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Fatigue delamination experiments on GFRP and CFRP specimens under single and mixed fracture modes

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Abstract

This paper deals with the experimental analysis of the delamination phenomena in composite materials under different loading conditions. Quasi-static and fatigue tests are performed on specimens made of glass-fibre (GFRP) and carbon-fibre (CFRP) reinforced plastic. In particular, experiments have been carried out under single fracture modes I and II (using standard DCB and ENF test configurations) and mixed modes I+II (using the MMB test configuration) with several mode mixtures. Results obtained for the two materials have been compared paying attention on the relationship between the parameters that describe the fatigue behaviour and the mode mixture acting during the crack propagation.

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1. Introduction

Among the several damage mechanisms of long-fibre composite materials, delamination is one of those that mostly draws the researcher's attention. Considering only plane cases, delamination can involve two fracture modes as: opening (mode I) and sliding (mode II); mixed modes I+II cases can be also present. The case of crack propagation under quasi-static loads (when the applied load increases monotonically very slowly) has been studied by several authors, both for single fracture modes and for mixed mode. A detailed formulation on the test coupons commonly used in experiments can be found in [1] and [2]. Single modes I and II are usually obtained with the Double Cantilever Beam (DCB) test and

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the End Notched Flexural (ENF) test [3], whereas, for the mixed mode I+II there are different test configurations [4] (see fig. 1).

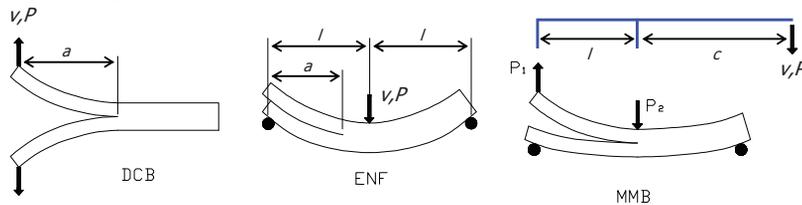


Fig. 1. Test configurations for single and mixed mode delamination

The Mixed Mode Bending (MMB) test [5-7] is the super-position of the DCB and the ENF tests and permits a fast change of percentage of mode I and mode II by a simple variation of the lever length c .

In quasi-static condition, crack propagates under single fracture modes when the Strain Energy Release Rate (SERR), G , equals its critical value (the interlaminar fracture toughness) G_c . This critical value is a material property and can be different for mode I and for mode II. It has been noted [8] that the critical SERR depends on the mode mixture $\phi = G_{II}/G$ (where G is the sum of G_I and G_{II}) and different criteria have been proposed to model the material fracture behaviour versus the mode mixture ϕ . In [8] different models are compared and applied to experimental results on a carbon/epoxy material.

In general, the fatigue delamination of composites, caused by the cyclic application of loads, can be described with the Paris approach, where the condition of a stable crack growth can be obtained when the instant SERR is greater than a threshold value and lower than the fracture toughness; under this hypothesis, the crack growth rate can be described with a power law function.

Fatigue tests on different composite materials have been performed in [9] for single modes I and II and in [10,11], where the load ratio effect and the threshold values for the SERR have been studied. In particular, in [10] results for graphite/thermoplastic resin lead to very high values for the Paris constants, suggesting that, for this material, a threshold-based design is more realistic than a propagation-based one. Single and mixed mode cases have been studied in [12] by considering a graphite/epoxy composite; a non monotonic trend of the Paris parameters with the mode mixture was observed. In [13] the effect of the temperature has been also verified for the same material and it has been proven that the crack growth rate increases with the temperature.

Semi-empirical monotonic models have been proposed in [14] and [15] to correlate the Paris parameters to the mode mixture ϕ , on the basis of experimental results on different materials. In [15] several mode mixtures have been analysed for glass/epoxy composites; the model fits quite well the peculiar behaviour of the tested composite, but no tests have been carried out by the authors on different materials. In [16] three values of the mode mixture parameter ϕ (0, 0.5 and 1) have been studied for carbon/epoxy material; although the non-monotonic model proposed to relate ϕ with the Paris parameters can be considered of general validity, it is based on very few experimental data.

In this work experiments of fatigue crack propagation on unidirectional GFRP and CFRP have been performed under single and mixed fracture modes. Preliminary quasi-static tests have been accomplished to calculate the fracture toughness of the materials. For the analysed material, the accordance between the monotonic and non monotonic criteria with the experimental results, has been verified.

2. Material tested

Two composite material plates have been manufactured by using the same epoxy resin: a unidirectional GFRP and a unidirectional CFRP. To create a pre-crack in the specimens, a short strip of

anti-adhesive has been stacked in the mid-thickness of the plates. Specimens for material characterization have been cut from the plate and tests have been carried out with an electro-mechanical testing machine with a 20 kN capacity load cell, under displacement control. Longitudinal elastic moduli for the two composite materials are: $E_{11} = 21$ GPa (for GFRP) and $E_{11} = 110$ GPa (for CFRP).

Specimens for delamination tests have been machined from the composite plate following the indications of the standard ASTM D5528. Width of the specimens is the same for all the tests performed in this work. In particular, a width $B_w = 20$ mm has been measured. Thickness is slightly different for the two materials: for the GFRP the total thickness is $2h = 4.7$ mm, for the CFRP is $2h = 4.3$ mm.

3. Quasi-static tests

Quasi-static delamination tests have been performed with an electro-mechanical testing machine mounting a 2 kN capacity load cell, under displacement control. The displacement, v , of the cross-head and the load, P , measured by the load cell have been recorded. The crack length, a , has been evaluated by optical observation of digital photos of the lateral face of the specimen taken with a high resolution Nikon camera equipped with a macro lens.

3.1. Data reduction

Fig. 2 shows the load-displacement curves for DCB, ENF and MMB tests performed under monotonic loads on representative specimens, only for CFRP for sake of concision.

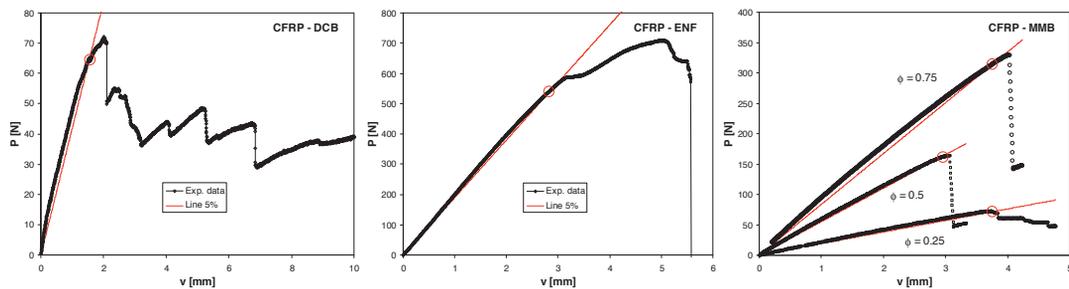


Fig. 2. Load vs. displacement diagrams of CFRP specimens during quasi-static delamination tests

Simplified and more efficient data reduction theories [2-6] can be found in literature to obtain the Strain Energy Release Rate from the recorded data. Taking into account spurious phenomena like rotations of the arms in correspondence of the crack tip, or shear deformations, the data reduction theory suggested in [12] is adopted. In this theory, the opening and shear components of the total strain energy released can be found, respectively, (for DCB, ENF and MMB) via the relationships:

$$G_I = \frac{P_I^2(a + \Delta)^2}{B_w E_L I_H} \quad \text{and} \quad G_{II} = \frac{3P_{II}^2 a^2}{64B_w E_L I_H} \left(1 + \frac{E_L h^2}{9K G_{LT} a^2} \right) \quad (1)$$

where I_H is the moment of inertia of half-thickness of the specimen, Δ is a correction factor of the crack length a , $K = 5/6$ is the shear factor.

Following the generalised power criterion proposed in [8], the equation that describes the resistance of a material under mixed mode is:

$$\left(\frac{G_{IC}^\phi}{G_{IC}} \right)^\alpha + \left(\frac{G_{IIC}^\phi}{G_{IIC}} \right)^\beta = 1 \quad (2)$$

In fig. 3 the experimental points are drawn together with the equation (2) obtained by the best-fitting procedure implemented in Matlab® environment. It is seen that a linear resistance criterion ($\alpha=\beta=1$) works better for the GFRP. For the CFRP the best fitting procedure has returned $\alpha=1.34$ and $\beta=1.49$.

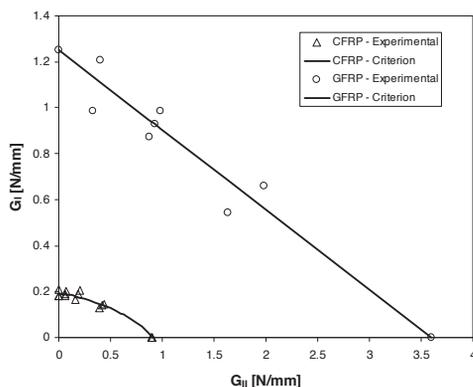


Fig. 3. Fracture domains of GFRP and CFRP materials.

4. Fatigue tests

Fatigue tests have been carried out by using a MTS servo-hydraulic testing machine, equipped with a in-house made 1 kN load cell. Both displacement and load control have been used to carry out the experiments. Similarly to quasi-static tests, the crack length is measured via optical observation of high resolution digital photos. Typical loading frequency was 2 Hz. Mixed mode fatigue tests have been performed with the MMB test. A constant load ratio $R = P_{min}/P_{max} = 0.1$ was adopted. All the output files given by the MTS software have been post-processed in Matlab® environment.

DCB and ENF fatigue tests have been carried out under load control. In order to obtain a wide interval of variation for the SERR, specimens were analysed with different initial crack lengths and/or under different load levels. For both the DCB and the ENF test under load control, the crack rate increases with cycles up to sudden failure in proximity of the critical value of the static toughness G_c . MMB fatigue tests have been performed under displacement control because of the complexity of the kinematics of the loading system.

To plot the fatigue diagrams (da/dN vs. G_{max}) the crack length with cycles, $a(N)$, and the maximum load with cycles, $P_{max}(N)$, have been recorded; the crack length is obtained from the digital photos and the load is given by the testing machine software. The experimental data of the crack length are fitted with power or exponential curves and the derivative da/dN has been calculated analytically from the fitting curve. The instant value of G_{max} is evaluated from the load, $P_{max}(N)$, and the current crack length, $a(N)$, via equations (1).

In fig. 4 the crack growth rate is plotted versus the maximum value of the total SERR only for the tests performed on CFRP specimens (for sake of concision). The Paris power law $da/dN = B(G_{max})^m$ has been used to interpolate the data. In some cases when G_{max} approaches to the static toughness G_c the curve becomes too steep; these points have been excluded from the interpolation procedure.

Parameters B and m can be related to the mode mixture by using the curve that fits the experimental data. Due to the particular distribution of the points in the diagrams, a quadratic curve can be used for both parameters. Three constants must be fixed for the curve $B(\phi)$ and for the curve $m(\phi)$ for each material.

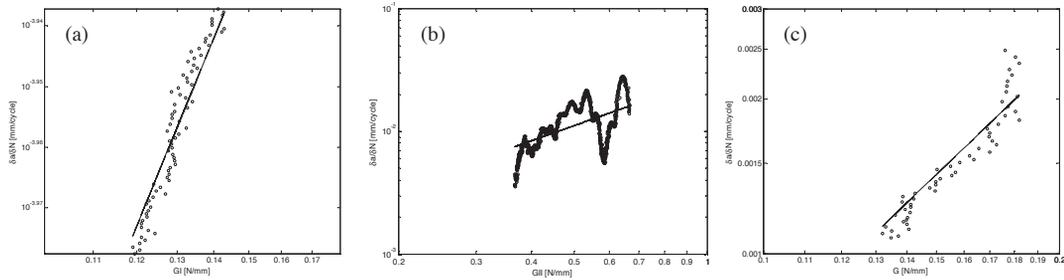


Fig. 4. Crack growth rate vs. Strain energy diagrams of CFRP specimens during fatigue delamination tests, (a) mode I, (b) mode II, (c) mixed mode $\phi = 0.75$.

The curves are expressed as follows:

$$\ln[B(\phi)] = -k_B \phi^2 + [\ln(B_{II}) - \ln(B_I) + k_B] \phi + \ln(B_I) \tag{3}$$

$$m(\phi) = -k_m \phi^2 + (m_{II} - m_I + k_m) \phi + m_I \tag{4}$$

It is to be noted that B_I , m_I and B_{II} , m_{II} are the intercept and the slope of the fatigue plots for single mode I and single mode II, respectively, whereas k_B and k_m are given by the best fitting procedure of data. This best fit procedure provides:

$k_B = -5.15E-3$, $k_m = 15.45$ for GFRP, and $k_B = 19.34$, $k_m = 6.98$ for CFRP.

The comparison between the two materials is shown in fig. 5, together with the curves obtained with the present model. The behaviour of the intercept B with the mode mixture for the two materials is different, while for the slope m a similar trend can be noticed.

For the GFRP, the intercept B increases monotonically with ϕ while the slope m has low values in correspondence of the single fracture modes and a maximum value in proximity of $\phi = 0.5$. For the CFRP, both Paris parameters have a maximum at intermediate values of ϕ .

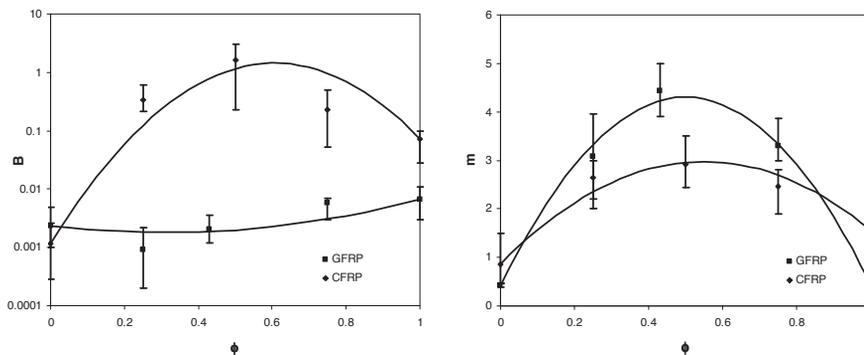


Fig. 5. Comparison of Paris parameters calculated for CFRP and GFRP, (left) intercept B , (right) slope m .

5. Conclusions

Quasi-static and fatigue delamination experiments have been performed in this work on glass fibre and carbon fibre reinforced composites. Materials has been manufactured using the same epoxy resin for the two materials. By means of different experimental configurations, single and mixed fracture modes

(opening, shearing and a mix of them) have been analysed under quasi-static and fatigue loading. Taking into account the experimental results obtained, the following remarks can be here summarised.

Fracture toughness values from quasi-static tests are quite different for these materials: the energy required for delamination of GFRP is definitely higher than that required for CFRP.

Also the variation of this energy with the mode mixture is different: a linear criterion can be used to describe the fracture condition of GFRP, while a generalised power criterion is needed for CFRP.

Fatigue Paris parameters (intercept and slope), that characterise the stable crack propagations, depend on the mode mixture; in particular the experimental results show that for GFRP the intercept increases with the mode mixture whereas the slope takes a maximum near to $\phi = 0.5$ while for CFRP both the intercept and the slope have a maximum at intermediate values of ϕ .

A simple quadratic model can be used to describe this dependency, whereas other monotonic models found in literature fail when applied to the analysed materials.

Future developments of the work include the analysis of cases where the mode mixture changes during the crack propagation, in order to verify the quadratic interpolation model under more realistic loading conditions. Furthermore, a study on other composite materials is going to be performed to assess the role of fibres and matrix on the material behaviour under fatigue loading.

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