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Plasticity induced crack closure in adhesively bonded joints under fatigue loading

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ABSTRACT

The mean load of a cyclic loading has a large effect on fatigue crack growth rates in metallic materials and bonded joints. In metallic structures, this effect has been attributed to plasticity-induced crack closure, but little is known about the mechanism responsible for this mean load effect on fatigue crack growth in adhesively bonded joints. This paper presents a computational investigation of the plasticity-induced crack closure mechanism affecting disbond growth in adhesively bonded joints under fatigue loading. The results show that the ratios of crack-opening and crack-closure are approximately independent of the level of plastic constraint, indicated by the ratio between the plastic zone size and the adhesive thickness. An effective strain-energy release rate parameter, which accounts for the crack closure behaviour, has been developed as a new correlating parameter for disbond growth. Comparisons with the experimental results pertinent to four different adhesive bonded joints reveal that this new correlating parameter is capable of unifying the fatigue growth rates by eliminating the effect of mean loads.

1. Introduction

Adhesive bonding is the preferred method of joining and repairing metallic and composite structures due to several advantages over mechanical fasteners, such as improved mechanical performance. With increased confidence from successful applications and the maturity of this technology, adhesive bonding is now widely employed in joining and repairing composite structures, including aircraft primary structures. However, the certification of adhesive bonding for field-repair of safety–critical structures remains a challenge due to concerns over their long-term durability. FAA Advisory Circular 20-107B mandates that composites and bonded structures must be designed for no growth or slow-growth to ensure continuous airworthiness [1]. A bonded repair or joint is required to sustain the design ultimate strength in the presence of detectable disbond. Therefore validated design methodologies are required to satisfy the regulatory requirements for cyclic fatigue loading in order to implement adhesive bonding in primary structures. Fatigue crack growth in bonded joints is conventionally characterised by the strain energy release rate (SERR). However there is no consensus regarding the definition of the correlating parameter under varying load ratio where the load ratio is given as: $R = P_{\min}/P_{\max}$.

The most prevalent definition found in the literature is the maximum strain energy release rate $G_{\max}$ [2–5] and the cyclic strain energy release rate $\Delta G = G_{\max} - G_{\min}$ [5–9]. More recently, a different definition of the SERR range, in keeping consistent with similitude principle as the use of ΔK for metals fatigue, has been proposed for delamination growth in composite structures [10,11]. Mean loads have been experimentally observed to significantly affect the fatigue lives of bonded joints in a deleterious manner [7,12,13]. All the correlating parameters presently used will require empirical calibration to account for mean load effects in the fatigue behaviour of bonded joints. A review of the fatigue models used for fatigue debonding or delamination is covered in [14], highlighting the variety of empirical models proposed by researchers over the years. The existing empirical method of curve fitting disbond growth rates under different stress ratios renders it difficult to predict fatigue behaviour under variable amplitude or spectral loading, as evidenced by the similar problem in fatigue of metallic structures. Moreover, when the disbond growth rates are plotted in terms of the conventional definition of strain-energy release rates, increases in mean loads would result in slower growth rates, which is contradicting to experimental evidence of short fatigue lives under high mean loads [15,16]. Therefore a

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new correlating parameter is needed to correctly account for the effects of mean loads and to enable predictions of fatigue lives under variable amplitude loading conditions, overcoming the limitations of existing methods.

Since its discovery by Elber [17], plasticity-induced crack closure is now a widely accepted model to explain and account for the effects of mean loads on the cyclic crack growth behaviour in metallic materials [18–21]. Essentially crack closure reduces fatigue crack growth rates by reducing the effective stress range experienced at the crack tip. This concept has enabled the development of practical life prediction methods of metallic structures under variable spectrum loading. By contrast, very little research has been reported in the literature on the crack closure phenomenon in adhesively bonded structures.

The aim of this paper is to investigate the mechanism of plasticity-induced crack closure in bonded joints and its relationship with the effects of mean loads on disbond growth rates. A review of existing definitions of SERR range is first presented to highlight the problems in accounting for the effects of load ratio on disbond growth. Computational modelling is then performed to quantify the effect of plastic-wake induced closure on the growth behaviour of disbonds, in which the adhesive layer is modelled as a constrained layer [22,23] undergoing elastic–plastic deformation. Based on the numerical results, a new correlating parameter is proposed, which has shown to significantly improve the correlation with experimental results of fatigue debonding under Mode I loading.

2. Review of fatigue crack growth correlating parameter

2.1. Mode I crack growth

Based on the analogy of the Paris relation for fatigue crack growth in metals, fatigue debonding rates of bonded joints have been conventionally plotted on a log–log scale against the strain energy release rate, resulting in typical power-law relationships. In this context, two different parameters, the maximum strain energy release rate $G_{\max}$ and the cyclic strain energy release rate ΔG, have been most commonly employed to correlate the fatigue disbond growth rates:

$$\frac{da}{dN} = C_1 [G_{I,\max}]^{m_1} \tag{1}$$

$$\frac{da}{dN} = C_2 [\Delta G_I]^{m_2} \tag{2}$$

where $\Delta G_I = G_{I,\max} - G_{I,\min}$ for $R > 0$. Under negative load ratios ($R < 0$), no reports could be located in the literature on pure mode I fatigue behaviour; hence there is no consensus on the definition of ΔG_I for $R < 0$. The parameters, C_1, C_2, m_1, and m_2 depend on load ratio R, so they are not truly material properties. The strain energy release rate G is calculated using the Irwin–Kies relation,

$$G = \frac{P^2}{2b} \frac{\partial C}{\partial a} \tag{3}$$

where b is the specimen width and C is the compliance of specimen given as displacement divided by applied load. When fatigue crack growth rates are plotted in terms of $G_{I,\max}$, a strong dependency on load ratio has been reported [5,15,24]. This behaviour is not unexpected, given that the cyclic load range is absent in this definition. The cyclic load range plays a critical role in disbond growth under fatigue loading. In order to predict this load ratio dependency behaviour, past research proposed a number of empirical expressions to determine the Paris law parameters for various load ratios by making certain assumptions about the fatigue behaviour [15,24]. However extensive experimental testing is still required to calibrate these parameters to obtain a good fit.The SERR range, $\Delta G_{I,}$ attempts to address the load ratio dependency of $G_{I,\max}$ by defining the SERR range, similar to which ΔK is defined in metal fatigue. However, it should be pointed out that the existing definition of ΔG_I is inconsistent with ΔK because $\Delta G \neq \Delta K^2/E$, as shown below,

$$\Delta G_I \equiv \frac{K_{max}^2 - K_{min}^2}{E} = \frac{2K_{mean}\Delta K}{E} \neq \frac{\Delta K^2}{E} \tag{4}$$

The fundamental concept of similitude in fatigue implies that the crack-tip deformation and, hence, crack increment per cycle is uniquely controlled by a single loading parameter such as the stress intensity factor as in the case of metals [10,25]. Considering a growing crack under constant amplitude loading, a cyclic plastic zone forms at the crack tip and a plastic wake is left behind as the crack advances. If the plastic zone is sufficiently small and within the elastic singularity zone, the crack tip condition is uniquely defined by the stress intensity factor, since the similitude condition prevails. In keeping consistent with the Irwin relationship, the cyclic SERR range $\Delta G_{I,eq}$ [10] should be defined such as that $\Delta G = \Delta K^2/E$. Consequently the following definition for $\Delta G_{I,\mathrm{eq}}$ will be employed in this investigation, given as: -

$$\Delta G_{I,\mathrm{eq}} = \left(\sqrt{G_{I,\max}} - \sqrt{G_{I,\min}}\right)^2 = G_{I,\max}(1-R)^2 \tag{5}$$

The above cyclic SERR range $\Delta G_{I,\mathrm{eq}}$ has been reported to be a better correlating parameter than ΔG_I [10,11]. Hojo et al. adopted ΔK to describe the fatigue delamination growth in composite laminates, but did not consider whether ΔG was a suitable correlating parameter [26]. Moreover fractography analysis did not indicate any signs of fibre bridging which can affect the crack propagation rates. Rans et al. [10] presented the $\Delta G_{\mathrm{I,eq}}$ definition to be used for mode I composite delaminations. He highlighted the potential misinterpretations of delamination growth behaviour if the underlying assumptions behind the two definitions were not understood.

The experimental results of the mode I fatigue disbond growth data of four epoxy-based adhesives, taken from the literature, are plotted in Fig. 1 in terms of ΔG. It can be seen in Fig. 1(a) that the load ratio has negligible effects on the disbond growth rates for the results from [5]. However the disbond growth rates and threshold SERR values from [4,7,8], as shown in Fig. 1(b–d), exhibit strong dependency on the load ratio. The threshold SERR refers to the value at which the disbond growth rate is less than 10^{-6} mm/cycle. Moreover, the load ratio dependency in Fig. 1(b) and (d) appears to be counter-intuitive: higher mean load appears to reduce debonding rates under the same ΔG. These results contradict completely with the experimental observations that higher mean stress would lead to shorter fatigue lives [7,12]. It is also worth noting that experimental results [27–29] confirmed that disbond growth rates were slightly influenced by the bondline thickness. This influence has always been attributed to the constraint of plasticity by the stiffer substrates. Jablonski attempted to quantify the bondline thickness effect on the fatigue growth rates with crack closure [29]. By measuring the crack opening displacement locally behind the crack tip, he detected non-linearity in the compliance and was able to merge the fatigue growth rates of the two different bondline thicknesses into one narrow band.

Re-analysing the experimental data presented in Fig. 1 using the $\Delta G_{I,\mathrm{eq}}$ defined in Eq. (6), shows that a lower load ratio yields higher threshold and lower debonding growth rates, as presented in Fig. 2. This trend is similar to the observations of metals' fatigue behaviour. Therefore, the equivalent SERR definition is consistent with the similitude requirements in fatigue. The counter-intuitive behaviour, previously observed when ΔG was employed as the correlating parameter, has now been eliminated.