Effect of maximum load on cyclic crack growth in UD E-glass/vinyl ester composites with constant and alternating stitch density

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Abstract. DCB specimens, manufactured from composites with constant and alternating stitching density, are tested under pure mode I for static and cyclic loading. The tests are carried out for different maximum load values, but keeping the same R-ratio. The crack growth is recorded from pictures at different cycle intervals, and the energy release rate (ERR) is computed using an approach based on the J-Integral. Along with the crack-tip, the length of the fracture process zone (FPZ) is recorded with the number of cycles. A curve relating the crack growth rate (CGR) and the cyclic fracture resistance, $\Delta J$, which can be directly applied in the design/repair process of composite structures, is derived.

1. Introduction
Composite materials are widely used in many modern engineering lightweight structures. Their high specific mechanical properties (e.g. specific strength, and stiffness) coupled with their good fatigue performance make them preferable to metals for some applications such as aircraft and wind turbine blades. Currently, damage tolerant designs of composite structures are being evaluated. However, such designs can only be implemented if accurate damage propagation prediction tools exist. The separation of initially bonded adjacent layers, which comes from the inherently weak interfaces (out-of-plane strength) of layered materials, is a common damage mechanism known as delamination. Such a process can lead to large stiffness and load-carrying capacity losses, which is why delamination is widely acknowledged as one of the most important failure mechanisms [1]. Most engineering structures are subject to cyclic loading, and thus cyclic crack growth is more relevant.

Accurate predictions of fatigue delamination largely depend on the accuracy of the fracture parameters of the material at hand. Predictions of fatigue delamination in composite structures are commonly based on numerical simulations either using a linear elastic fracture mechanics (LEFM) framework or using the cohesive zone model (CZM) concept originally proposed (independently) by Dugdale [2] and Barenblatt [3]. Cohesive models have become more widely adopted given that they circumvent some of the inherent limitations of LEFM, such as specific mesh requirements at the stationary crack tip, while also providing a framework to account for large scale fracture process zones. Cohesive models require fracture material properties such as critical fracture toughness, critical opening displacements or tractions as input. These fracture
properties are commonly derived for each material system typically from experiments like the double cantilever beam (DCB) [4, 5], end-notched flexure (ENF) [6], and the mix-mode bending (MMB) specimens [7], among others. The present work lays out a methodology to obtain the mode I fracture toughness and cyclic crack-growth rate from based on experimental data from DCB specimens. To demonstrate the approach, several tests with different maximum loads (but constant R-ratio) are carried out on laminates manufactured from constant and alternating stitching density. The effects of the maximum load, $P_{\text{max}}$ and the stitching density of the composite laminates in the crack growth rate (CGR) and the cyclic fracture resistance $\Delta J$ are discussed.

2. Methods

2.1. Materials and DCB specimens

The laminate used for the DCB specimens is an E-glass/vinyl ester laminate manufactured by vacuum infusion with a curing cycle of 24 hrs at room temperature followed by 24 hrs at 60 °C. The E-glass fabric consisted of nearly unidirectional bundles, and the laminates had a volume fraction of approximately 55%. Two laminates were manufactured using the same fibers, and matrix, but different stitching density. Both configurations use glass yarns as support threads and a tricot stitching pattern, but one has a constant number of stitch ends per inch equal to 6 (6 gg), and the other has a stitching density alternating between 6 gg and 2 gg. The support threads are arranged so that they face each other, leaving alternating interfaces free of threads and thus exclude the effect of support threads in the cyclic crack growth rate. Prior to vacuum infusion, the middle interface (free of support threads) is used for introducing an artificial crack initiation through a release foil of 35 ±15 µm (See Fig. 1).

![Figure 1. DCB specimen schematic](image)

The DCB specimen dimensions are; Length, $L$, equal to 500 mm, width, $B$, equal to 30 mm, and height, $2h$, of approximately 2 mm. The DCB specimen was glued to steel beams on the top and bottom of the beams to add flexural rigidity in order to prevent large rotations. The steel beams have the same length, $L$, and width, $B$, but a thickness, $H$, of 6.67 mm. A schematic of the sandwich structure is shown in Fig. 1.

2.2. Test configuration

Both quasi-static and cyclic tests were carried out by applying equal, but opposite constant moments at the top and bottom ends of the DCB specimen. The constant moment is applied through an adjustable lever-arm for both fatigue and static tests as shown in Fig. 2. The load, $P$, is measured by two load cells and the average value is used to calculate the applied moment, $M$. The approach of applying constant moment instead of constant load was introduced by Sørensen et al. [8, 9] and it offers the advantage of producing stable crack growth as this no longer depends on the crack length. More importantly, the approach produces more accurate measurements in the case of large scale FPZ typically observed in composite materials.

The static and fatigue test are carried out on the same specimen sequentially, starting with the static test, and then followed by cyclic loading. This allows for more testing per specimen and
also ensures a sharp crack at the beginning of the cyclic loading. For the static test, the normal opening is measured with an extensometer mounted on the end top and bottom of the DCB specimen (See Fig. 2a). For the cyclic test, instead of the normal opening, the crack growth is measured using digital pictures taken from the same location at different cyclic intervals. The post-processing is carried out manually, which means that it is subject to reading errors and interpretation. The presence of large scale bridging made it so that the definition of the start and end of the FPZ is not trivial. The start of the FPZ, i.e. the crack-tip, is defined as the first observable colour discontinuity, whereas the end of the FPZ is defined as the beginning of the last observable fibre bridge (farthest from crack tip, see Fig. 8). Reading errors are accounted to an extent by carrying multiple measurements and using mean crack length values.

![Figure 2. Schematic of test configuration: a) Static test-stand, b) Cyclic test-stand](image)

2.3. Calculation of Fracture Resistance

The strain energy release rate of DCB specimens is commonly calculated using principles of LEFM (see for instance the ASTM D5528-01 [5]), however, LEFM is no longer valid when large scale bridging is present. For non-negligible FPZ cases, the J-integral method [10] is a powerful tool to obtain the energy release rate. Due to the relatively high width to height ratio plain strain condition is assumed. Under such condition, the J-integral for an orthotropic sandwich DCB specimen loaded with constant end moments is [8, 11]:

\[
J = \frac{1 - \nu_s^2}{E_s} \frac{M^2}{B^2 H^4 \eta^3 I}
\]

with,

\[
I = \frac{1}{3} \left\{ \frac{1}{\eta^3} + 3 \frac{\Delta}{\eta} \left( \Delta - \frac{1}{\eta} \right) + \Sigma \left[ 1 + 3 \left( \Delta - \frac{1}{\eta} \right)^2 - 3 \left( \Delta - \frac{1}{\eta} \right) \right] \right\}
\]
\[ \Delta = \frac{1 + 2\Sigma \eta + \Sigma \eta^2}{2\eta(\Sigma \eta + 1)}, \quad \Sigma = \frac{E_c}{E_s} \left( \frac{1 - \nu_s^2}{1 - \nu_c^2} \right), \quad \eta = \frac{h}{H} \]

(3)

3. Results and discussion

The static fracture resistance, \( J_R \), as a function of the end normal opening mode, \( \delta_n \), calculated using Eq. (1) is shown in Fig. 3. The upper portion of the curve corresponds to the loading part and the bottom to the unloading. The initiation of delamination corresponds to point 1 in Fig. 3, whereas point 2 indicates the steady-state delamination growth. It is observed that the initiation \( J_R \) value in the static case (point 1, approximately 200 N/m) is larger than any of the \( J_{\text{max}} \) values from the cyclic tests shown later in Table 1.

![Figure 3. Static fracture resistance of a DCB specimen from alternating stitching density fabric](image)

For the cyclic test, the cyclic fracture resistance \( \Delta J \) is calculated instead of \( J_R \), where \( \Delta J \) is defined simply as the difference of \( J_{\text{max}} \) and \( J_{\text{min}} \). In Table 1 all of the tested cases are listed with their corresponding maximum load, R-ratio, moment, and \( \Delta J \). It is to be noticed that given the applied moment remains constant through the cyclic loading, the computed \( \Delta J \) corresponds to that of a single cycle.

| Stitching density | P max. | P min. | R-ratio | M max. | M min. | \( J_R \) max. | \( J_R \) min. | \( \Delta J \) |
|-------------------|--------|--------|---------|--------|--------|----------------|----------------|-----------|
| [gg]*             | [N]    | [N]    | [-]     | [N-m]  | [N-m]  | [N/m]          | [N/m]          | [N/m]     |
| 6                 | 500    | 50     | 0.1     | 42.5   | 4.3    | 109.2          | 1.1            | 108.1     |
|                   | 400    | 40     | 0.1     | 34.0   | 3.4    | 69.9           | 0.7            | 69.2      |
|                   | 350    | 35     | 0.1     | 29.8   | 3.0    | 53.5           | 0.5            | 53.0      |
| 6-2               | 400    | 40     | 0.1     | 34.0   | 3.4    | 69.9           | 0.7            | 69.2      |
|                   | 375    | 37.5   | 0.1     | 31.9   | 3.2    | 61.4           | 0.6            | 60.8      |
|                   | 385    | 38.5   | 0.1     | 32.7   | 3.3    | 64.7           | 0.6            | 64.1      |

* Number of stitches per inch

Readings from the first cycle and close to the last one are shown in Fig. 4. By using the markings in the figure as a reference it can be clearly observed how the crack has propagated from
cycle 1 to 22000. As previously mentioned several readings were carried out at each acquired picture to estimate the reading error. For all of the crack-tip measurements, the maximum standard deviation is 1.74 mm and the mean standard deviation is 0.19 mm.

![Figure 4](image)

**Figure 4.** Crack-tip growth for DCB under $P_{\text{max}} = 500\,\text{N}$ and constant 6 gg at, a) 1 cycle, and b) 22000 cycles

The crack growth as a function of the number of cycles is shown in Fig. 5a for different maximum loads of the constant stitching specimens. Note that the crack tip growth is tracked only during the cyclic loading, as such throughout the present paper the term crack growth refers to the growth due to cyclic loading. From Fig. 5a it is observed that as the load increases the crack growth rate increases. As the crack grows it can take up to two orders of magnitude more cycles for the case with a $P_{\text{max}} = 350\,\text{N}$ to reach the same crack length as the case with $P_{\text{max}} = 500\,\text{N}$. On the right side of Fig. 5, a similar plot shows the comparison of results from the DCBs made with different stitching density. From Fig. 5b, it can be noticed that for the same load (400 N, and 350 N) the constant stitching density specimens are more resilient to fracture than those with alternating stitching density. This observation is somehow expected as the constant 6 gg is more dense than the alternating 2-6 gg. This dependency on stitching density, however, contradicts the observations from Mouritz in [12], where it is concluded that fatigue is not dependent on stitching density.

![Figure 5](image)

**Figure 5.** Crack length vs number of cycles: a) different maximum load (constant stitching density), b) constant vs alternating stitching density

A plot of the Paris region (linear in a log-log plot) is shown in Fig. 6. From visual inspection of the crack growth, it was observed that once the crack reached about 1 mm length its growth
behave (close to) linear in a log-log plot. This value was used as a threshold for data to be included in the linear regressions shown in the plot.

![Graphs showing linear part of crack growth](image)

**Figure 6.** Linear part of the crack growth

The crack growth rate, \( da/dN \), versus \( \Delta J \) is shown in Fig. 7 for each of the studied cases. The crack growth rate is calculated using the 2 and 3-point secant method, and the scatter reduction method proposed by Zheng et al. in [13], however, the 3-point method was selected because it yielded the least amount of scatter. Historically, secant methods have shown to yield large scatter data [13], however, they are easily implemented for any test configuration where the crack growth and the number of cycles are monitored. For the case with the constant stitching density, the three different loads lie almost in the same line, which is expected given that they have the same R-ratio. In the case of the alternating stitching density, one of the data sets seems to deviate. With only three points it is hard to make assertions, however, a likely scenario is that the CGR from the point with \( P_{\text{max}} = 385 \text{N} \) is under-estimated as it shows a decrease from the previous point, which does not make sense physically. Linear regression is performed to fit the data in the Paris’ relation as shown in figure 7. The values of the obtained Paris’ constants are given in Table 2. Both configurations, constant and alternating stitching densities, present similar slopes (constant n), but the intersection constant C is affected (see Table 2).

![Table 2: Paris constants values](image)

| Stitching density \([gg]\) | \( \log(C) \) \([\text{mm}}_{\text{cycle}}/(\text{MPa} \cdot \sqrt{m})^n\) | n |
|---------------------------|-------------------------------------------------|---|
| 6                         | 4736.33                                         | 6.47 |
| 2 - 6                     | 3035.06                                         | 6.04 |

As it is common in DCB tests of composite materials with 0° interfaces, all of the specimens showed large scale fibre bridging (LSB). This made the reading of the FPZ more challenging, which is reflected by the measurements statistics. The maximum standard deviation and mean standard deviation were 4.25 mm and 0.53 mm respectively, for the measurements of the FPZ. Fig. 8 shows a measurement of FPZ. It should be mentioned that for some of the cases there were isolated fibre bridges that originated from the static load but remain virtually unchanged.
Figure 7. Crack growth rate (CGR) as a function of $\Delta J$ for constant and alternating stitching density during cyclic loading. This can be due to relatively small end openings. Because of the two-dimensionality of pictures, it is unclear if the observed isolated fibres are indeed isolated or there are more of these fibre across the width of the DCB. As such they are still considered as part of the FPZ.

Figure 8. Illustration of large scale fibre bridging (LSB) under cyclic loading

The length of the FPZ as a function of the number of cycles was normalised with the static FPZ length. As observed from both Fig. 9a and Fig. 9b the length of the FPZ increases in a similar way as the crack-tip does. For the case of constant stitching density at $P_{\text{max}} = 500 \text{N}$ an increase of up to 50% of the static FPZ is reached.
Figure 9. Normalised FPZ length a) constant stitching density, b) alternating stitching density

It can be observed that the bridging zone keeps increasing throughout the entire cycle range, which contradicts the hypothesis that the bridging zone would remain constant after reaching steady state grow [16]. However, it is important to acknowledge the difficulty of drawing conclusions from the FPZ readings without a meaningful identification of the fibre bridge zone that contributes to the cohesive traction force.

4. Conclusion
A series of DCB specimens made from constant and alternating stitching densities (6 gg and 6 gg- 2 gg respectively) were tested for static and cyclic loading with different maximum loads, but equal R-ratio. The loading was applied via constant end-moments with the same amplitude but opposite directions, i.e. pure mode I. The crack propagation is measured from pictures taken at different cycle intervals. A list of observations from the experiments is presented below.

- Contrary to previous findings [12], the stitching density was found to affect the cyclic (fatigue) fracture properties of the DCBs. More specifically, the tested DCB specimens with constant stitching density (6 gg) are more fracture-resistant under cyclic loading than those with alternating stitching density (2 gg- 6 gg).
- The stitching density is found to have an effect on the intersection of the crack growth rate curve, which is expressed by the Paris’ constant C. Little to no dependency is found on the slope described by the constant n.
- A curve relating to the crack growth rate and $\Delta J$ has been derived. This curve can be directly applied in the design and/or repair of composite structures subject to cyclic load.
- The length of the FPZ increases with the number of cycles for all of the cases.

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