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# 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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ABSTRACT

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.



## 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

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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 $G_{I\,max}$ 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×) was used. 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 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