



On the relationship between disbond growth and the release of strain energy



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ABSTRACT

Current prediction methods for growth of disbands under fatigue loading are generally based on a correlation with either the maximum strain energy release rate (SERR) or the SERR range. This paper highlights some issues with this approach. In particular, it is argued that the maximum SERR or the SERR range alone do not give sufficient information to uniquely characterise the driving force for crack growth. Furthermore it is argued that the relationship between crack growth rate and loss of strain energy should be considered on the scale of the entire load cycle. By means of disbond growth experiments it is shown that there is indeed a very strong correlation between the crack growth rate and the strain energy lost during a fatigue cycle. Unlike methods based on the SERR, this correlation is not affected by the *R*-ratio. Based on the found correlation a possible basis for a new approach to disbond growth prediction is suggested.

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1. Introduction

A lack of understanding of the fatigue disbonding behaviour of adhesive bonds is one of the major obstacles preventing their wide-spread application as a primary joining method in the aerospace industry. Until the growth of disbands under fatigue loading can be accurately predicted, adhesive bonding's promise of more efficient (i.e. lighter) structural joints will go unfulfilled. This challenge has of course been recognised for quite some time, and over the past four decades many researchers have investigated fatigue disbond growth (FDG). However, as the present authors have discussed elsewhere [1], these investigations have mainly resulted in a large collection of empirical correlations of most likely limited validity. This paper presents a consideration based on the energy balance considered on a per-cycle (d/dN), rather than an instantaneous, per-crack-extension, (d/da) basis. The discussion will be limited to FDG by means of growth of cracks in the adhesive layer (i.e. cohesive failure of the adhesive) and thus the terms disbond and crack may be considered interchangeable throughout this paper.

This paper will start with a historical review of the development of current approaches to the prediction of crack growth rate. Several issues with these methods will be discussed, leading to the hypothesis that crack growth rate is correlated to the total amount of energy lost during a fatigue cycle, and not to the strain energy release rate (SERR). The next section will describe the experiments performed to test this hypothesis, followed by a discussion of the results of these tests. Finally the applicability of the findings to the prediction of FDG will be considered.

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Nomenclature

a	disbond length (mm)
A	disbond area (mm ²)
C	parameter in the Paris relation
d	displacement (mm)
E	Young's modulus (MPa)
E_k	kinetic energy (mJ)
F	work (mJ)
G	strain energy release rate (N/mm, mJ/mm ²)
G^*	average strain energy release rate (mJ/mm ²)
I	moment of inertia (mm ⁴)
K	stress intensity factor (MPa $\sqrt{\text{mm}}$)
N	number of cycles
n	parameter in the Paris relation
n	compliance calibration parameter
P	force (N)
R	ratio of minimum to maximum force
U	strain energy (mJ)
W	work of fracture (mJ)
w	specimen width (mm)

Greek symbols

ν	Poisson's ratio
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Subscripts

c	critical
cyc	cyclical
max	maximum
min	minimum
mono	monotonic
tot	total

2. Critical analysis of the development of current approaches

This section provides a review of the development of the current approach to understanding FDG and then highlights and discusses some shortcomings inherent in this approach.

2.1. Historical review

The vast majority – if not all – of the current methods for predicting FDG, even those based on finite element techniques such as the cohesive zone models or XFEM, describe the crack growth behaviour with an expression from the realm of linear elastic fracture mechanics (LEFM) [1]. The basis of these expressions was formed by the work of Griffith [2], who proposed that to create or propagate a crack, one has to supply a quantity of energy equal to the surface energy of the material multiplied by the area of the new fracture surfaces.

The theory as proposed by Griffith was only applicable to perfectly brittle materials. Orowan extended this theory to ductile materials, by adding the energy dissipated by plastic deformation in the vicinity of the crack tip to the consumption side of the energy balance [3,4]. This was also independently proposed by Irwin [5].

The consumption side of the energy balance for crack growth thus being determined, attention shifted to the supply side. Irwin and Kies [6] pointed out that Griffith had already shown that growth of a crack would cause a release of strain energy. Based on this finding Irwin and Kies argued [5–7] that under *fixed grip* conditions the energy required for crack growth must be supplied by the strain field surrounding the crack. Thus, they argued, a crack can grow only if the rate of release of strain energy per unit area of crack growth (dU/dA) exceeds the energy required per unit area of crack growth (dW/dA). This is now more commonly stated as:

$$G \geq G_c \quad (1)$$

where G is the SERR. Note that this is a stability criterion. If a hypothetical crack extension would release more energy than required for crack growth, then the crack growth is self-sustaining and thus unstable cracking will occur. Eq. (1) determines

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