FATIGUE DELAMINATION GROWTH ONSET OF TWO WOVEN LAMINATES

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Abstract

In this work the fatigue delamination growth onset of two woven laminates will be evaluated for different nesting/shifting values. Due to the importance of the fatigue property for structural design, mode I fracture fatigue test is applied to the materials. The analysed woven composites are manufactured using the same resin-reinforcement and same architecture, but having different tow size (3K/12K). The material is a carbon fibre reinforced woven laminate made of 2/2 twill woven layers and it is manufacturated from prepeg sheet layers in an autoclave. Three different shifting/nesting configurations are applied to the material at the fracture surface: zero shifting, middle shifting and maximum shifting. In a previous work, static mode I tests showed considerable differences between the fracture toughness of the materials. In contrast, all materials show a similar behaviour for normalised fatigue onset values.

1. Introduction

Nowadays dynamic requirements for composite applications are highly important when designing a new component. From the safety point of view the delamination threshold value, below which no fatigue crack growth occurs, might be a design parameter to prevent failure. The growth of delaminated areas creates a loss of stiffness that can lead to the collapse of the component. The S-N curve (S for the cyclic stress range; N is the number of cycles to failure) is obtained testing a series of samples to failure at various stress ranges. In the recent years fatigue analyses are increasing due to the importance of this characteristic of the composite material. Most of the works are focused on UD materials and there is a lack of work concerning multilaminates or textiles. Peng [1] studied the mode I fatigue delamination growth of multidirectional laminates. He concluded that fatigue threshold is almost proportional to the fracture toughness of the material (~28%) for any interface orientation. Tay [2] resumed the developments in the analysis of static and dynamic delamination fracture. He defined as a typical value for the onset of delamination growth about a half or a third of the static value of fracture toughness. Brunner [3] defined the requirements for the characterization of fatigue delamination propagation in mode I. In a round robin exercise between three laboratories he proposed to use DCB specimens with displacement control and R value of 0,1. Different test frequencies did not show differences on the results (5Hz-10Hz).

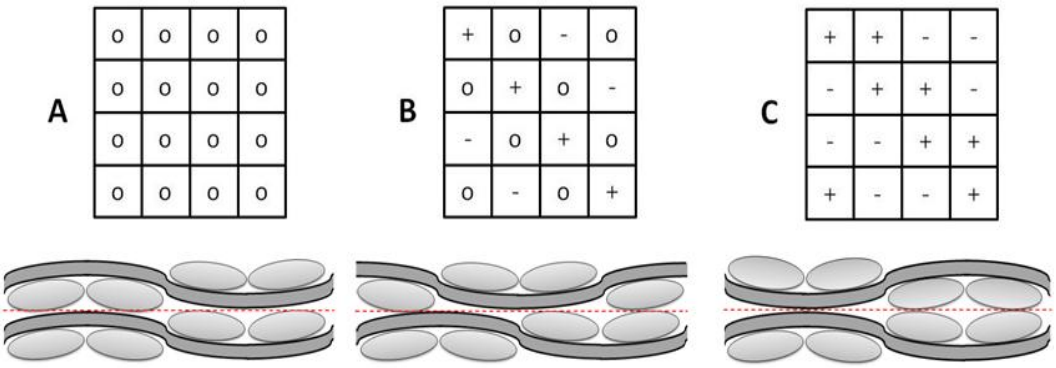
Argüelles [4] tested in mode I fatigue 5 specimens made of UD carbon fibre reinforced epoxy material. Onset was determined visually and a frequency of 3Hz applied on the samples and an R value of 0.2. He defined the fatigue limit as the 50% of the critical fracture energy in mode I. He did not see differences on the fracture surfaces in static and fatigue. In another work Argüelles [5] compared two different matrix materials under mode I fatigue. Fatigue life curves were obtained for delamination initiation and no fatigue limit was observed for the analyzed materials; even with small energy levels the delamination takes place at very low propagation rates. For this reason a practical fatigue limit value was determined around 10^7 cycles (47% and 30% of the critical fracture toughness values). Chen [6] obtained a threshold value of $0.18G_{IC}$ for a T700 carbon/vinyl ester composite material. In this work the mode I fatigue threshold value is obtained for different woven composites and the shifting/nesting effect on the delamination growth onset is evaluated.

2. Material

The material for this research is a carbon fibre reinforced woven laminate made of 2/2 twill woven layers and it is manufacturated from prepeg sheet layers in an autoclave. The unit cell dimension for 12K is almost 3 times bigger than for 3K when dealing with the same thickness. Three different fracture surface configurations are manufactured controlling the shifting of the textile geometry between the middle layers in the material. The delaminated area´s configuration patterns are described in Figure 1. The symbols used for describing the configuration are related to the fibre angles between layers (Table 1).

Symbol	Fibre angle configuration in the adjacent layers (θ_1/θ_2)
o	0/90 or 90/0
+	0/0
-	90/90

Table 1. Relation between symbols and fiber angle configuration between layers.



o	o	o	o
o	o	o	o
o	o	o	o
o	o	o	o

+	o	-	o
o	+	o	-
-	o	+	o
o	-	o	+

+	+	-	-
-	+	+	-
-	-	+	+
+	-	-	+

Figure 1. Three configurations manufactured on the delaminated surface.

2. Double cantilever beam (DCB) fatigue test

2.1. Test procedure

In the fatigue delamination growth plot (Figure 2) three different regions can be identified, the threshold (without delamination), a stable crack propagation zone and a catastrophic failure in a single load cycle (unstable rapid growth).

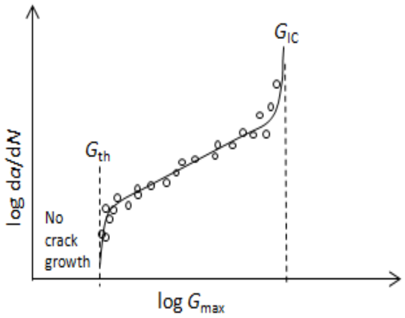


Figure 2: Fatigue delamination growth rate

There is no standard for textiles or multi directional laminates for fatigue delamination growth onset. This is the reason why this research is based on the standard D6115 for UD fibre reinforced polymer matrix composites [7]. This standard is used for obtaining the fatigue onset and consequently the S/N curve. The tests are done in a DCB set-up with displacement control. Constant opening amplitude (3mm) is applied to the samples at different G levels at a frequency rate of 5Hz. The R ratio between the minimum and maximum peak displacement is 0,1. An initial pre-crack is needed to avoid previously created any surface condition that may distort the fatigue onset result. During the test load and displacement of the opening device is recorded. The D6115 standard defines three methods for defining the cycle number when the delamination starts:

i. Number of cycles when crack start to open observed visually,
ii. Number of cycles when the compliance increases 1%
iii. Number of cycles when the compliance increases 5%.

The first method is not easy to measure, as the sample is dynamically opened; visual definition of crack front is difficult to define. It can overestimate the number of cycles needed for crack initiation, because the crack is already propagated before the crack front is visually observed. The increase of 1% of the compliance is also a small change to be measured, the noise in the data can lead to a non-real value. In consequence, the 5% of compliance increase is defined as the method used for measuring crack initiation.

The applied a_0 length is responsible for the maximum fracture toughness value applied on the sample (at the same maximum displacement value). Changing the initial crack length, the required maximum fracture toughness is obtained having the same opening displacement values (3-0.3mm). From the required G value is calculated the initial fracture length applied to the sample (1).

$$G_{Imax} = \frac{3P_{max}\delta_{max}}{2b(a+|\Delta|_{av})} \qquad (1)$$

$$a = a_0 \qquad (2)$$

The a value is a_0 (2), and the effective delamination extension is defined as the average value of $|\Delta|_{av}$ calculated from all static mode I tests carried out in a previous work [9] using the D5528 Standard [8] (table 2).

	Average value of $|\Delta|_{av}$ [mm]
3K A configuration	3,47
3K B configuration	4,3
3K C configuration	4,15
12K A configuration	3,2
12K B configuration	3,63
12K C configuration	3,92

Table 2. Effective delamination extension (average value of 5 samples per material type).

The test is performed at different G levels in order to obtain an overall overview of the S/N curve for the delamination onset. As the number of cycles is increasing, the maximum fracture energy required for delamination initiation decreases from the static fracture toughness value to the fracture threshold value G_{th} (Figure 3).

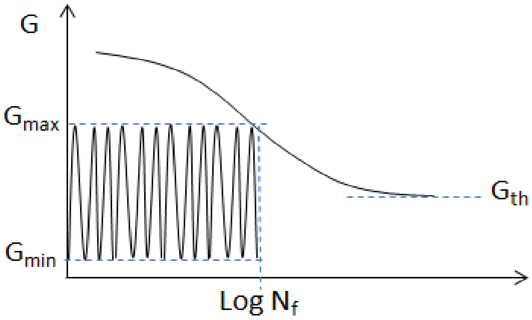


Figure 3. Fracture threshold value G_{th} in a S/N curve

One of the biggest difficulties on long-term tests is the data treatment: the sampling frequency is 1000 Hz, and for tests were the required cycle number is large, the data recording is non-feasible. For this reason, one second is recorded (5 cycles) every ten seconds, reducing the amount of recorded data drastically. Displacement and load data must be filtered in order to obtain a smooth curve (otherwise small noise peaks are recorded). The compliance is calculated using two methods:

a) Average values for maximum loads and displacement is calculated (from the recorded second). The compliance is obtained dividing the maximum displacement and load (3).

$$C = \frac{\delta_{max}}{F_{max}} \qquad (3)$$

b) The punctual compliance is calculated at the unloading linear zone (from the recorded second). The average slope is calculated.

The continuous compliance is afterwards plotted versus number of cycles (one point is obtained every 50 cycles). In order to reduce the noise appearing on the compliance data, moving average method is used for filtering the data. The number of cycles required for the onset of the crack propagation at the fracture energy level applied is afterwards defined when the compliance increases 5%. The results obtained using method a) or b) do not differ much. In this work results from b) method are shown.

2.2. Results

For each material 8-10 tests are performed at different levels. In figure 3 are plotted the results for all tests (different unit cell size and configurations). As the 12K material has higher fracture toughness values than 3K, it is difficult to obtain a conclusion from the S/N curve with G_{Imax} absolute values. In order to normalize the results (figure 4), the maximum fracture toughness values are divided by the static fracture toughness initiation value (G_{ICini}) obtained in a previous work [9] (table 3). The initial planning was to perform 3 tests at 3 different levels per material type. The problem at this point is that even applying the same initial crack length to the samples (for the same unit cell size and configuration) the obtained load is different (opening of 3mm), and consequently the maximum G_{Imax} value is also different. This is the reason why most of the obtained data points are randomly distributed and they are not at the same fracture toughness percentage.

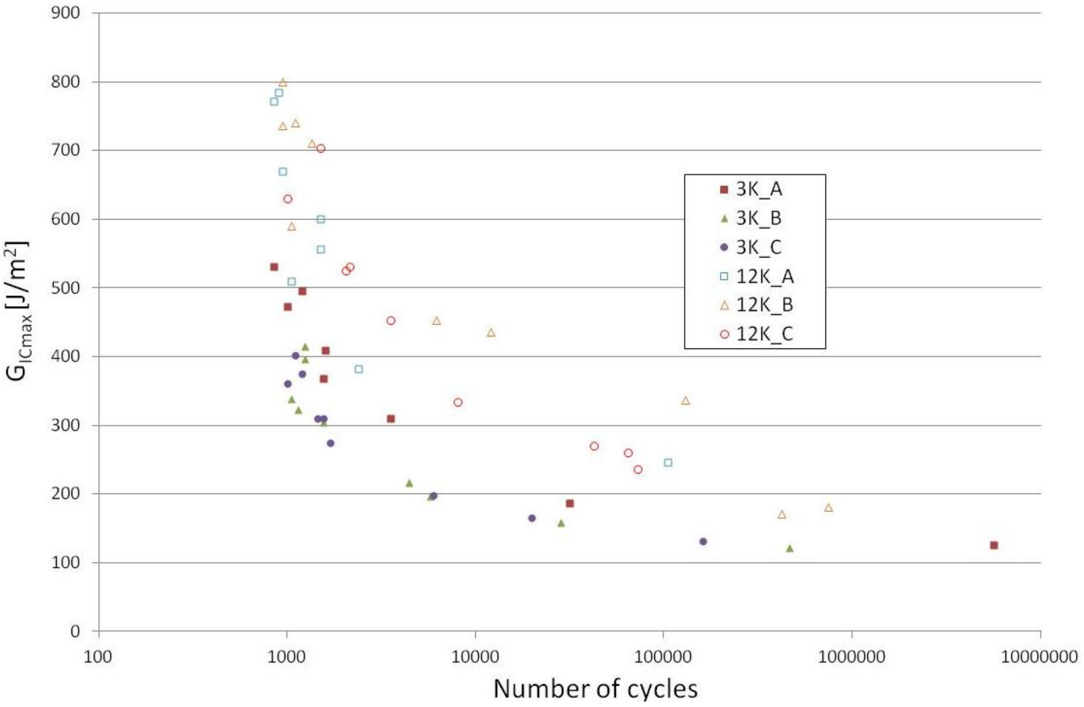


Figure 3. S/N diagram for 6 different material types (no-normalised values)

	3K_A	3K_B	3K_C	12K_A	12K_B	12K_C
Average G_{ICini} (J/m2)	584	561,7	488,6	874,2	858,7	699,4

Table 3. Initiation fracture toughness from DCB static mode I tests.

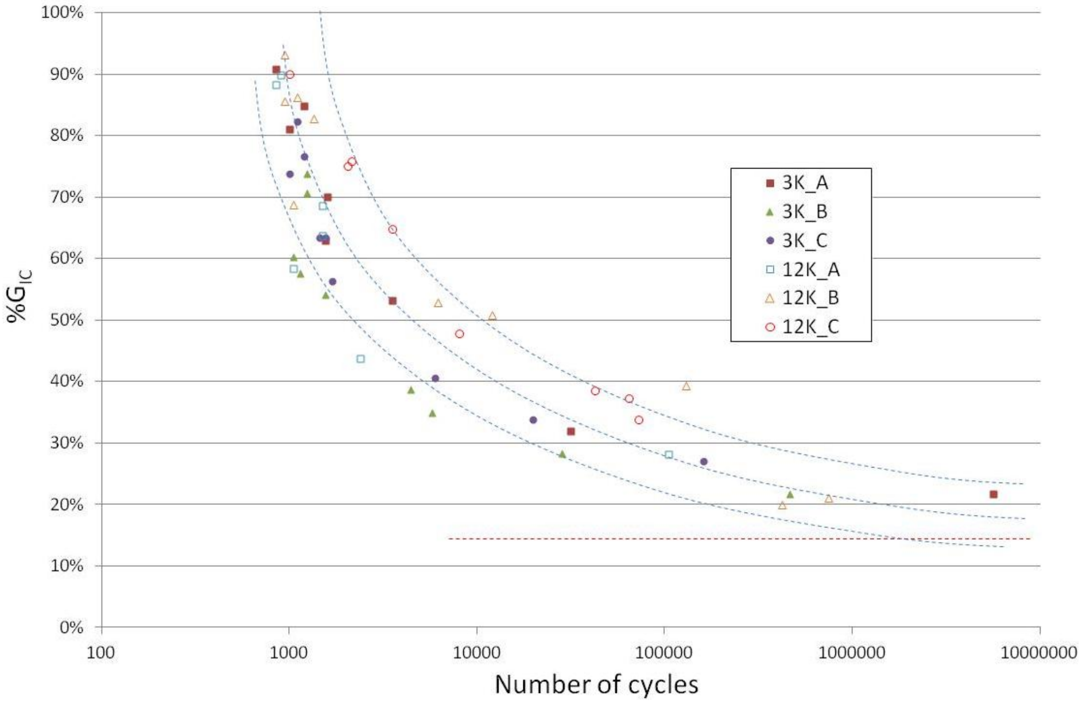


Figure 4. S/N diagram for 6 different material types (normalised values)

3. Conclusions

Fatigue delamination growth onset S/N curve is obtained for two woven laminates with different fracture configurations. A previous work showed differences on the static mode I fracture tests between unit cell sizes (static mode I fracture toughness values for 12K are almost twice than for 3K) and also between configurations (16-26% increment for A and B respect to C). These differences are not noticeable for fatigue growth onset values, where different materials follow the same trend.

The S/N curve using the absolute G_{Imax} values does not provide information about the behaviour of the material. The normalisation of the S/N curve respect to the static fracture toughness initiation value (G_{ICini}) is a better way of understanding the results. The general tendency in the normalised S/N diagram does not show significant differences between configurations (A/B/C) and unit cell sizes (3K/12K). The fatigue threshold (above 1.000.000 cycles) is close to 20%.

During the tests arose the difficulty of obtaining the same initial G_{Imax} value for the samples tested. Even applying the same initial crack length to the samples, the obtained load is different at the maximum opening displacement. The reason may be the static mode I fracture toughness variability in the samples (dispersion of static values was determined to be close to 10-12%).

Acknowledgments

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References

[1] L. Peng, J. Zhang, L. Zhao, R. Bao, H. Yang, and B. Fei, Mode I delamination growth of multidirectional composite laminates under fatigue loading, *Journal of composite materials*, vol. 45, p. 14, 2011.
[2] T. Tay, Characterization and analysis of delamination fracture in composites: An overview of developments from 1990 to 2001, *Applied Mechanics Reviews*, vol. 58, p. 31, 2003.
[3] A. Brunner, N. Murphy, and G. Pinter, Development of a standardized procedure for the characterization of interlaminar delamination propagation in advanced composites under fatigue mode I loading conditions, *Engineeting Fracture Mechanics*, 2009.
[4] A. Argüelles, J. viña, A. F. Canteli, and J. Bonhomme, Fatigue delamination, initiation and growth under mode I and mode II of fracture in a carbon-fiber epoxy composite, *Polymer composites*, vol. 31, p. 7, 2010.
[5] A. Argüelles, P. Coronado, A. Canteli, J. Viña, and J. Bonhomme, Using a statistical model for the analysis of the influence of the type of matrix carbon-epoxy composites on the fatigue delamination under modes I and II of fracture, *International Journal of Fatigue*, vol. 56, p. 6, 2013.
[6] H. Chen, K. Shivakumar, and F. Abali, Application of total fatigue life model to T700 carbon/vivyl ester composite, *Composites: Part B*, vol. 39, p. 6, 2008.
[7] D6115 Standard test method for mode I fatigue delamination growth onset of unidirectional fibre reinforced polymer-matrix composites, ed, 1997.
[8] D5528 Standard test method for mode I interlaminar fracture toughness of unidirectional in *D 5528*, ed, 1994.
[9] M. Olave, L. Aretxabaleta, D. Vandepitte, S.V. Lomov, Modeling of nesting effect on the delaminated surface for woven structures, *15th European Conference on composite materials*, Venice, 2012