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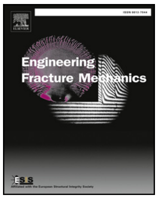

Using acoustic emission to understand fatigue crack growth within a single load cycle

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ABSTRACT

Current methods for prediction of fatigue crack growth are based on empirical correlations which do not take the crack growth behaviour within a single cycle into account. To improve these prediction methods, more understanding of the physical mechanisms of crack growth is required. In this research the acoustic emission technique was used to investigate the crack growth behaviour during a single fatigue cycle. It was found that crack growth can potentially occur both during loading and unloading, but only while the strain energy release rate is above a crack growth (CG) threshold value. The results suggest this CG threshold value is the same in both quasi-static and fatigue loading. Further work is necessary to fully understand the link between the received acoustic emission signals and the actual crack growth processes. Nevertheless, the paper shows the potential of acoustic emission to provide more insight into the physics of crack growth.

1. Introduction

In 1961 Paris and co-workers first introduced the idea that the stress intensity factor (SIF, K) could be used as a similitude parameter to describe fatigue crack growth (FCG) in metals [1]. Although this was considered quite a radical idea at first, it was soon found that the fatigue crack growth rate could indeed be correlated to the SIF range, ΔK, by means of a power-law [2,3]. This relationship has formed the basis for FCG predictions ever since.

Paris' relationship was not only found to work for metals, but was also adopted for fatigue delamination and crack growth in fibre-reinforced polymers (FRPs) and adhesive bonds [4,5]. As the SIF is difficult to compute in layered materials, Irwin's relationship [6] was used to replace K by G, the strain energy release rate (SERR). Other than this substitution, the relationships have the same form as those developed for metals: an empirical power-law correlation between a fracture mechanics parameter (i.e. K or G) and the crack growth rate $\mathrm{d}a/\mathrm{d}N$. Although models of this form can produce satisfactory predictions of crack growth for engineering purposes, from a scientific point of view they are somewhat unsatisfying.

The empirical nature of these FCG models means there is no physical theory explaining the link between the applied load and the crack growth. For example, no satisfactory explanation has so far been given as to why a power-law relationship between ΔK or G and $\mathrm{d}a/\mathrm{d}N$ should be expected. In the literature, only a few micro-mechanical models could be found that are applicable to crack growth in an adhesive or delamination of a composite [7–10] and of those, only [10] covers fatigue loading.

One reason for this lack of models for the micro-mechanics of fatigue crack growth is that there is little understanding of how the fatigue crack evolves over the course of a single load cycle. Generally a single parameter, e.g. $G_{\max}$ or $\Delta G = G_{\max} - G_{\min}$, is assumed to

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Nomenclature

a	crack length (mm)
d	displacement (mm)
G	strain energy release rate (mJ/mm^2, N/mm)
ΔG	strain energy release rate range (mJ/mm^2, N/mm)
K	stress intensity factor (MPa $\sqrt{\text{mm}}$)
ΔK	stress intensity factor range (MPa $\sqrt{\text{mm}}$)
N	cycle number
P	force (N)
R	load ratio
t	time (s)
w	width (mm)

Subscripts

c	critical
I	mode I
min	minimum
max	maximum
th	threshold

be representative for the crack driving force during an entire cycle. Similarly, a single value of $\mathrm{d}a/\mathrm{d}N$ is assumed to be representative for the crack growth rate during an entire cycle. This means that either $\mathrm{d}a/\mathrm{d}N$ is interpreted as an average value, or that the crack growth rate is (implicitly) assumed to be constant during the entire load cycle.

As during a fatigue cycle the imposed load is constantly changing, it would seem logical that the crack growth rate is also not constant. It may also be the case that the crack only grows during certain portions of the load cycle, e.g. only when the load is above a certain value, or only during the loading phase. For the purposes of engineering predictions, it may be sufficient to neglect this. However, from a scientific standpoint a full description of the crack growth process is desirable. Such an understanding could help resolve outstanding questions, such as how to deal with the R-ratio effect which has been reported for fatigue crack growth in adhesives and composites [11–14].

The existence of the R-ratio effect implies that it is not possible to describe a fatigue cycle by just one parameter; more information about the fatigue cycle needs to be taken into account.The question then becomes, which information? Thus the research presented in this paper aimed to identify experimentally during which portions of the load cycle crack growth occurs, as a step towards identifying which aspects of the fatigue cycle are relevant for crack growth. This will hopefully lead to a more fundamental description of the relationship between the applied load and fatigue crack growth.

In order to determine during which part of the cycle crack growth occurred, the acoustic emission (AE) technique was used. This technique is based on the research of Kaiser [15] and works by using one or more piezoelectric transducers to measure the ultrasonic sound-waves produced when crack growth occurs. This allows the detection of the occurrence of crack growth, even if the crack growth increment is too small to be detected visually. It was hypothesised that by measuring the time at which signals are detected and comparing this with the applied load, it is possible to determine during what portion of the load cycle fatigue crack growth actually occurs.

AE is under active investigation as a means of locating damage and measuring damage size in composite or adhesively bonded materials, as e.g. recently reported in [16–19]. It should be stressed that this was not the purpose of the current research. The question was not *where* damage occurred, but *when* it occurred, within a single cycle. In other words, the question this research addresses is: should the entire load cycle be taken into account to describe the fatigue crack driving force, or only a portion of the cycle? If only a portion is important, which portion?

This paper presents a proof-of-concept of using AE to investigate this question experimentally, as well as discussing some results that can be used to inform the development of more physically correct models for crack growth. Some similar work has been done in this area previously [20,21], but focussing on damage in FRPs. Additionally only [20] attempted to identify during which portion of the cycle crack growth occurred.

The contents of this paper is as follows: Section 2 discusses why it is necessary to gain more understanding of the fatigue crack behaviour within a single cycle. Section 3 describes the test set-up and the applied loads. In order to build up towards understanding crack growth under fatigue loading, first crack growth was examined under quasi-static loading, followed by fatigue loading with a low displacement rate (1 mm/min). The final stage of the experiments involved fatigue load cycles with a frequency of 5 Hz. Section 4 presents the results of the quasi-static loading, and Section 5 discusses the fatigue experiments. The conclusions are summarised in Section 6.

2. Need for an understanding of FCG behaviour within a single cycle

Since the work of Roderick et al. [4], and Mostovoy and Ripling [5], the models that have been proposed for FCG in FRPs or adhesive bonds are generally of the form:

$$\frac{da}{dN} = Cf(G)^n \tag{1}$$

where C and n are empirical parameters determined by curve-fitting, and $f(G)$ is some function of G; generally $G_{\max}$ or ΔG. Various modifications are then introduced in order to account for effects such as R-ratio or mode-mixety, but the underlying form is always the same [22].

The Paris equation was originally introduced as being based on the stress at the crack tip. While the Irwin equivalence means that G can also be understood as being representative for the crack-tip stress, it is fundamentally an *energy* parameter. Thus it makes sense