Development of a standardized procedure for the characterization of interlaminar delamination propagation in advanced composites under fatigue mode I loading conditions

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A R T I C L E   I N F O

Article history:
Received 7 October 2008
Received in revised form 25 June 2009
Accepted 13 July 2009
Available online xxxx

Keywords:
Fracture toughness
Fatigue loading
Delamination crack propagation
Standardized test procedure

A B S T R A C T

A round robin exercise on opening mode I fatigue delamination propagation has been performed with the aim of developing a standardized test procedure. The material chosen for the test was one type of carbon–fiber reinforced polymer–matrix laminate (IM7 fiber, 977-2 epoxy). The Double Cantilever Beam specimen from the quasi-static mode I delamination resistance test (ISO 15024) has been used for the fatigue test. Test set-up, measurements and data acquisition have been defined with an emphasis on applicability in an industrial test environment. Selected test parameters have been varied in order to investigate their effect on the results. Three different approaches for delamination length determination have been compared. Visual determination of delamination length, a compliance-based approach and an effective delamination length calculation based on a separate measurement of the modulus of elasticity yield reasonable agreement. This agreement suggests that further development of the test procedure to incorporate automated data acquisition and analysis may be worthwhile.

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1. Introduction

The application of advanced fiber-reinforced, polymer–matrix (FRP) composite materials in primary aerospace structures offers many potential advantages. They include, among others, reduction in structural weight, improved corrosion resistance and significant economic savings in system life cycle cost. A major concern in the utilization of FRP composites is the occurrence of delaminations and their growth. Delaminations may initiate from manufacturing defects or are induced in service by low velocity impact. Delamination growth can cause pronounced reductions in stiffness and strength and can result in a massive reduction of the fatigue life.

Recognizing the important role of fatigue related damage accumulation in advanced FRP composites, a number of research groups have been working in this field. The aim was to obtain a better understanding of the phenomena involved in the fatigue failure process and to develop appropriate models to predict life times of cyclically loaded specimens or components [1]. In order to characterize the behavior of FRP laminates under cyclic loads conventional S–N tests (a stress based approach) are used. The generation of S–N-curves is very time-consuming and requires many test specimens. However, this solely allows the inference of failure criteria for cyclically loaded components and thus the definition of allowable stresses as a function of load cycles. However, the number of cycles to failure gives no information about possible structural changes in
the material. Moreover, generally it does not allow for differentiating between the period of delamination initiation and propagation.

An appropriate way to characterize the delamination resistance of advanced FRP composite materials is using fracture mechanics test methods. Davies et al. [2], Tay [3], and Brunner et al. [4] present broad reviews of the status of the development of test methods for fracture mechanics properties of FRP composites. Nowadays, fracture tests under quasi-static and fatigue loads are using different loading modes (mode I = opening, mode II = shear, mode III = twisting, various mixed modes) to assess the delamination resistance. The information from the tests can be applied in material development and structural design. Although intensive efforts have been undertaken in recent decades to generate standardized test methods, only a few standards for unidirectionally reinforced materials were introduced. For mode I (tensile opening) loads, these are determination of delamination resistance under quasi-static loads [5–7] and determination of mode I fatigue delamination onset [8].

Fatigue delamination propagation, however, is not considered in the latter procedure.

Fatigue tests based on linear elastic fracture mechanics (LEFM) concepts consider material behavior at delamination propagation rates below critical values. As for metals [9], in general, three different stages may be identified, provided that all test parameters such as frequency, minimum-to-maximum load ratio (R-ratio), temperature and environment are kept constant. The region of very slow delamination propagation rates (i.e., threshold) is followed by stable crack propagation finally resulting in catastrophic failure within a single load cycle. With regard to FRP composites, especially Hojo and coworkers [10–14], but also others [15–20] have performed extensive and significant fundamental research. Fatigue tests under mode I, mode II and mixed mode conditions on different FRP materials are reported. The focus was on optimizing the test methodology [12,13,15,16], looking at effects like R-ratio [10,13] or delamination length [11,13], and identifying relevant threshold values [10,12]. So far, however, no standardized procedure was proposed for the characterization of fatigue delamination propagation.

Within the Technical Committee on Fracture of Polymers, Composites and Adhesives of the European Structural Integrity Society (ESIS) activities with regard to fatigue delamination propagation were started a few years ago. This lead to a first round robin (RR) test with three participating laboratories. The principal goal was to develop a standard test procedure for delamination propagation in unidirectional FRP laminates under fatigue mode I loading conditions (tensile – opening mode). The primary intention was to measure delamination propagation rates. The identification of the threshold region should be possible but was not the main goal. A test protocol was drafted allowing tests at different frequencies and R-ratios with a strong emphasis on the applicability of the procedure in an industrial test environment (short test duration, automated data acquisition and analysis). In the following, the results and major conclusions of this first ESIS RR on mode I fatigue delamination propagation are presented and discussed.

2. Experimental

Preliminary tests were performed on two types of carbon–fiber reinforced (CFRP) composites, one with thermoplastic (poly-ether–ether–ketone, PEEK) and one with thermoset (epoxy) matrix. In the first RR, CFRP-epoxy (IM7/977-2) was preferred over the CFRP PEEK because more stable delamination propagation was observed in the preliminary tests. Glass–fiber reinforced polymer–matrix (GFRP) composites were not considered in this first RR.

Double Cantilever Beam (DCB) specimens were manufactured following the specifications for the quasi-static test [7]. Specimens were about 4 mm thick (slightly more than the 3 mm recommended in [7]), 20 mm wide and about 140 mm long (minimum length according to [7] is 125 mm) and contained a non-sticking polymer–film insert (12 μm thick and about 50 mm long) at the mid-plane. Aluminium load-blocks (10 mm thick, 15 mm long and 20 mm wide) were mounted for load introduction.

The test procedure for the ESIS RR asked for pre-cracking under quasi-static conditions [7], and then first testing each specimen under displacement control, followed by load control. The R-ratio was fixed at 0.1 for all participants. The test frequency should be chosen as high as possible, preferably 10 Hz or 5 Hz. The choice of the start value of $G_{I \text{max}}$ for the fatigue loading was recommended to be somewhat less (e.g., about 10%) than the quasi-static value determined from pre-cracking. Effectively, it proved more practical to start with the last displacement or load value from the quasi-static test for the fatigue test under displacement or load control, respectively. Delamination propagation was observed visually with the help of a travelling microscope. If necessary for visual observation, the fatigue cycling could be interrupted but the specimens should not be removed from the test-fixture. In parallel, load and displacement values from selected load cycles were recorded from which the change in compliance could be determined for the duration of the test.

Tests reported in this paper were performed at three different laboratories (labelled A, B, C) using three different test machines.

The tests at laboratory A were performed on a servo-hydraulic test machine (type MTS 858) with a 15 kN load cell calibrated in the load range between 0 and 400 N (see Fig. 1a). The tests were conducted at two different frequencies (5 and 10 Hz) under load and displacement control. For observation of delamination propagation, a travelling microscope (magnification $40 \times$) was used. The tests were performed in a climate controlled laboratory ($+23 \, ^\circ \text{C}, 50\%$ relative humidity). The specimens had been stored under these conditions before testing for at least 24 h.

The tests at laboratory B were performed on a servo-hydraulic test machine (type Instron 1273) with a 1 kN load cell (calibrated in the load range between 0 and 200 N). Preliminary tests indicated that the maximum frequency for attaining the
required initial displacements under displacement control was about 8 Hz. Hence a frequency of 5 Hz was chosen for all tests (displacement and load control). Delamination lengths were monitored at selected intervals using a travelling microscope. The tests were performed in a climate controlled laboratory (+23 °C, 50% relative humidity). The specimens had been stored under these conditions before testing for several weeks.

The tests at laboratory C were carried out on a custom-built pneumatic testing rig (Fig. 1b). A 25 mm diameter pneumatic cylinder was employed in this case, and the rig was connected via a pressure regulator to the 7 bar laboratory compressed air supply. The modular nature of the rig ensured that the pneumatic cylinder could easily be replaced to obtain an appropriate dynamic response for a wide range of materials and specimen geometries. This simple, inexpensive solution should allow small laboratories to greatly improve their fatigue testing capabilities, running parallel tests on numerous rigs if required. When operating under displacement control conditions, accurate control of the displacement amplitude was achieved using an adjustable nylon sleeve to mechanically limit the stroke of the pneumatic cylinder. Under load control, the (manual or preferably computer-controlled) pressure regulator is used to control the force applied to the specimen. A 200 N load cell was employed for the tests in this study. A Linear Variable Differential Transformer (LVDT) displacement measurement device accurately monitored the cyclic displacement amplitude during the test, which was controlled using National Instruments Labview® software. A convenient graphical user interface was created which allowed the frequency and duration of the test to be specified, automatically pausing to allow the delamination length to be measured with a travelling microscope. In this way, tests could be run overnight without fear of losing crack length data. The nature of this test-rig dictated that specimen pre-cracking was carried out on a separate tensile testing machine. The actuator displacement prevailing at the end of the pre-cracking stage was then used to set-up the fatigue rig for the displacement controlled test.

Test duration varied among the different laboratories. In an attempt at determining threshold values, selected specimens were tested under displacement control for between 10 and 19 million cycles, mainly at laboratory B. Laboratory A focussed on short term tests with a duration of typically less than 24 h. Laboratory C provided additional tests for estimating the reproducibility of the data using a custom-built test-rig instead of commercial test machines.

Fig. 1. Overview of test set-ups: (a) laboratory A using a servo-hydraulic test machine and the fixture mounted inside an enclosure, a similar set-up on a servo-hydraulic test machine without enclosure has been used in laboratory B (not shown), and (b) custom-built test-rig used at laboratory C.
The variation of test parameters used by the three laboratories in the RR allows their influence on the results to be investigated. However, this holds for the specific material (IM7/977-2) and additional or other effects may be observed in specimens made from other materials (see literature cited in the introduction for examples).

Variations in the following test parameters were investigated:

1. the test control mode (displacement or load) including some variation of the initial value of the control parameter (displacement or load) which amounted to between 90% and 100% of the last value from the quasi-static test for pre-cracking;
2. the initial delamination length (10, 60 and 80 mm);
3. the test frequency (5 or 10 Hz, with a few tests under load control at lower frequencies);
4. the test duration for each test control mode (from about 8 h up to several weeks).

The $R$-ratio ($R = 0.1$) and the specimen geometry were kept constant in all tests. In the data analysis, visual determination of delamination length was compared with delamination length calculated from machine compliance (using a few visual observations from the early and late phase of the test for calibration) and with a back-calculated “effective” delamination length. This was derived from an independent measurement of the elastic modulus combined with machine compliance data (see [21] for details of the calculations). Also, plots of raw data (from visual observation of delamination length) were compared with plots where averaging procedures had been applied to the data. These either required a minimum delamination length increment of 1 mm or applied a multi-point polynomial fit as described in [22].

The draft test procedure prescribed using an initial $G_{I_{\text{max}}}$ “just below” the value of $G_{IC}$ from quasi-static testing. For load and displacement control this corresponds to a specific selection of the maximum load and displacement, respectively. There was, however, no guidance on what “just below” meant. Trials with varying initial values (between 90% and 100% of the last value from the quasi-static test) during the first few tests indicated that, for displacement control, a practical approach was to use the last displacement value from the quasi-static test to pre-crack the DCB-specimens from the starter film. This procedure was then used in all of the remaining tests. For load control which was performed after testing under displacement control, the last load value from fatigue cycling under displacement control was tried. It sometimes proved difficult to promote delamination propagation under load control, probably due to an arrest phenomenon (see below). In those cases higher load values would be required.

3. Results

Fig. 2 compares data that have been obtained on one hand under displacement and on the other under load control. The data have been analysed by the averaging polynomial method (using seven point averaging) as described in [22]. The data obtained at laboratory A agree for both modes of test control. However, data obtained under load control at laboratory B show little change in $d_a/dN$ as a function of the applied $G_{I_{\text{max}}}$. For specimens B3 and B5, the range observed for $d_a/dN$ is roughly one decade compared with two to three decades for the other specimens. On the other hand, data from laboratory B from displacement control mode (not shown here), agree with those from the other laboratories. It appears, therefore, that depending on the level of $G_{I_{\text{max}}}$ chosen for load control, the delamination will propagate or, at least partly, exhibit this arrest effect in the Paris-plot. It should be noted that visual observation in laboratories A and B yielded delamination length increments with increasing test duration.

![Fig. 2. Displacement versus load control, data have been analysed with the seven-point averaging procedure according to [22]. The test results shown for specimens B3 and B5 under load control show indications of delamination arrest, since the $d_a/dN$-range limited to about one decade for full range of $G_{I_{\text{max}}}$, note that this is not the case for specimen A5.](image-url)
Fig. 3 compares data obtained on specimens tested under displacement control at different laboratories (A, B and C). Each laboratory used a different initial delamination length, i.e., A one of 10 mm, B one of 65 mm and C one of 80 mm. The data have again been analysed by the averaging polynomial method (using seven point averaging) as described in [22]. The data do agree within the typical in-laboratory variation (compare specimens A1, A2 and A5 in Fig. 2) independent of the initial delamination length. The material tested in the RR (IM7/977-2) hence does not demonstrate a significant dependence on initial delamination length, contrary to data for other FRP composites reported in the literature [12]. This observation will be discussed below in more detail.

Data obtained from laboratory A with a frequency of 5 and 10 Hz, respectively (two specimens each under displacement control and with the same initial delamination length of 10 mm) is shown in Fig. 4. Again, the averaging polynomial method [22] has been applied. There is comparable scatter between the specimens tested at either frequency and the data for tests at different frequencies agree fairly well. Checking the surface temperature of the specimens tested at 10 Hz with a thermography camera did not yield any indication of a significant temperature rise (the observed increase was at most +5 °C).

Fig. 5 shows the behavior of both the visually observed delamination length and of the measured compliance with increasing number of cycles from three long-duration tests. Shown are raw data without averaging. The aim was to determine threshold values under displacement control. Neither delamination length nor compliance reach an asymptotic value with virtually “zero” slope that would be indicative of a threshold value, even after as many as 19 million cycles. Also, the da/dN values determined after these large numbers of cycles are still above $5 \times 10^{-8}$ mm/cycle.

In recent years, there have been attempts at improving the determination of delamination length. The visual observation of the tip of the delamination on the edge of the specimen was considered to be operator-dependent, even if a travelling microscope was used. One approach that eliminates visual observation is that based on an independent measurement of the E-modulus of the DCB-specimen and back-calculating the delamination length from the measured compliance [21]. Machine data recorded during the test at specific intervals (e.g., every 5000 or 10,000 cycles) allow for the changing specimen compliance to be determined and the corresponding delamination length to be back-calculated. It should be noted that an E-modulus of 140 GPa which is similar to an average determined on another batch of the same material was used for the analysis. Three-point bending tests on beams from DCB-specimens after failure with a span of 120 mm had yielded about 145 GPa (courtesy of Mr. C.J. Murphy and Dr. B.R.K. Blackman, Imperial College). A comparison of Paris-plots obtained from visual observation of the delamination length approach yields a less conservative value than visual observation.

Fig. 6 shows a comparison of data analysis for one specimen tested under displacement control at laboratory B. The raw data from visual observation of the delamination length with the aid of a travelling microscope with a reticle of lines allowing a resolution of about 100 μm show considerable scatter. This scatter in the data is significantly reduced if a minimum delamination length increment of 1 mm between successive points is specified. A comparable result is obtained from the polynomial fitting procedure described in [22] using a seven-point sliding average.

The data from individual laboratories (e.g., Figs. 2–4, with averaging [22] applied) and the summary of all tests (Fig. 8, raw data without averaging) indicate a similar in- and inter-laboratory variation. From the band of data points the average da/dN amounts to about $10^{-3}$ mm/cycle for a $G_{\text{lim}}$ max of 200 J/m² and to about $10^{-6}$ mm/cycles for a $G_{\text{lim}}$ max of 100 J/m². The accuracy of these values is on the order of half a decade (logarithmic scale!), i.e., the average is between about $7 \times 10^{-3}$ and $3 \times 10^{-4}$ mm/cycle for the former, and between about $3 \times 10^{-6}$ and $3 \times 10^{-7}$ mm/cycle for the latter.
Fig. 4. Effect of test frequency under displacement control. Note that no indication of significant heating was found when testing at 10 Hz; data were analysed using the seven-point averaging procedure described in [22].

Fig. 5. Plots of: (a) visually observed delamination length and (b) measured compliance versus number of cycles for three specimens tested under displacement control at laboratory B, even after 15–20 million cycles an asymptotic value (with essentially “zero” slope) that would indicate a threshold value is not reached.
Fig. 6. Comparison of delamination length measurements: visual (open symbols) versus effective delamination length back-calculated from an $E$-modulus of 140 GPa and measured compliance; the seven-point average procedure \[22\] has been used in the analysis. (a) Specimen B3 shows some disagreement and (b) specimen B5 indicates agreement between the two methods.

Fig. 7. Effect of data analysis (smoothing by requiring a minimum delamination length increment of 1 mm or applying an averaging procedure \[22\]) compared with raw data from visual observation of delamination length.
already exists a standardized test method for determining the onset of fatigue delaminations in FRP composites [8]. For estimating the behavior of existing delaminations or for comparing different laminates with respect to delamination propagation under fatigue loads and for design purposes, this is not sufficient. For these two aims, the test method under development will yield rough results within a reasonable time (minimum test duration between 8 and 10 h per specimen). Of course, a longer test duration will yield better estimates. It is recommended to run each specimen for 24 h while periodically recording machine data (for the determination of delamination length via compliance change) supplemented by occasional visual checks of the delamination length. Determination of threshold values, e.g., for design, however, is more time-consuming. The data in Fig. 5, do indicate that for the material tested (IM7/977-2) a clear indication of a threshold is not observed, even if testing for close to 20 million cycles. For design, an arbitrary definition of a threshold value, e.g., based on an expected number of cycles during the life-time of the structure would have to be used. The choice of the number of cycles could include a sufficient safety factor. If 10 million cycles are chosen as a nominal threshold value, for example, this will require about 280 h for testing at 10 Hz and correspondingly longer for lower frequencies.

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A standard test procedure should also state information defining the limits of applicability. Typically, fracture mechanics test methods for FRP composites are applicable to different fiber types (carbon or glass, eventually hybrid) and different types of matrix materials (thermoplastic and thermoset) covering a sufficient range of toughness. Standard fracture mechanics test procedures are limited to unidirectional lay-up. Applying the procedures to other lay-ups (e.g., cross-ply or multidirectional) may not be feasible in all cases. The RR has been performed with only one type of FRP, but exploratory test results for other FRP materials from individual participating laboratories are available. Even though it may be more difficult to obtain results of comparable consistency for brittle matrix systems (such as e.g., PEEK), there are no indications that the procedure would not be applicable to FRP laminates with other fiber or matrix types. The recommended test parameter choices are summarized in the conclusion.

A trial and error procedure to find suitable start values of load and displacement, respectively, that will yield sufficiently fast delamination propagation turned out to be time-consuming. Hence, for displacement control, starting with the last value from the quasi-static test is recommended. This value may yield fairly rapid delamination propagation in the initial cycles, but in any case the delamination speed will decrease with increasing delamination length. The recommended minimum length of 125 mm for DCB-specimens for quasi-static tests may be too short depending on the da/dN-range that shall be achieved. It may thus be advisable to prepare specimens with sufficient total length (150–200 mm). Load control was only used after fatigue under displacement control. Choosing the last load value from that test, in principle, proved feasible. However, this choice did not prevent occasional problems with delamination stops. As noted above, specimens B3 and B5 in Fig. 2 yield a limited range of da/dN-values for the full range of applied G1 max. This is interpreted as evidence of delamination arrest phenomena that dominate the delamination behavior in these specimens. Problems are also expected when taking the last load value from quasi-static testing for tests under load control starting from the pre-crack. If this value is too high, the test may not yield a sufficient number of data points for determining the slope of the Paris-plot before failure of the specimen. If load control is used for fatigue cycling from the pre-crack, it is recommended to start with a value lower than the last load from the quasi-static test (e.g., by 10%). Depending on the choice of load value and on the material, this value may have to be adjusted by trial and error to get sufficient delamination propagation. If the chosen value is too low, test duration before the fatigue delamination propagation speed (da/dN) reaches a reasonable level may be too long for practical purposes. In view of the problems with arrest of delamination propagation occasionally observed under load control, and considering the diffic-

4. Discussion

It is important to briefly discuss the scope of the fatigue test method that shall be developed for FRP laminates. There already exists a standardized test method for determining the onset of fatigue delaminations in FRP composites [8]. For estimating the behavior of existing delaminations or for comparing different laminates with respect to delamination propagation under fatigue loads and for design purposes, this is not sufficient. For these two aims, the test method under development will yield rough results within a reasonable time (minimum test duration between 8 and 10 h per specimen).

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Please cite this article in press as: Brunner AJ et al. Development of a standardized procedure for the characterization of interlaminar delamination propagation in advanced composites under fatigue mode I loading conditions. Engng Fract Mech (2009), doi:10.1016/j.engfracmech.2009.07.014

Fig. 8. Inter-laboratory comparison for displacement control (all data from three laboratories), the plot shows the raw data (no averaging applied).
culty of choosing an initial load value under these conditions, it is recommended that the test should be performed under
displacement control only. In this case the last displacement value from the quasi-static pre-cracking is a suitable choice
for the initial value under cyclic conditions.

The specific FRP composite (IM7/977-2) used in the ESIS RR did not demonstrate any dependence on the initial delami-
nation length. When observed, the effects were usually attributed to fiber-bridging which yielded an apparently higher
toughness with increasing delamination length [11,13]. In quasi-static mode I tests, the CFRP material (IM7/977-2) had
shown little effects from fiber-bridging [21]. Assuming this to be the case under fatigue mode I loading as well would explain
the observed result. On the other hand, the effective initial delamination lengths of 10 and 65 mm (laboratories A and B)
were probably much closer than the values suggest. Specimens in both labs were pre-cracked from the insert starter film
and the delamination propagation stopped after a few mm. The 10 mm initial delamination length was obtained by cutting
the specimen at the end containing the starter film or by equivalently mounting the load-blocks closer to the tip of the
delamination. The delamination length increment beyond the tip of the starter film, and hence the amount of fiber-bridging,
from which fatigue cycling started, may hence have been similar. Therefore, it is advisable to prescribe an initial delamina-
tion length or length range for all composite materials. In view of shortening the test duration, i.e., applying as high a fre-
quency as possible, a short initial delamination length is preferred. For purposes other than comparative testing, the
procedure described by [12], effectively extrapolating to “zero” initial delamination length shall be used for the analysis.
It has to be noted that delamination length values below 45 mm beyond the end of the load-block are not in agreement with
the recommendation for quasi-static testing [7]. The load-block correction described in [7] shall, therefore, be applied to data
from fatigue testing.

Under displacement control, the achievable maximum test frequency depends on the stiffness of the DCB-specimen and
on the length of the initial delamination. For certain types of composites, it does seem advisable to manufacture specimens
that are thicker than the 3 and 5 mm for CFRP and GFRP, respectively, recommended for quasi-static testing in [7]. However,
there are not sufficient data to recommend suitable specimen thicknesses. Preliminary tests on CFRP specimens have indi-
cated that doubling the thickness (i.e., up to 6–7 mm instead of 3 mm) does seem feasible. Beyond a test frequency of 10 Hz,
potential thermal effects have to be considered. It is recommended to periodically check on the temperature of the specimen
if tests are performed at frequencies above 10 Hz.

From an application point of view, e.g., for design, the determination of a “threshold” value, i.e., a $C_{\text{I, max}}$ value for which
the delamination ceases to propagate, is clearly of interest. The aim originally was to develop a procedure which would yield
fatigue delamination propagation data within a relatively short period of time (e.g., 10–24 h). The same procedure, in prin-
ciple, is also suitable to search for a threshold under displacement control. However, even though tests have been performed
under displacement control for up to 19 million cycles (about 22 days at 10 Hz, correspondingly more for lower frequencies),
no indication of a threshold has been found for this material (see Fig. 5). Hence, when determining fatigue delamination
propagation values for design, it may be necessary to define an (arbitrary) number of cycles, e.g., from expected life-time
or service operation. In that case such a value should not be designated as the “threshold” value in the traditional sense
of the word, since it would not represent the limit below which delamination propagation would cease altogether.

The test duration in an industrial environment should preferably be as short as possible, usually due to manpower and
machine cost constraints. The minimum recommended duration shall be about 8 h, in order to obtain data for $\text{da/dN}$ down to
between $10^{-5}$ and $10^{-4}$ mm/cycle. Test duration could be extended to 24 h without much additional effort, as long as ma-
chine compliance data recorded during an unsupervised period (e.g., at night) can subsequently be converted to correspond-
ing delamination lengths. Two such schemes have been investigated, as described below.

Three different approaches have been used to determine the delamination length. Visual observation yielded apparently
consistent results from three laboratories (see Figs. 2 and 8). Data derived from the “effective crack length” approach pre-
sented above (using independent $E$-modulus measurements and machine compliance data) proved less consistent. As shown
in Fig. 6, there is agreement with the visually observed data in some cases, but in others a distinct shift of the curve is ob-
tained. Unfortunately, the effective crack length approach yielded less conservative results than the directly measured values
in this case. A promising approach appears to be offered by combining selected visual crack length measurements (together
with corresponding compliance data) with additional compliance data recorded automatically at selected intervals. Data
from tests that are running unattended, e.g., overnight or at weekends without the corresponding manpower costs, can then
be utilised as follows. Fig. 9 shows specimen compliance determined from machine data (load and displacement) versus
number of cycles and the calibration curve obtained from a few visual observations. The calibration assumes a power-law
dependence of the compliance (Eq. 1) on delamination length and the constants from the linear fit are used to calculate the
delamination lengths from compliance as recorded by the test machine (initial intervals of 5000, later of 10,000 cycles).
For fitting the power law as shown in Fig. 9, visual observations from the early and late phase of the test have been used. The
fit indicates reasonable agreement with the power-law assumption, even without correcting for the compliance of the test-
fixture.

$$C = Ba^n$$

where $C$ is the compliance determined from machine load and displacement, $B$ is a constant, $a$ is the delamination length,
and $m$ is the exponent of the power law.

The cause of the observed disagreement between visually determined and delamination length back-calculated from $E$
-modulus is not clear at present. As noted above, a typical $E$-modulus value for this type of material had been used in the

Please cite this article in press as: Brunner AJ et al. Development of a standardized procedure for the characterization of interlaminar
J.engfracmech.2009.07.014
The possible explanation that there may have been specimens for which the $E$-modulus deviated sufficiently from the average value has not proven to be true (measured modulus for specimen B3 around 136 GPa).

The $R$-ratio was one of the test parameters that were fixed for the first RR ($R = 0.1$). From literature, it is known that the position of the curve in the Paris-plot depends on the choice of $R$-ratio. For comparison between different FRP materials, it is best to test at one fixed value of $R$. For low $R$-ratios (e.g., $R = 0.1$) more conservative curves tend to be obtained when $da/dN$ is plotted versus $G_{I max}$, and are thus preferred. Please note that this will not apply when plotting $da/dN$ against $D_{G_I}$. At the same time, such ratios imply larger displacements which may limit the test frequency, depending on the stiffness of the DCB-specimen. If data are going to be used in design, it is important to note the independent parameter ($G_{I max}$ or $D_{G_I}$) and the $R$-ratio for considering the choice of suitable safety factors.

Combining the raw RR data from displacement control in one single graph yields average results for mode I fatigue behavior of IM7/977-2 with a scatter of about one half of a decade for $da/dN$. Averaging schemes do reduce some of the scatter (e.g., seven-point sliding average used in Fig. 7) but still result in a similar spread. Of course, if data for one FRP composite from different sources are compared, it is important to note all test parameters and to use data obtained under comparable conditions (e.g., same $R$-ratio, probably comparable initial delamination length, etc.). Conditioning effects also have to be considered in such a comparison.

From the perspective of industrial applications, test requirements can be summarized as “simple set-up, fast test and analysis, and sufficiently accurate results”. The first two requirements directly relate to test cost which is of primary concern. The procedure for mode I fatigue testing in its current form satisfies these requirements to a large extent (test duration 8–10 h with occasional visual checks, and data analysis that can be performed with programmed spread-sheets). Test duration and therefore, to some extent, machine costs typically scale inversely with the frequency that is chosen for the test. A practical limit of around 10 Hz is imposed by both the limitations of the test machine and by potential thermal effects if too high a frequency is selected. If a lower frequency is dictated by the elastic properties of the FRP composite, increasing the stiffness (using thicker specimens) and shortening the initial delamination length may help. Another factor that will affect test cost is the number of specimens that have to be tested per condition. Many standard tests prescribe five repeats. The current data

Fig. 9. Combination of visual observation of delamination length with additional compliance data for determining the Paris-plot; (a) compliance versus number of cycles with indication of data from visual observation and (b) linear fit assuming a power-law dependence of compliance on delamination length (Eq. 1).
base from the RR is yet too limited to decide whether, for example, three specimens would suffice. There may be potential for further automation, e.g., by using a compliance-based determination of (effective) delamination length, thereby eliminating the need for visual observation.

5. Conclusions and outlook

Inter-laboratory comparison indicates that the typical precision for \( \frac{da}{dN} \) for IM7/977-2 is about one decade for \( G_{\text{I max}} \) values between about 100 and 200 J/m². For a full fracture mechanics characterization of the IM7/977-2 CFRP–epoxy laminate, fatigue tests would also have to be performed in mode II and mixed mode I/II, at least at one ratio of mode I to mode II. There are plans for the development of such standards, but this will take some time. A full characterization of delamination resistance under quasi-static loads for the different modes is reported in [23–25].

Data from RR testing of a carbon–fiber reinforced composite with thermoset matrix (IM7/977-2) and preliminary testing of other fiber-reinforced polymer–matrix composites indicate that the test procedure proposed by the Technical Committee on Fracture of Polymers, Composites and Adhesives of the European Structural Integrity Society (ESIS) is well suited to yield information on delamination propagation under fatigue mode I loading of Double Cantilever Beam (DCB) specimens.

Based on the RR results and the discussion above, the proposed test parameters are as follows:

1. The test shall be performed with DCB-specimens as described in [7], however, thicker specimens (up to 6 mm for CFRP and up to 9 mm for GFRP, in particular for composite laminates with a high compliance), short initial delamination lengths (not shorter than 30 mm) and longer specimens than the minimum of 125 mm are preferred (especially for brittle matrix systems, specimens shall be at least 150 mm long). With short initial delamination lengths, the load-block corrections defined in [7] have to be used, if applicable. Conditioning before the test shall be performed according to the material supplier’s specifications.

2. The test shall be performed under displacement control, from a pre-crack obtained under quasi-static conditions according to [7], the initial displacement value for fatigue shall be the last value recorded from the quasi-static test. If specimens are shortened after pre-cracking in order to obtain short initial delamination lengths, the initial displacement value may have to be set lower than the last value from quasi-static pre-cracking (about 5% less is recommended).

3. The \( R \)-ratio can be set arbitrarily. However, to obtain conservative Paris-plots of \( \frac{da}{dN} \) versus \( G_{\text{I max}} \), \( R = 0.1 \) is recommended.

4. The test frequency shall be set as high as possible (10 Hz, if feasible on the test machine). It is recommended to check for specimen heating if higher frequencies are chosen.

5. Data acquisition shall record sufficient load and displacement values (e.g., every 5000 or 10,000 cycles) for a compliance-based determination of delamination length. This shall be verified by visual observation with a travelling microscope. Increments between visually determined delamination lengths shall be at least 0.5 mm, unless averaging procedures (e.g., that described in [22]) are used. If the effective delamination length approach according to [21] is used, an independent measurement of the modulus of elasticity is required.

With these parameter choices useful Paris-plots can be obtained with test durations between 8 h (minimum test duration) and 24 h (recommended test duration).

Determination of “threshold” values will require definition of an arbitrary limit, e.g., testing up to 10 million cycles or whatever corresponds to expected life-time use (eventually including a suitable safety factor).

Back-calculating an effective crack length from an independent modulus measurement (maybe measured on each individual specimen) and compliance data is, in principle, feasible but should be confirmed by comparison with visual observations (particularly in the initial and final stages of the test, if one specimen is run for 24 h for example), since the round robin data did not agree in all cases. The operator-independent schemes for determination of delamination lengths in principle open a perspective for the development of automated routines for data acquisition and analysis.

Acknowledgments

Supply of prepreg from Cytec Engineered Materials and specimen manufacturing by Dr. D.D.R. Cartié (Cranfield University), as well as discussion with Dr. M. Hojo (Kyoto University) and Dr. A.J. Kinloch (Imperial College) are gratefully acknowledged. Part of the work was performed at the Polymer Competence Center Leoben GmbH (PCCL, Austria) within the framework of the Kplus-program of the Austrian Ministry of Traffic, Innovation and Technology with contributions by the University of Leoben (Institute of Materials Science and Testing of Plastics) and FACC AG (A). The PCCL is funded by the Austrian government and the State Governments of Styria and Upper Austria. Technical assistance of Mr. D. Völki for tests at Empa is also acknowledged.
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