CYCLIC CRACK PROPAGATION AND -ARREST IN A UNIDIRECTIONAL POLYMER MATRIX COMPOSITE EXHIBITING LARGE SCALE BRIDGING

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ABSTRACT

A test configuration for characterizing stable cyclic crack growth in fibre reinforced composites displaying large-scale bridging under mixed mode fracture has been proposed and sample results of tests conducted on a glass reinforced polymer in pure mode I have been presented. These show that shielding of the crack tip due to fibre bridging has significant impact on crack development and is capable of fully stopping crack growth below certain load levels. Beyond this threshold load level, crack growth will eventually reach steady state, at which the fracture process zone propagates a constant rate that is significantly lower than that of an unbridged crack. It has furthermore been shown that the steady state crack growth rate can be expressed by a Paris type law.

INTRODUCTION

Paris' Law (Paris, Gomez, & Anderson, 1961) relates sub-critical crack growth rates to changes in stress intensity factor caused by the cyclic change of applied loads through the power law:

$$\frac{da}{dN} = C\Delta K^m \quad (1)$$

where da and dN are changes in crack length and cycle number respectively, C and m empirical parameters and $\Delta K = K_{\max} - K_{\min}$ the change in the crack tip stress intensity factor K, where max and min denote maximum and minimum values respectively. The relation calls for the requirements of linear elastic fracture mechanics (LEFM) to be fulfilled. These are, that the material must be linear elastic as well as isotropic and that the fracture process zone (FPZ) must be small compared to the crack length and other specimen dimensions such as thickness.

When the FPZ is small, a requirement of LEFM, external loading and geometry communicate with the FPZ through a singular crack tip stress field, controlled by the stress intensity factor, which is related to the strain energy release rate, G, by:

$$G = \frac{K^2}{\overline{E}} \quad (2)$$

where $\overline{E}$ is the effective Young's modulus depending on stress state.

Laminated fibre reinforced polymers (FRPs), however, do not fulfil these criteria as they are usually orthotropic and the presence of fibres may give rise to intact fibres intersecting the fracture plane of an advancing crack front causing surface tractions behind the crack tip. The traction-separation relation (stress as a function of displacement, $\sigma(\delta)$) of these bridging fibres is known as a bridging law. Orthotropy in FRPs can be handled by the technique or orthotropic rescaling (Suo, 1990), but depending on the FRP configuration with respect to fibre and matrix materials, the fracture zone, now including that of fibre bridging, may be of various scales relative to other crack dimensions and in some instances it may be small enough to be considered as part of the FPZ at the crack tip which does not violate the LEFM assumptions. However, for multiple configurations (e.g. glass fibre reinforced polymers) a bridging zone several times beam thickness, is often seen as fibres parallel to the advancing crack tip direction can be observed, a phenomenon known as *large-scale bridging* (LSB). It is well known that LSB increases the fracture resistance beyond that of the crack tip fracture toughness (Hashemi, Kinloch, & Williams, 1990) (Zok, Sbaizero, Hom, & Evans, 1991) (Spearing & Evans, 1992) (Kaute, Shercliff, & Ashby, 1993) (Shercliff, Vekinis, & Beaumont, 1994) (Albertsen, Ivens, Peters, Wevers, & Verpost, 1995). This is an important feature as FRPs are usually significantly weaker in planes parallel to fibres than in the plane perpendicular to the fibre direction. One may argue that the toughening mechanism occurs after an initial crack has grown; however, it is still worthwhile to take in to consideration as it can provide a level of safety compared to crack initiation, retarding further crack development.

The basic idea of the bridging zone shielding the advancing crack tip can be formulated as:

$$J_{tip} = J_{ext} - J_{br} \qquad (3)$$

where subscripts ext and br denote *external* and *bridging* respectively and J is calculated by the J integral (Rice, 1968).

For LEFM problems $J = G$, and thus not under LSB. The assumption is still, however, that fracture of bridging and crack tip can be viewed as acting in superposition, making it possible to separate the contributions. Despite LSB it is still assumed that the potential energy release rate at the crack tip drives crack growth and that the crack tip can be viewed as a local LEFM problem. Inserting equation (2) into equation (1), considering the J integral at the crack tip as the driving force, gives an expression for crack growth under LSB:

$$\frac{da}{dN} = C\left(\sqrt{\Delta J_{tip}\,\overline{E}}\right)^m \qquad (4)$$

For static loads and known bridging laws, J is easily calculated (Li & Ward, 1989) by:

$$J_{ext} = J_{tip} + \int_0^{\delta^*} \sigma_n(\delta)\,d\delta \qquad (5)$$

where the integral contains the contribution of the bridging zone. Due to non-uniform degradation of the bridging law along the bridging zone and the variation in the bridging tractions as the crack opening changes during cyclic loading, it is difficult to determine J_{br} analytically in fatigue.

A hypothesis is, that for a special type of steady-state specimen, for cyclic loads at a fixed range of external loading, $\Delta J_{ext} = J_{ext,\max} - J_{ext,\min}$, an FPZ will develop at an initial and unbridged crack tip at a relatively high crack growth rate which will decrease as the bridging zone grows, shielding the crack tip. The failure process zone will develop until the crack tip is either fully shielded by fibre bridging and crack growth comes to a halt or until the fibre bridging zone is fully developed after which it will move along with the crack tip in a self-similar manner resulting in a steady-state crack growth rate. These principles are depicted in Figure 1

The purpose of this paper is to describe a novel test configuration used to characterize crack development on double cantilever beam test specimens loaded with uneven bending moments (DCB-UBM) that has a number of desirable characteristics: a) it allows steady-state cracking (i.e. fully developed bridging zone length remains invariant during crack growth), b) enables testing in the full range of mixities from mode I to II by using the same specimen geometry, c) eliminates crack length- and opening influence on loading, d) uses a test specimen that allows for easy analytical determination of the J integral that is independent of the bridging zone. The concept is based on a method to characterize static crack growth (Sørensen, Jørgensen, Jacobsen, & Østergaard, 2006) which may serve as further reading.

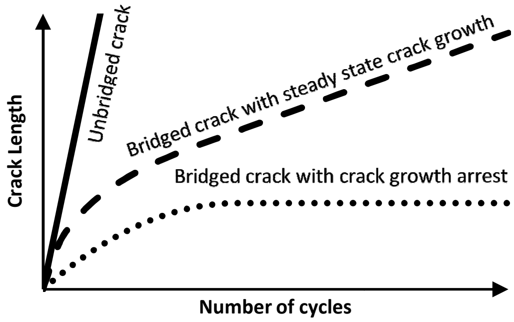

Figure 1: Crack growth concepts

DESCRIPTION OF TEST CONFIGURATION

The test setup consists of a DCB test specimen loaded by uneven bending moments as shown in Figure 2. Pure mode I is achieved by $M_1 = -M_2$ and pure mode II by $M_1 = M_2$, however, pure mode II is not practical as identical moments leads to identical beam curvatures that causes undesirable contact of the upper and lower beams of the specimen, but it is still possible to get so close that the difference may be insignificant. Mixed mode fracture can be obtained for any other combination of applied moments with the limitation $|M_1| < M_2$.

The J integral is easily determined along a path, Γ_{ext}, at the perimeter of the specimen (plane stress):

$$J_{ext} = \frac{21\left(M_1^2 + M_2^2\right) - 6M_1M_2}{4B^2H^3E_{11}} \qquad (6)$$

where M_1 and M_2 are applied moments, B and H specimen width and half-height respectively and E_{11} the Young's modulus in the x_1 direction. For problems in plane strain the expression should be multiplied by $\left(1 - \nu_{13}\nu_{31}\right)$ where ν is the Poisson's ratio and indices indicate directions of the orthotropic material as in Figure 2.

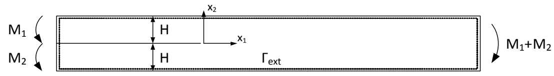

Figure 2: DCB specimen loaded with uneven bending moments. (DCB-UBM)

Loading is controlled as in Figure 3 by a set of arms/levers attached to the beams of the DCB specimen. The force, P, is applied by a free moving, thin steel wire running through a system of low friction rollers in a closed circuit ensuring constant force in the wire anywhere in the system. The magnitude of moments M_1 and M_2 are controlled by P as well as roller distances L_1 and L_2. The path of the wires through each set of rollers attached to the arms controls the direction and, thus, the sign of the moments. It is this part of the configuration that allows for stable crack growth as external loading does not depend on the extension of the crack. Relative transverse displacements are recorded by two LVDTs attached to the end of the bridging zone (the initial crack tip) and the crack opening by an extensometer mounted on pins also at the end of the bridging zone. Crack lengths are recorded by visual evaluation of captured images.

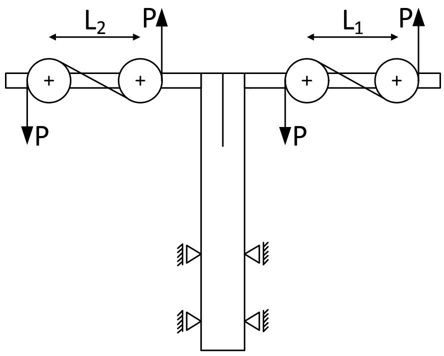

Figure 3: DCB-UBM loading schematics

CASE STUDY

Mode I tests have been run on DCB specimens consisting of a GFRP laminate. Two types of tests have been completed; load control, ΔJ, and displacement control $\Delta\delta_n^*$, where δ_n^* is the crack opening displacement at the initial crack tip.

Load controlled tests provide information about crack growth at a specific load level as the crack develops from the unbridged initial crack to being fully bridged (transient crack growth) as well as for the fully developed fracture process zone (steady state crack growth).

In displacement control, cyclic loading is carried out on specimens that have been subjected to a monotonic static loading creating a fully-developed static bridging zone (the static bridging zone may however differ from that developing during cyclic loading). Nevertheless, this procedure is assumed to cause crack growth to reach a steady state cyclic configuration within relative few load cycles. At fixed $\Delta\delta_n^*$, compliance of the test specimen rises as the crack grows, causing a lower load response to attain the same crack end opening. Using this method, steady state crack growth rates can be recorded for continuously decreasing load ranges, ΔJ . This potentially provides the same information from just one test specimen that would require a number of tests carried out in load control. It should be noted, however, that the bridging fibres of the two test methods develop differently as crack growth is steady state in ΔJ controlled tests and may not necessarily be in $\Delta\delta_n^*$. Thus, the bridging fibres experience a different development history which means that the effective bridging laws may be different for the two types of tests despite equal loading. Furthermore, it is expected that in displacement control, crack growth will eventually come to a halt at a certain load level which may be considered as an engineering threshold value below which fibre bridging is capable of fully retarding crack development.

RESULTS

Figure 4 shows the results of two load controlled tests. Both start out at relatively high growth rates for shorts cracks, compared to those found for longer cracks, steadily decreasing as crack extensions increase. For the test run at the higher load, it is clearly visible that this is followed by a course of constant crack growth indicating steady state propagation of the entire fracture process zone, including bridging. For the test run at a lower load, the crack growth rate levels out, approaching arrest.

Figure 5 shows the result of a displacement controlled test. Here it is seen, that the applied load drops rapidly with crack propagation and that both level out towards the end of the test. In the experiments it was in fact observed that eventually, both crack propagation as well as change in applied load would come to a complete stop even when allowed to run for an extensive number of cycles. This load level can be interpreted as the aforementioned engineering threshold value.

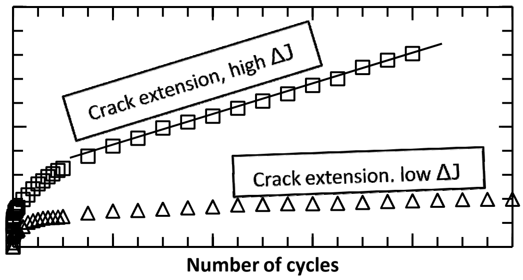

Figure 4: Sample results of load controlled tests

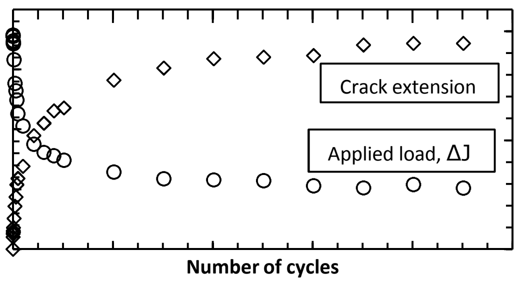

Figure 5: Sample result of displacement controlled tests

In Figure 6, steady state crack growth rates found by either test method have been plotted together for comparison.

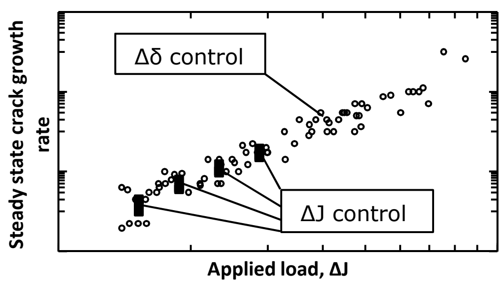

Figure 6: Comparison of steady state crack growth rates from load- and displacement controlled tests in a log-log coordinate system

DISCUSSION

The results in Figure 4 show that the hypothesis of decreasing crack growth rate proportional to increasing bridging zone development holds true for both load levels tested and that fibre bridging does in fact shield the crack tip increasing fracture resistance. It is apparent that the load controlled test run at the higher load at some point reaches a steady state crack growth rate that remains unchanged despite further crack development, indicating that shielding from fibre bridging remains constant and thus that crack tip and bridging zone propagate at the same rate. The test run at the lower load approaches an arrest in crack growth, but full crack development retardation was not fully achieved in the test and it remains speculation if this would have happened eventually, had the test been allowed to run further. However, the load level was below that determined as the engineering threshold level in the displacement controlled test, at which the crack ceased to grow any further, thus, crack growth arrest should be expected at some point for loads below this value. An interesting property of the engineering threshold level is that it was actually found to be lower than the static fracture toughness of an initial and thus unbridged crack.

It is clearly seen that the steady state crack growth rates found by either load- or displacement control are similar, strongly indicating that steady state crack growth rates successfully can be determined by use of displacement controlled tests, thus greatly reducing the requirement of test specimens as well as testing time. Furthermore, it is apparent that crack growth rates found in displacement control fit a power law, as in equation 1, quite well, implying that steady state crack growth can be described by a Paris type law. This is remarkable, since the cyclic crack growth rate is not controlled solely by an unbridged crack tip but by the entire fracture process zone. This illustrates the usefulness of using steady-state specimens.

CONCLUSION

It has been shown that the proposed test configuration can be successfully used to characterize cyclic crack growth under LSB and that both load- and displacement control test methods yield results that support a hypothesis of crack development dependent fibre bridging. Results of the displacement controlled test show that an engineering threshold value exists, below which a crack will initially grow at a continuously decreasing rate that subsequently reaches zero. For loads above this level, the crack growth rate will decrease until a certain point at which it will remain unchanged for the following load cycles and propagate under steady state. Where load controlled tests capture transient and steady state crack growth for a specific load level, tests in displacement control supply information about steady state crack growth rate for a whole range of load levels on one test specimen as well as the engineering threshold value.

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BIBLIOGRAPHY

Albertsen, H., Ivens, J., Peters, P., Wevers, M., & Verpost, I. (1995). Interlaminar fracture toughness of CFRP influenced by fibre surface treatment: part 1 Experimental results. *Composite Science and Technology 54* , 133.

Hashemi, S., Kinloch, A., & Williams, J. (1990). The analysis of interlaminar fracture in unidirectional fibre–polymer composites. *Proc. R. Soc. Lond. A427* , 173.

Kaute, D., Shercliff, H., & Ashby, M. (1993). Delamination, fibre bridging and toughness of ceramic matrix composites. *Acta Metall. Mater* , 1959.

Li, V. C., & Ward, R. J. (1989). A Novel Testing Technique for Post-break Tensile Behavior of Cementitious Materials. *Fracture Toughness and Fracture Energy, Mihashi et al. (eds)* , 183--195.

Paris, P. C., Gomez, M. P., & Anderson, W. E. (1961). A Rational Analytic Theory of Fatigue. *The Trend in Engineering 13* , 9-14.

Rice, J. R. (1968). A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks. *Journal of Applied Mechanics 35* , 379--386.

Shercliff, H., Vekinis, G., & Beaumont, P. (1994). Direct observation of the fracture of CAS-glass/SiC composites, part I delamination. *Journal of Materials Science 29* , 3643.

Spearing, S., & Evans, A. (1992). TThe role of fiber bridging in the delamination resistance of fiber-reinforced composites. *Acta Metall. Mater. 40* , 2191.

Suo, Z. (1990). Delamination Specimens for Orthotropic Materials. *J. Appl. Mech. 57* , 627--634.

Sørensen, B. F., Jørgensen, K., Jacobsen, T. K., & Østergaard, R. C. (2006). DCB-specimen loaded with uneven bending moments. *International Journal of Fracture 141 (1-2)* , 163--176.

Zok, F., Sbaizero, O., Hom, C., & Evans, A. (1991). Mode I fracture resistance of a laminated fiber-reinforced ceramic. *J. Am. Ceram. Soc. 74* , 187.