Mixed-mode Cyclic Fatigue Delamination Growth with Large Scale Bridging in Composites

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Summary. An innovative experimental apparatus utilizing double cantilever beam specimens loaded with uneven bending moments (DCB-UBM) was developed to study the mixed-mode cyclic crack growth along weak planes in adhesively bonded composite interfaces with large-scale fiber bridging (LSB). The cyclic growth of delaminations in typical fibre-reinforced polymer composites was investigated at ambient temperature for a loading frequency of 2 Hz. The specimens under pure mode I, mode II and mixed mode cracking were examined. The results, analyzed using a J-Integral approach, show that the DCB-UBM specimen configuration provides a suitable experimental approach to investigate the cyclic crack growth of composites under pure mode and mixed mode loading conditions with LSB, and the crack growth can reach a steady state for all fatigue cracking specimens examined. The approach allows the mixed-load cyclic cohesive law to be determined for delamination growth in the presence of LSB.

INTRODUCTION

Observations show that many of the composite materials used in advanced wind turbine blades can develop large-scale bridging (LSB) of cracks when subjected to a monotonically increasing load and cyclic load. Bridging fibres can restrain the crack opening and raise the fracture resistance (R-curve behavior) of a composite or adhesive joint. However, large-scale bridging complicates the analysis and interpretation of experimental results since, in general, standard linear-elastic fracture mechanics (LEFM) test methods are not applicable when LSB is present. For a small scale fracture zone, cyclic crack growth can be predicted reasonable well by LEFM, e.g. Paris-Erdogan relation. However, LEFM is insufficient for the characterization and modeling of cracking problems with a large-scale fracture process zone, such as LSB. Then cohesive laws become well suited for describing delamination growth with LSB.

In order to establish cyclic cohesive laws, which can be measurable from experiments and used for modelling for reliable predictions of loading carrying structures, this often requires the use of mixed-mode fracture and fatigue testing. An important issue in regard to cyclic crack growth testing is that of steady-state crack growth, which refers to the condition where the crack opening in the cohesive zone occurs in a steady-state manner from zero separation to a critical separation under the same cyclic loading conditions, retains the same steady-state fracture process zone length and translates along the specimen in a self-similar fashion. Thus, to determine a complete cyclic cohesive law, it is necessary to utilize specimen geometry and loading conditions that can provide steady-state crack growth.

The modeling of microstructural damage evolution by bridging laws for fracture process zones and the characterization of material behavior for the lifetime prediction of composite structures subjected to complex cyclic loading history with large-scale crack bridging is an area of critical concern for composite structures. It is important to develop an experimental method to provide steady-state delamination growth in composites with LSB under cyclic mixed-mode loading condition. The analytical J integral solution is also available for specimen configuration and traction-separation cohesive laws (bridging laws), as the basic fracture controlling material laws, can be obtained base on experimental data. With this in mind, the primary objectives of the present paper was to extend the use of the DCB specimen loaded with uneven bending moments test configuration and develop an experimental technique for mixed-mode cyclic loading of laminated composites, which will allow determination of cyclic cohesive laws for composites structures that experience LSB of delamination cracks and adhesive debonding.

BASIC MECHANICS

The test specimen configuration used in the present study is a double cantilever beams specimen loaded with uneven bending moments (DCB-UBM). This test specimen belongs to a small family of steady-state DCB specimens (loaded with axial forces and/or bending moments) for which the J integral can be obtained in close analytical form - the solutions for J are valid for (and independent of) the properties of the large-scale bridging zone. The J integral gives a rigorously correct connection between the crack tip stress field, the bridging zone and the J integral evaluated along the external boundaries.

EQUIPMENT DESIGN

The developed test method was designed to be mounted at a standard materials testing machine. The uncracked end of the specimen is fixed at a central support; transverse arms are mounted at the two beams at the other end of the specimen. The uneven pure bending moments are created by different distances between rollers (different moment arms) of forces of equal magnitude but opposite direction applied to transverse arms by a wire. The wire runs from an upper beam, where two load cells are mounted, to the transverse arms, down to a lower

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beam via rollers, past a servo-hydraulic actuator and up again on the other side. In order to minimize errors in the applied moments as a result of specimen deflection, the distance between the transverse arms and the upper and lower rollers is maximized by mounting the load cells on a transverse beam above the upper cross-member, giving long wire lengths (See Fig. 1). The cyclic load is generated by the servo-hydraulic actuator that is mounted upside down on the materials testing machine, see Fig.1.

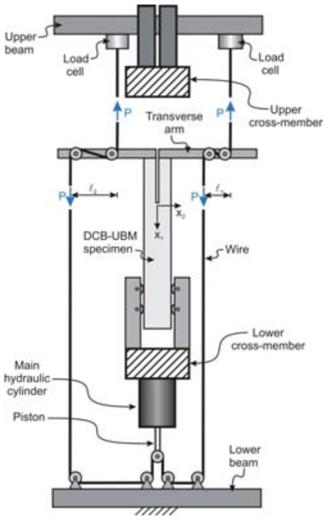

Fig.1 Schematic illustration of the proposed cyclic loading frame for DCB-UBM specimens.

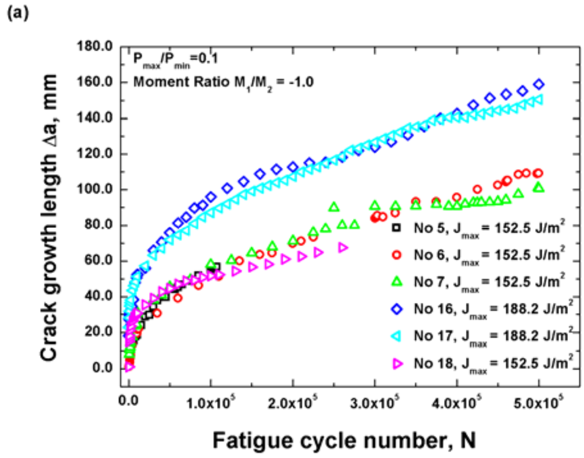

Fig.2 Crack growth length vs. fatigue cycles number for specimens subjected to mode I loading;

TEST RESULTS AND DISCUSSION

The first tests were made on specimens made of a unidirectional glass fiber polymer matrix composite **-** i.e., providing data for characterization of cyclic growth of delamination cracks. The cyclic load varied in a sinusoidal shape between fixed maximum and minimum loads at 2 Hz, i.e., between fixed maximum and minimum moments (and thus constant maximum and minimum values of J). The crack length was determined from the images. Generally, the crack length was found to increases fastest in the early stages, i.e. when the crack was short. With increasing crack extension, the crack growth rate decreased significantly, particularly for Mode I tests. Fig. 2 shows some typical results. It is seen from it that the crack growth rate decreases as a function of time, eventually reaching a constant rate. Note also that there is only a small difference between the cracks extensions of the specimens tested under identical conditions. The results can be understood as follows. Initially, in the very early stages of cycling, the crack is virtually without bridging. Thus, the growth rate in the early stages represents the crack growth rate on a near-unbridged crack. With increasing number of cycles, the crack tip advances away from the initial starter crack and creates a bridging zone between the end of the slip foil and the crack tip. Within the bridging zone, ligaments of unbroken fibres and single fibres transmit stresses between the crack faces, effectively unloading the crack tip stress field. The decrease in the crack tip stress field reduces the growth rate of the crack tip. With increasing number of cycles, the bridging zone length increases. However, bridging ligaments may also fail in the bridging zone. Eventually all ligaments have failed at the location of the crack starter, creating a finite length (fully developed) bridging zone. Then, a steady-state situation can be anticipated: The crack tip and the bridging zone translate along the specimens in a self-similar fashion, creating a constant growth rate. The steady-state crack growth under a fully developed large-scale bridging zone provides information regarding the degradation of the bridging ligaments under cyclic loading and potentially can be used to measure the cyclic mixed-mode cohesive laws in composites with LSB.

CONCLUSIONS

It concludes that DCB-UMBconfiguration under cyclic uneven bending moments can provide a true steady-state crack growth condition with LSB effect. As results, it offers a method to uncover the “cyclic” cohesive law for laminated and sandwich composites with LSB effect and study the effect of applied load and damage front material resistance separately.

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