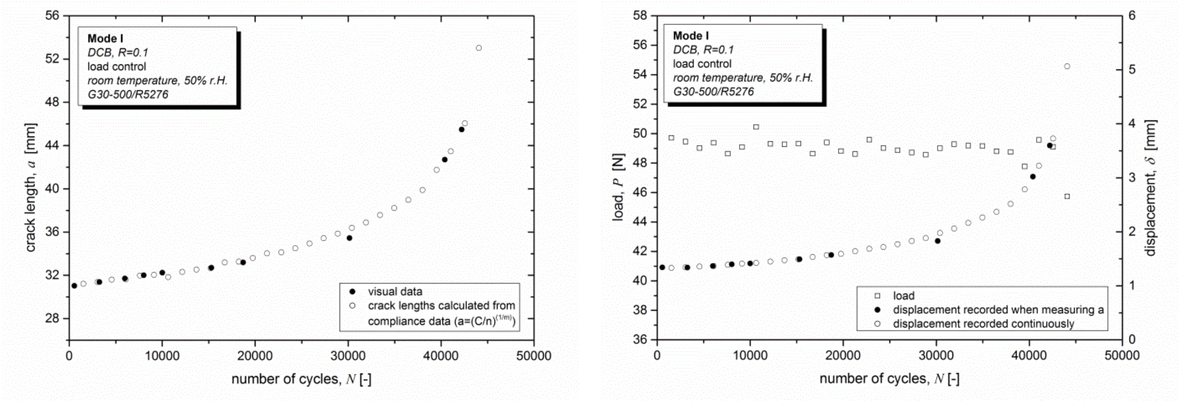

Fig. 3. Carbon fiber polymer-matrix composite (G30-500 fiber, epoxy Rigidite 5276 matrix) crack length (left) and load and displacement (right) from load controlled mode I cyclic fatigue fracture test.

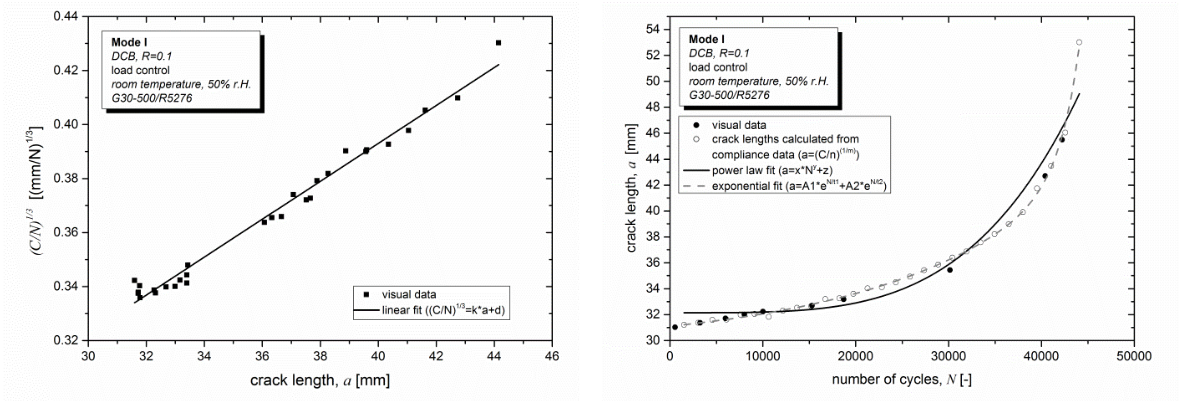

Fig. 4. Corrected Beam Theory (CBT) data analysis and linear fitting (left) and comparison of power law and exponential fitting of displacement (right) for the epoxy CFRP (G30-500 fiber, epoxy Rigidite 5276 matrix) tested under mode I cyclic fatigue fracture using load control.

As shown in Fig. 4, further data analysis proves difficult, since simple, second order power law fitting of the measured displacement (analogous to the power law fitting successfully used for displacement controlled tests as discussed by Stelzer et al. 2014) did not yield satisfactory fits. In the example shown, the deviation of the fitted power law curve from the experimental data set will not yield reasonably reliable Paris law type of data for an assessment of the cyclic mode I fatigue fracture behavior of the epoxy CFRP tested under load control. A better fit to the experimental displacement data points, but still affected by scatter has been obtained by using exponential functions, specifically the sum of two exponential functions with four fitting parameters (Fig. 4). This is rather unsatisfactory, since a range of other fitting functions would possibly yield similar agreement. The interpretation of a sum of exponentials is difficult and gives rise to further questions. Does this imply that there are two regimes with different exponentials, e.g., one dominating the low and the other the larger displacement? Can this be interpreted as indicating two different mechanisms that are active in load controlled cyclic fatigue? If so, why is this not obvious for data from displacement controlled tests? However, it has to be noted that these results are preliminary based on a few specimens tested so far, that the interpretation and the questions are tentative and that further round robin testing and data analysis will be required to resolve this.

3. Summary

After a brief review of issues in cyclic fatigue fracture testing of CFRP composites under mode I, mode II and fixed-ratio mixed mode I/II loading, and a comparative analysis of preliminary tests of mode I cyclic fatigue fracture run under displacement and load control is presented. Experimental realization of sufficiently accurate load control does seem to be more difficult than displacement control to start with and data analysis has been shown to be more difficult. For selected, preliminary results from displacement controlled tests, simple second order power law fitting of the load signal does look promising for data reduction, specifically for reduction of scatter in the Paris-law type of graph. Load control, so far, does not yield satisfactory power law fits and if more complex fitting functions with more parameters are used, the fit quality may be improved, but the interpretation of this raises additional questions. Therefore, additional round robin testing and data analysis will have to be performed for resolving this.

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