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The relation between the strain energy release in fatigue and quasi-static crack growth

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ABSTRACT

This work proposes to use an average Strain Energy Release Rate (SERR) to characterise similarly fatigue and quasi-static delamination growth. Mode I quasi-static and fatigue tests were performed. The quasi-static crack extension was considered as a low-cycle fatigue process, discretized to different levels and correlated to the fatigue data. Fracture surfaces were analysed and damage mechanisms were related to average SERRs for each case. The strain energy released in crack extension showed to be dependent on the decohesion mechanisms, and it is demonstrated how the values of the SERR for fatigue and quasi-static loading can be linked through physical principles.

1. Introduction

The number of applications of Carbon Fibre Reinforced Polymers (CFRP) in aerospace structures is increasing significantly because of the necessity of lighter and, at the same time, more damage tolerant and durable structures. CFRP are attractive for aerospace applications because of their high specific strength and stiffness [1]. However, their application in primary structures is limited by the poor interlaminar strength [2], which causes delamination to be the most frequently observed damage mode in CFRP structures [3]. Therefore, several studies have been conducted to assess delamination growth in composite structures [1–11].

The appropriate similitude parameter that should be used for the assessment of fatigue delamination is still under discussion [12]. Some authors use the maximum Strain Energy Release Rate (SERR) G_{max} to characterise delamination under fatigue loading [13], while others prefer the SERR range $\Delta G = G_{max} - G_{min}$ [14] or even $\Delta\sqrt{G} = (\sqrt{G_{max}} - \sqrt{G_{min}})^2$ as a parameter that describes the similitude [10].

Amongst these propositions, some authors propose obtaining an actual SERR from measured data only, and not from a theoretical model. The procedure consists in measuring, during a fatigue test, the crack length a, the displacement δ, the force P and the number of cycles N. With these data it is possible to obtain a graph plotting da/dN versus dU/dN. In this presentation of the data, the SERR dU/dA is obtained from the inverse of the slope of the curve, defined by Eq. (1), where b is the width of the specimen. It is notable that this procedure is based on an energy balance, and it accounts for the stress ratio in its definition, often collapsing fatigue curves for different stress ratios [15–18].

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

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Nomenclature

A	delamination area (m^2)
a	delamination length (m)
b	width (m)
G	Strain Energy Release Rate (J/m^2)
G_{max}	Strain Energy Release Rate at maximum fatigue load (J/m^2)
G_{min}	Strain Energy Release Rate at minimum fatigue load (J/m^2)
G^*	average Strain Energy Release Rate over the cycle (J/m^2)
N	number of cycles
P	force (N)
U	strain energy (J)

Greek symbols

ΔG	Strain Energy Release Rate range (J/m^2)
δ	displacement (m)

Subscripts

crit	critical
max	maximum
min	minimum
on	onset

In general, fatigue and quasi-static delamination growth are evaluated with different methods. For quasi-static delamination growth, the SERR is calculated just before the crack propagates [19]. This value is generally referred to as the onset value G_{on}. Meanwhile, fatigue delamination is usually assessed through the relation of a SERR based parameter (G_{max}, ΔG or $\Delta\sqrt{G}$) with da/dN, or via delamination resistance curves [4–11,20]. Although several studies have performed both quasi-static and fatigue tests [2,21–25], a clear relation between what is done for both loading conditions does not seem to be available. Moreover, although the energy balance introduced by Griffith [26] proposed a release of strain energy per unit area of crack independently of the load, the SERR parameter that is used nowadays to assess crack extension seems to be regarded as dependent on the load type.

2. Problem statement

The question that arises is where do these quasi-static and fatigue SERR definitions meet? These different approaches to assess fatigue and quasi-static delamination complicate the establishment of a correlation between the energy released by crack growth in both loading conditions. Moreover, some authors [7] normalise the SERR used to characterise fatigue delamination data with a critical SERR calculated from quasi-static tests. This seems to imply that there is a straightforward correlation between the crack growth resistance in fatigue and in quasi-static loading. However, the exact nature of such correlation has not been established yet. Thus, the questions that need to be answered are: what are the differences in the energy dissipation in delamination growth in quasi-static and fatigue loading, and to what mechanisms should such differences be attributed?

For that reason it is proposed here to analyse the quasi-static data with the same procedure as proposed in [16], described by Eq. (1). Assessing both quasi-static and fatigue delamination data with the same procedure may shed light on how these parameters of similitude may correlate. Thus, the objective of this study is to correlate quasi-static and fatigue loading using identical energy balance principles. To this end, the difference in the energy released in both fatigue and quasi-static loading conditions is characterised and related to fracture surfaces observed with microscopy.

3. Hypotheses

3.1. Analysing quasi-static data as low-cycle fatigue data

A schematic load–displacement curve is shown in Fig. 1(a) for a typical mode I quasi-static test performed on a CFRP double cantilever beam (DCB) specimen in displacement controlled conditions, according to ASTM D5528-01 standard [19]. In this illustration, Point 1 represents the conditions just before the test starts. When the applied force P is increased and reaches a critical value, Point 2, crack growth occurs, which under displacement control condition causes a decrease in