Energy based study of quasi-static delamination as a low cycle fatigue process

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Abstract: This work proposes to treat quasi-static mode I delamination growth of CFRP as a low-cycle fatigue process. To this end, mode I quasi-static and fatigue delamination tests were performed. An average physical Strain Energy Release Rate (SERR), derived from an energy balance, is used to characterize the energy released in crack extension. The physical SERR is then compared to the SERRs calculated by the ASTM standard, and the physical background of the standard is questioned. Furthermore, when normalizing the physical SERR for fatigue delamination by the one obtained for quasi-static crack extension, a stress ratio dependence is observed. This stress ratio effect is physically explained to be present due to the relation between quasi-static and fatigue loading at high stress ratios.

INTRODUCTION

Carbon Fibre Reinforced Polymers have become, due to their high specific strength and stiffness, a suitable option to build lighter and more damage tolerant aerospace structures [1]. However, their range of applications is limited by the poor interlaminar strength [2], which causes delamination to be the most frequently observed damage mode in CFRP structures [3]. Delaminations represent a crack-like discontinuity between the plies, and they propagate during the application of mechanical or thermal loads, or both [4], causing a reduction in the load bearing capacity of the structure. Therefore, several studies have been conducted to assess delamination growth in composites [1-3, 5-9].

The appropriate similitude parameter to be used to assess fatigue delamination is still under discussion [10]. While some authors use the maximum Strain Energy Release Rate (SERR) G_{max} [11], others prefer the SERR range $\Delta G = G_{max} - G_{min}$ [12] or even $\Delta\sqrt{G} = (\sqrt{G_{max}} - \sqrt{G_{min}})^2$ [13].

Amongst different propositions, some authors propose obtaining an actual physical SERR from measured data. The procedure is based on measuring, during a fatigue test, the crack length *a*, the crosshead displacement δ, the force *P* and the number of cycles *N*. With these data it is possible to obtain a graph plotting of *da/dN* versus *dU/dN*. This presentation of the data allows to obtain an average SERR over the cycle, G*, from the inverse of the slope of the curve, as defined in Eqn. 1, where *b* is the width of the specimen. This procedure is based on an energy balance analysis of the crack growth, and it accounts for the stress ratio in its definition, often collapsing fatigue curves to a narrow band for different stress ratios [14-17].

$$G^* = \frac{1}{b}\frac{dU/dN}{da/dN} = \frac{dU}{dA} \tag{1}$$

Although an ASTM standard has been published [18] to aid the assessment of quasi-static delamination growth, questions related to its physical background, to be discussed in the next section, still remain unanswered. Thus, given the successful use of a real physical SERR G* to characterize crack extensions under fatigue loading, how could this same similitude principle be used to assess quasi-static crack growth?

To answer this question this work proposes to analyse quasi-static data with the same procedure proposed in [15], described by Equation 1. A comparison between G* and the SERR calculated according to the ASTM standard for quasi-static delamination is presented, and the differences are highlighted. Normalization of the data is proposed, relating fatigue and quasi-static delamination. Furthermore, the observation of a stress ratio effect in the physical SERR is discussed.

HYPOTHESES

Quasi-static delamination growth by ASTM D5528-01

The ASTM D5528-01 standard describes the determination of the opening mode I interlaminar fracture toughness of continuous fibre-reinforced composite materials. The Double Cantilever Beam (DCB) specimen is used and the test is limited to carbon fibre and glass fibre tape laminates with brittle and tough single-phase polymer matrices [18]. Three different values of SERR can be used as fracture toughness, according to this standard. The first is the fracture toughness at the point of deviation from linearity in the load-displacement curve, which will be referred to as G_{NL}. The second is the SERR at the point at which delamination is visually observed on the edge of the specimen, referred to in this work as G_{VIS}. Finally, the third value is the SERR at the point at which the compliance has increased 5% or the load has reached a maximum value, referred to as G_{CRIT}. Typically, G_{NL} is the smallest of these three values and it is used as a conservative approach, while G_{CRIT} is the largest value of SERR obtained through this standard.

It is notable the fact that none of these three definitions are correlated to the growth of the crack. The SERR is the strain energy released when a crack extends. However, these three parameters (G_{NL}, G_{VIS} and G_{CRIT}) are not calculated based on measured growth. They are artificial SERR values calculated when no crack extension has occurred yet. Thus, G_{NL}, G_{VIS} and G_{CRIT} have never been correlated to the creation of any crack surface or to the rate at which the crack extended.

Quasi-static data treated as low-cycle fatigue

An illustration of a load-displacement graph plotting for a typical mode I quasi-static test performed on a CFRP DCB specimen in displacement controlled conditions is shown in Figure 1. Point 1 illustrates the conditions just before the test starts. When the measured force *P* increases and reaches a critical value, Point 2, crack extension occurs, which under displacement control conditions causes a decrease in the measured force. The system is thus taken to Point 3, due to the displacement rate imposed by the machine upon the test specimen. Because of the external work applied by the testing machine, the measured force increases once more. This is represented in the illustration by moving from Point 3 to Point 4. This incremental decrease in the measured force by crack extension and subsequent increase by the application of additional displacement to the specimen is repeated continuously in a gradual negative slope of the curve.

Therefore, the quasi static mode I delamination of CFRP DCB specimens seems to be well represented by a low-cycle fatigue process. For example, each drop and increase in force can be considered a cycle *N*, and a strain energy *U* can be associated with each *N*, as illustrated in Figure 1.

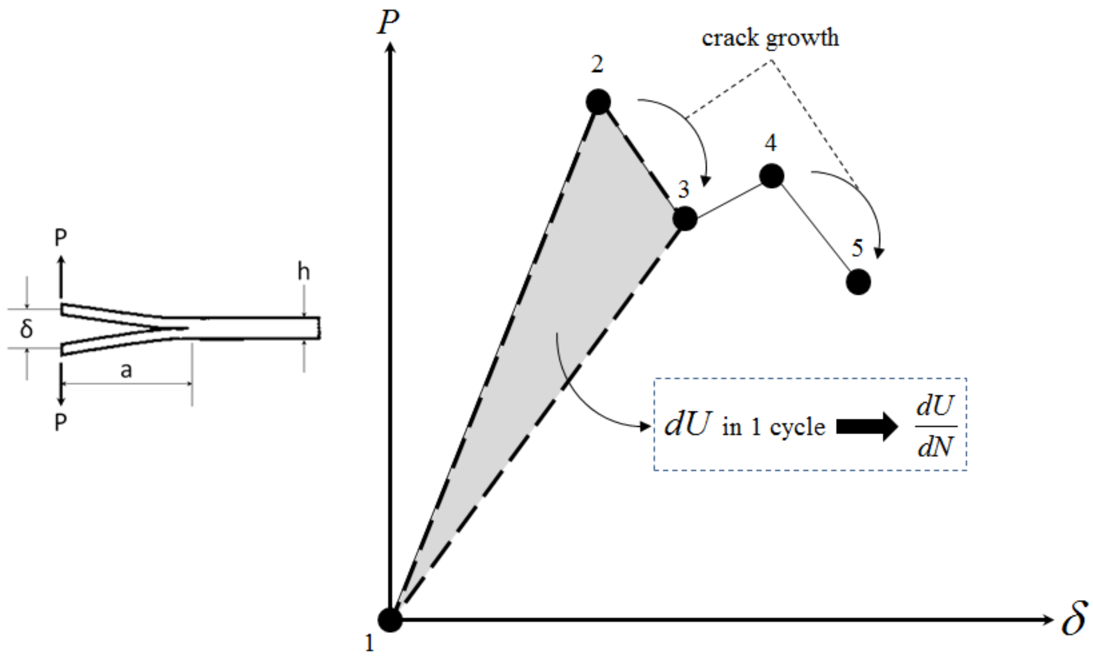

Figure 1. Illustration of a quasi-static force-displacement curve for a DCB CFRP specimen

The physical SERR: G*

Such as stated in the Introduction section, measuring the crack length *a*, the displacement δ, the force *P* and the number of cycles *N* allows to graph a plot between the crack growth rate and the change in strain energy with the number of cycles: *da/dN* versus *dU/dN*. Fatigue data has been shown to align linearly for CFRP mode I delamination in this type of presentation of data, under different stress ratios [14, 15].

If the fatigue data can be fit by a straight line in a linear scale, such as illustrated in Figure 2, the strain energy released by crack extension is given by Eqn. 1. Therefore, the energy released in crack extension can be characterized by a single physical parameter, the average SERR over the cycle, G*.

It is important to note the difference between G* and G_{NL}, G_{VIS} and G_{CRIT}. The parameters defined by the ASTM standard describe a theoretical and artificial SERR that is calculated when there is no crack extension. However, if no crack extension occurred, no energy was actually released. Thus, what do these values mean?

Meanwhile, G* is a physical parameter calculated from the crack extension itself. It is the average of the actual physical SERR.

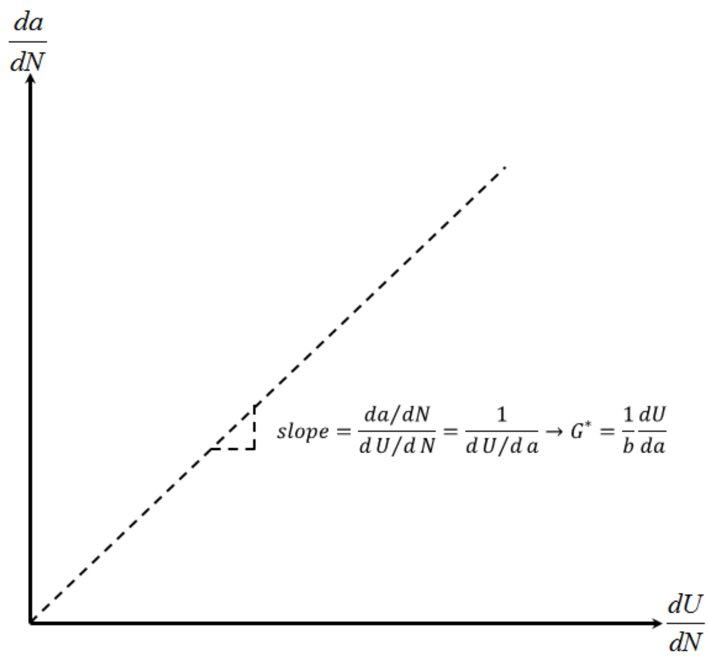

Figure 2. Obtaining a physical SERR from a *da/dN* versus *dU/dN* plot

When data are aligned along the same slope in the *da/dN* versus *dU/dN* plot, it means they have the same release of strain energy per crack increment, *dU/da*. Therefore, the same amount of energy dissipation corresponds to the same amount of crack surface created. In addition, since the composite material used in this study presents neither relevant plasticity nor other significant dissipation mechanisms, any curve fit to the data in the *da/dN* versus *dU/dN* plot must go through the origin, because it is deemed impossible to dissipate energy without extending a crack [19].

DATA INTEGRATION

Five CFRP DCB specimens were tested quasi-statically. All test specimens were manufactures from the same material batch (M30SC-150-DT 120-34 F) and the tests were reported in [14, 20]. Although the integration of the quasi-static data was thoroughly explained in [19], it is repeated here for convenience for the reader.

“Each of the five sets of quasi-static data was discretized in order to calculate *dU/dN*. This discretization was performed as explained in Figure 3 (a), in which each shaded area is a *dU* in one cycle. As the quasi-static data is being treated as low cycle fatigue, each shaded area in Figure 3 (a) can thus be considered a *dU/dN*.

As an outcome of this discretization, a cloud of points was obtained when plotting the results in terms of *da/dN* versus *dU/dN*. This is shown by the blue markers in Figure 4. The average of these points, in *da/dN* and *dU/dN*, resulted in one point in the graph plotting *da/dN* versus *dU/dN*, shown by the red marker in Figure 4. However, this result is not enough to enable full understanding of the trend of *dU/da* with respect to an increasing *da/dN*, because a single data point contains no information on the slope. In which fashion would this point move if *da/dN* increased or decreased? Thus, new ways of analysing the same data with different discretization methods were necessary. Therefore, in order to analyse the trend of the data properly, each of the five sets of data was discretized in four different ways. The data was discretized to different levels, considering different number of cycles for the same crack growth, such as illustrated in Figure 3 (a) to (d). In Figure 3 (a), for instance, 3 cycles were considered, and thus 3 values of *dU/dN* and *da/dN* were calculated. Meanwhile, the exact same crack was considered to be grown in 6 cycles in Figure 3 (b), resulting in 6 values of *dU/dN* and *da/dN*. In each of these integrations what differs is the step *da* in crack growth that is used to calculate *dU/dN*. In this illustration, each shaded area limited by dashed lines represents a *dU/dN*. In Figure 3 (b) and (c), for example, the steps *da* are smaller than in Figure 3 (a). Meanwhile, in Figure 3 (d) the step *da* is bigger than in Figure 3 (a).

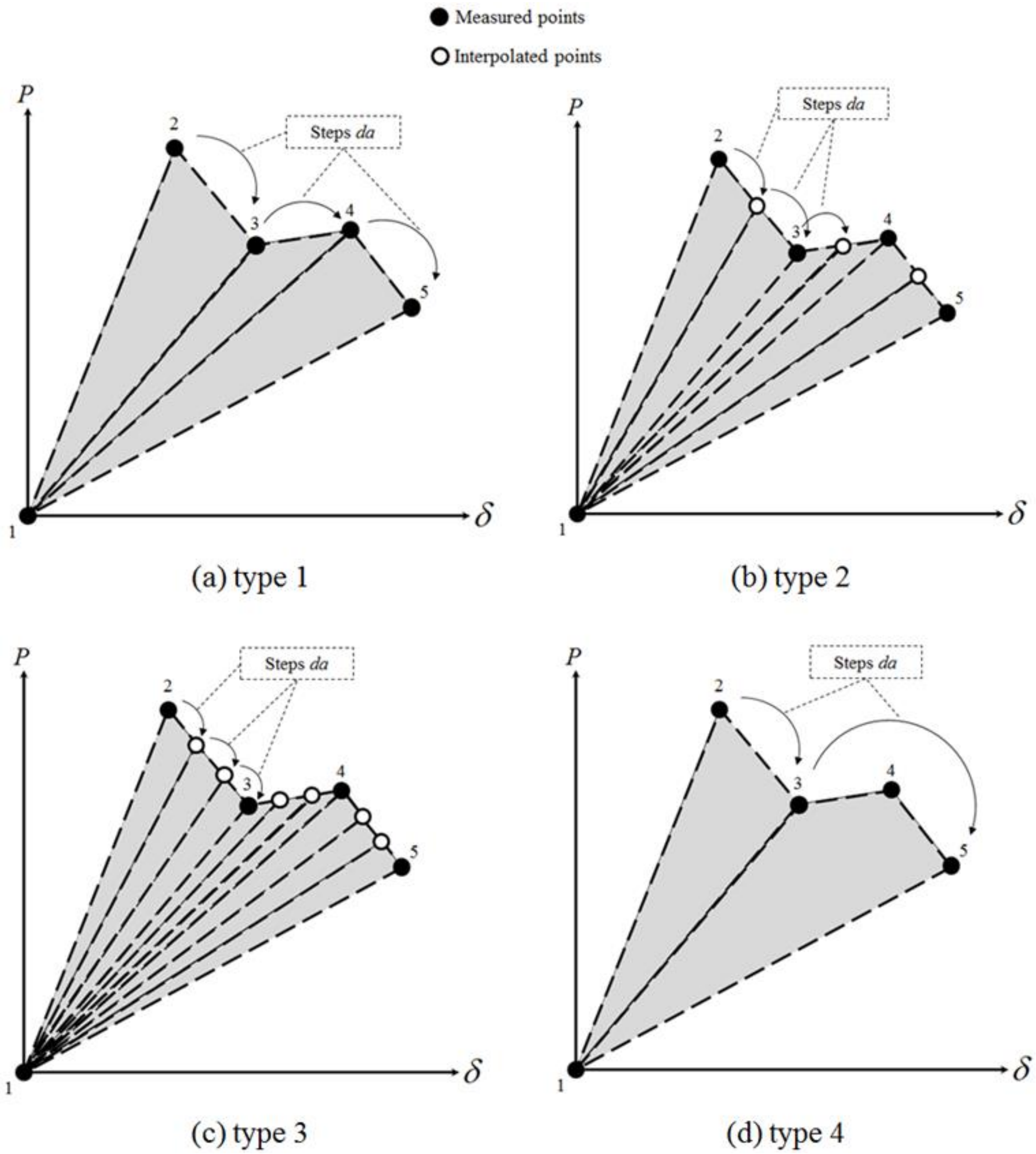

Figure 3. Discretization of the quasi-static data as low-cycle fatigue [19]

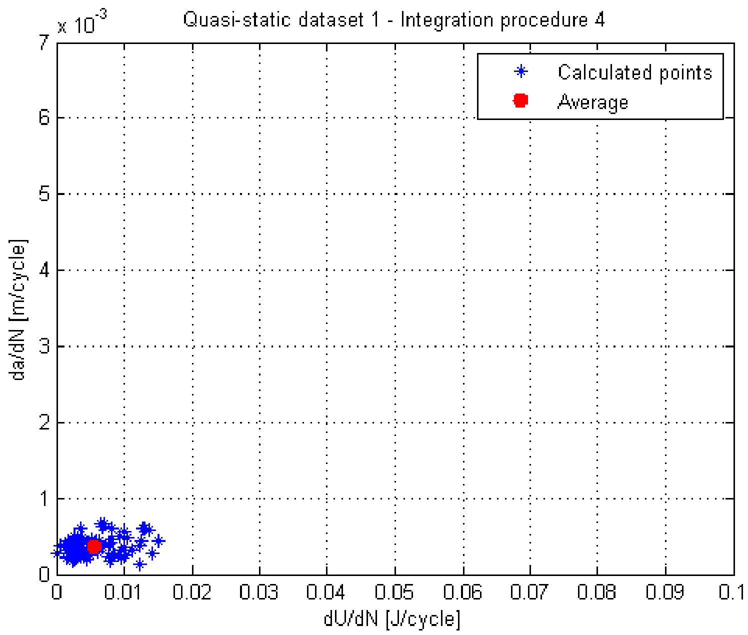

Figure 4. Quasi-static dataset 1: the blue markers show the points that resulted from the integration procedure 4, and the red marker shows the average [19]

It is important to note that, although each set of data is discretized with four different procedures, each set still represents the same crack extension. In other words, the fracture surface and the energy spent in creating this fracture surface quasi-statically is the same, independently of the way *dU/dN* is calculated. This is observed by the fact that all integration procedures, for a given test specimen, yield the same value for the sum of individuals *dU/dN*. This can be easily observed in Figure 3: the sum of the shaded areas always results the same total area. This shows that the procedure is consistent, because the total energy spent in extending the crack is the same for a given dataset.

Therefore, the average values of *dU/dN* and *da/dN* were calculated with these four discretization procedures and plotted together. Data obtained from five specimens were discretized in four different increments, yielding 20 points in the *da/dN* versus *dU/dN* plot. These points were plotted together, and a linear regression was used to produce the best linear fit by the minimization of the sum of the square of the error. The result, presented in Figure 5, shows a good correlation (i.e. coefficient of determination R^2 = 0.9894). This graph shows that a quasi-static test can be analysed as low-cycle fatigue in a consistent way, and the SERR can be easily calculated from the slope of the linear fit, i.e. 1/(*dU/da*). Thus, quasi-static crack extension can consistently be considered as a special case of fatigue crack growth, is given by Eqn. 2” [19].

$$G^{*}_{quasi-static} = 611.6\ J/m^{2} \tag{2}$$

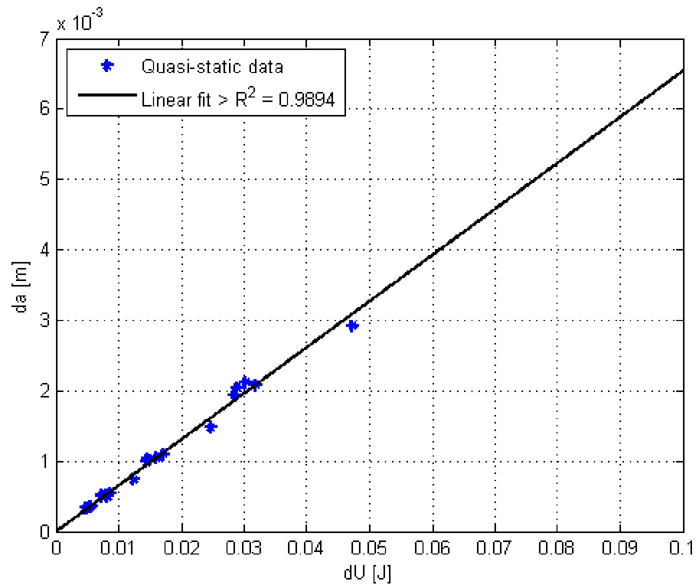

Figure 5. Linear fit through the average values of *da/dN* and *dU/dN* obtained from 5 quasi-static tests discretized in 4 different levels [19]

The values of G_{NL} and G_{CRIT} were calculated for each of the five test specimens according to the ASTM D5528-01 standard [18]. The average value was then considered for comparison, and the results are presented in Table I. One should note the large difference between the values calculated through the ASTM standard and the physical SERR G*. This difference is due to the fact that G_{NL} and G_{CRIT} are artificial values for the SERR that are not calculated from the measured crack growth, as discussed in the "Quasi-static delamination growth by ASTM D5528-01" section. Meanwhile, G* is related to the crack extension that occurred during the quasi-static fracture, representing the average of the actual strain energy released during crack extension.

If G* is the real physical SERR, as it is calculated directly from measured crack extension, then G_{NL} and G_{CRIT} have no physical meaning, as they are not based on physical principles of crack extension and energy balance. Furthermore, using such artificial parameters to assess delamination growth can be misleading and it does not lead to a physical understanding of the phenomenon.

Table I. Comparison between the physical SERR and the SERRs obtained by the ASTM standard

G* [J/m^2]	G_{NL} [J/m^2]	G_{CRIT} [J/m^2]	G_{NL}/G*	G_{CRIT}/G*
611.60	244.02	423.03	0.40	0.71

FATIGUE AND QUASI-STATIC DELAMINATION: NORMALIZATION PROCESS

Fatigue tests were performed at three stress ratios (0.1, 0.5 and 0.7) in DCB specimens made from the same material and with the same dimensions as the ones used in quasi-static tests. These are reported in [14], and the relation between the actual strain energy released in fatigue and in quasi-static delamination is thoroughly discussed in [19].

The fatigue data obtained at three different stress ratios align linearly in a *da/dN* versus *dU/dN* plot along a narrow band [14]. A small stress ratio is still distinguishable, but it is possible to fit the fatigue data with a straight line and a good coefficient of determination (R^2 = 0.8756), shown in Figure 6. At low values of *da/dN*, however, this linear fit correlates to a lesser extent with the measured data points. This occurs due to the fact that, at this crack growth rate, the dissipation mechanisms observed in the fracture surfaces consum less energy, as explained in [19].

From the slope of this linear curve fit it is possible to calculate the average physical strain energy released during fatigue delamination growth, which is $G^*_{Fatigue}$ = 289.70 J/m^2. As mentioned before, this is the average value for all the data points obtained in fatigue tests. However, it is observed in the stress ratio effect in Figure 6 that the SERR changes with the crack growth rate, and the use of an average SERR per test is incorrect. In fact, the physical SERR should be calculated at any instant during the test when the crack extends. This is performed calculating the value of $G^*_{Fatigue}$ for each data point obtained during the fatigue test. The procedure consists in plotting a straight line from the origin, because it is deemed impossible to dissipate energy without extending a crack for this material system, to each measured point. From the slope of this straight line the physical SERR can be obtained for that particular measured data.

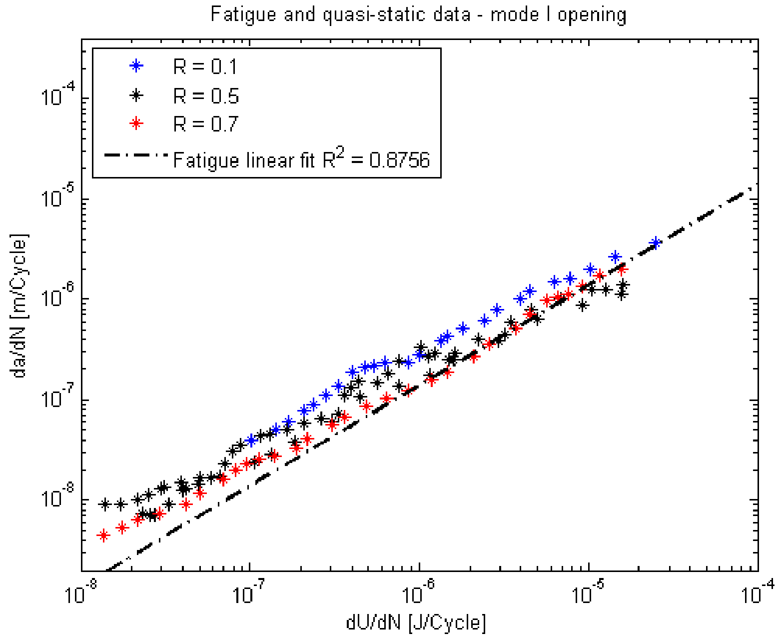

Figure 6. Fatigue data with linear fit

Normalizing the value of $G^*_{Fatigue}$ for each fatigue data point by the quasi-static physical SERR is then possible, and the result is presented in Figure 7. This graph allows the better observation of what appears to be a stress ratio effect. Figure 7 shows that the extension of a crack by the same rate *da/dN* requires higher energy for higher stress ratios. In fact, the presence of a stress ratio effect can be explained by the relation between fatigue and quasi-static fracture. Growing a crack in fatigue is more efficient than growing it quasi-statically, because requires less energy to extend the same unit surface *dA*. The higher the stress ratio, the closer to the quasi-static condition the load is, and therefore more energy is required for crack extension.

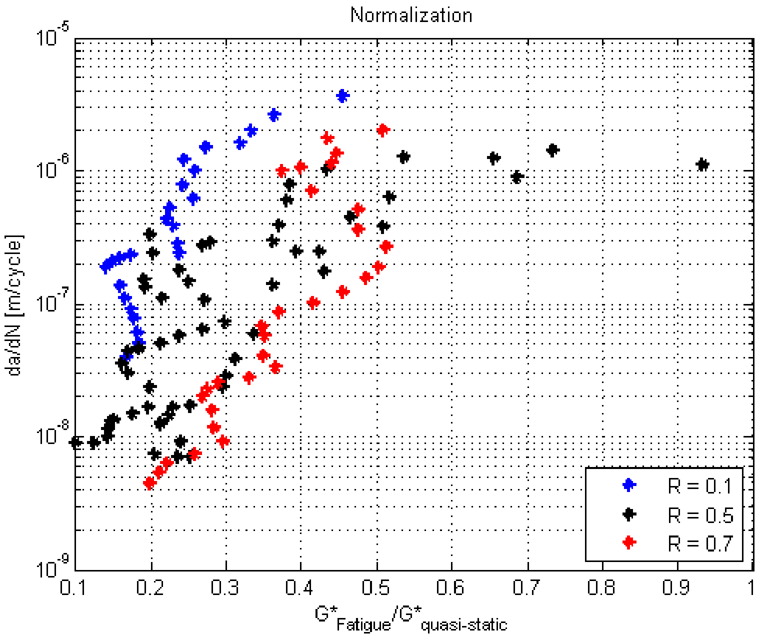

Figure 7. Normalization by the quasi-static SERR

Moreover, a reasonable scatter can be observed in Figure 7, mainly for R = 0.5. This is due to the limited dataset and to the fact that prior to the test the parameters that influence the results were not completely understood. New tests with more accurate measurement systems and better calibrated load cells are recommended.

CONCLUSIONS

Quasi-static mode I delamination data were considered as low-cycle fatigue data, discretized to different levels and characterized by a real physical SERR. The average SERR over the cycle, G*, can be used as the parameter to characterize crack extensions in both fatigue and quasi-static loading conditions, as it is obtained from a material characterization.

The experimentally obtained value of G* was compared to G_{NL} and G_{CRIT}, both obtained according to an ASTM standard. The difference between the results showed that the strain energy values calculated through the ASTM standard are artificial and over conservative. In addition, G_{NL} and G_{CRIT} do not equate the physical condition of crack extension. As G* is a physical value obtained from measured data, further research in this topic is recommended to solidify the use of this parameter to assess delamination growth.

When the physical SERR G* for the fatigue data was normalized by the quasi-static value of G*, a stress ratio dependence is clearly observed. This can be explained by the fact that, at higher stress ratios, the load condition is more similar to quasi-static loading, which requires more energy for crack extension.

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