TOWARDS A DELAMINATION FATIGUE METHODOLOGY FOR COMPOSITE MATERIALS

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Abstract

A methodology that accounts for both delaminaton onset and growth in composite structural components is proposed for improved fatigue life prediction to reduce life cycle costs and improve accept/reject criteria for manufacturing flaws. The benefits of using a Delamination Onset Threshold (DOT) approach in combination with a Modified Damage Tolerance (MDT) approach is highlighted. The use of this combined approach to establish accept/reject criteria, requiring less conservative initial manufacturing flaw sizes, is illustrated.

1 Current State of the Art

The current safe life approach used for establishing retirement times for aircraft components, such as rotor blades for rotary wing vehicles, does not account for any pre-existing flaws, cracks, or delaminations. Over the past 25 years, significant progress has been made in research efforts to utilize fracture mechanics principles to characterize and predict delamination fatigue failures in composites laminates [1] and more recently in composite rotor hub flexbeams and stiffened panels [2,3]. These studies have utilized a Delamination Onset Threshold (DOT) methodology where fatigue life of the part is determined by the onset of delamination under cyclic loading from an initial flaw or material discontinuity. This approach utilizes a characterization in the form of the maximum cyclic strain energy relase rate, G_{max}, plotted as a function of the number of cycles to delamination onset, N_{th} (fig.1).

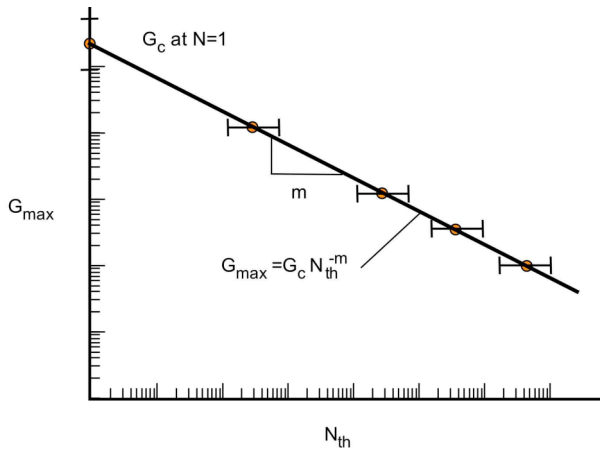

Fig. 1. Delamination onset threshold

The virtual crack closure technique (VCCT) [4] is widely used for computing energy release rates based on results from continuum (2D) and solid (3D) finite element analyses to supply the mode separation required when using a mixed-mode fracture criterion. A comprehensive summary of the development and application of VCCT was recently published [5].

Although these studies have demonstrated the promise of this approach, they have also highlighted some of the difficulties and differences between the DOT approach and the classical damage tolerance (CDT) methodology used for metallic structures. For example, using the DOT methodology to define the life of the component as the onset of delamination from a very small initial delamination, established by the detection threshold for Non-Destructive Inspection (NDI) methods, may prove overly conservative. Alternatively, the CDT approach has been used to determine the rate of delamination growth with fatigue cycles as a function of the maximum applied cyclic strain energy release rate, G_{max}. The delamination growth is usually described

as a log-log plot of da/dN vs. G_{max} as shown in fig. 2.

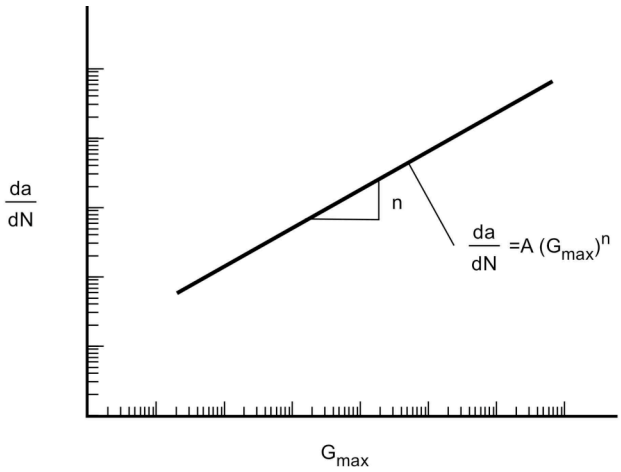

Fig. 2. Delamination growth law

In analogy with metals, the delamination growth rate can therefore be expressed as a power law function

$$\frac{da}{dN} = A\left(G_{\max}\right)^n \qquad (1)$$

where A and n are determined by a curve fit to the experimental data. However, the exponent "n" is typically high for composite materials compared to metals. The exponent for composites may vary between 6 and 10 for mode I delamination growth. This exponent may be lower (between 3 to 5) for mode II delamination growth and for toughened resin composites. However, typical exponents for metallic materials are around 1 to 2. As a consequence, very small changes in G_{max} can result in large changes in the delamination growth rate, which makes it difficult to establish reasonable inspection intervals for implementing the CDT slow crack growth methodology used for metals.

2 Proposed Methodology

Several modifications to the classical Paris law have been suggested, including normalization by the static R-curve and adding additional terms to account for R-ratio effects and near threshold non-linearity [6-7]. These studies indicate that a Modified Damage Tolerance (MDT) methodology where the G_{max} is normalized by the static R-curve will result in lower power law exponents that would enable inspection intervals to be established that are more reasonable. Currently, ASTM committee D30 is conducting a round robin exercise to evaluate these modifications for Mode I delamination growth using the Double Cantilever Beam specimen. More benefits may be obtained by combining the delamination fatigue threshold characterization with a modified Paris law for slow delamination growth.

3 Combined threshold and slow growth approach for establishing acceptable flaw size.

In order to assess the acceptability of manufacturing flaws, herein assumed to be initial delaminations, an approach may be adopted that utilizes both the slow growth characterization in the MDT approach and a delamination threshold characterization in the DOT approach. To illustrate this combined approach, the following heuristic explanation is developed which assumes constant amplitude cyclic loading and ignores, for the moment, complexities such as the mixed-mode dependence on delamination onset and growth.

Typically, in a slow crack growth approach, the smallest initial delamination, a_i, is assumed to be the smallest flaw that is detectable by Non-Destructive Investigation (NDI). For the MDT approach, the slow crack growth law has the form

$$\frac{da}{dN} = A\left(\frac{G_{\max}}{G_R}\right)^n \qquad (2)$$

where G_{max} = f(a), and G_R = f(a) is the crack growth resistance curve determined experimentally. Using a slow growth approach alone assumes that the initial delamination, a_i, starts to grow on the first cycle. The extent of the delamination at any point is determined by integration of eq. 2. Solving for the number of cycles required for a given extent of delamination yields

$$\frac{1}{A}\int_{a_i}^{a}\left(\frac{G_{\max}(a)}{G_R(a)}\right)^{-n} da = \int_{1}^{N} dN \qquad (3)$$

The functional relationship must be determined by analysis of the particular configuration and loading to obtain $G_{max}(a)$ and by performing interlaminar fracture tests to determine $G_R(a)$. As shown in fig. 3, a maximum slow growth life (or initial inspection interval), $L_{sgai} = N_{sgai}/f$, where f is the cyclic frequency, may be defined that corresponds to the point where $a = a_c$ and unstable delamination growth would occur.

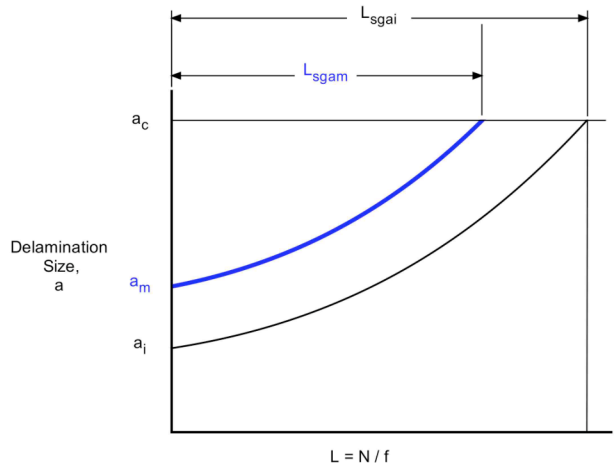

Fig. 3. Maximum possible lives for slow growth evaluation

As also shown in fig. 3, if a larger manufacturing flaw in the form of an initial delamination, $a_m > a_i$, exists, then the slow growth life, L_{sgam} would be less than L_{sgai}. In both cases, however, the assumption that the initial delamination will begin to grow on the first cycle of loading is overly conservative because the onset of growth from an existing delamination requires a finite number of cycles to initiate depending on the maximum cyclic load level, P_{max} [1-3].

Delamination onset threshold behavior of composite materials is typically characterized through development of a delamination onset threshold curve, G_{max} vs. N_{th} (fig.1), where N_{th} is the number of cycles for delamination onset. These curves may be obtained by fitting the data to an equation of the form

$$G_{\max} = G_c N_{th}^{-m} \tag{4}$$

where "m" is a positive constant determined from curve fit of the data generated in a delamination fatigue characterization test (fig.1) [8] .
Solving for N_{th} yields

$$N_{th} = \left(\frac{G_c}{G_{\max}} \right)^{\frac{1}{m}} \tag{5}$$

Hence, a delamination threshold life, were $N_{th}=L_{th}$ f, would be

$$L_{th} = \frac{1}{f} \left(\frac{G_c}{G_{\max}} \right)^{\frac{1}{m}} \tag{6}$$

As noted earlier, in general G_{max} is a function of delamination length, a. For simplicity of further illustration, assume a structural configuration where the maximum cyclic strain energy release rate, G_{max}, is proportional to the delamination length, a, and the square of the maximum applied cyclic load, P_{max},

$$G_{\max} = CP_{\max}^2 a \tag{7}$$

where C is a coefficient determined by analysis of the particular structural configuration and loading. Substituting eq.7 into eq.6 for the threshold life, L_{th}, yields

$$L_{th} = \frac{1}{f} \left(\frac{G_c}{CP_{\max}^2 a} \right)^{\frac{1}{m}} \tag{8}$$

Hence, the threshold life, L_{th}, is inversely proportional to the delamination length, a. Therefore, for $a_m > a_i$, $L_{tham} < L_{thai}$, as shown in fig. 4.

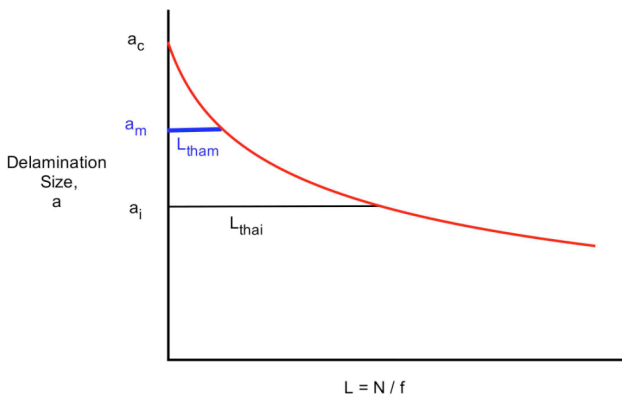

Fig. 4. Delamination onset threshold curves

In the limit, as $a = a_c$, and $CP^2_{max}a_c = G_c$, failure occurs in the first cycle, $N_{th} = L_{th}f = 1$.

If we were to take advantage of both the threshold life and the slow growth life, a total life could be determined for a given flaw size, as illustrated by combining fig. 3 and fig. 4 in fig. 5.

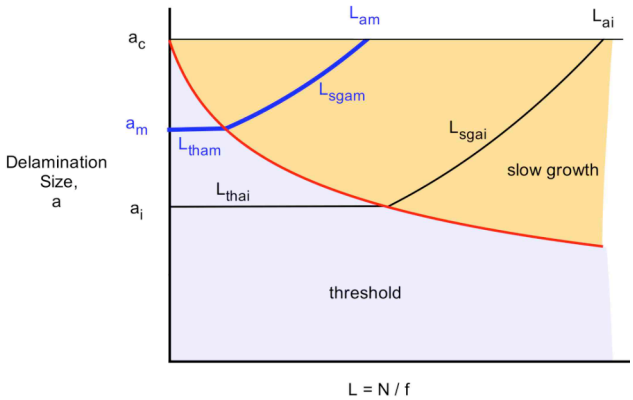

Fig. 5. Maximum possible lives utilizing a combined threshold plus slow growth approach

Hence, for example, the total life for an initial delamination, a_i, would be

$$L_{ai} = L_{thai} + L_{sgai} \tag{9}$$

whereas the total life for a larger initial delamination, a_m, corresponding to a manufacturing flaw would be

$$L_{am} = L_{tham} + L_{sgam} \tag{10}$$

For the purpose of defining accept/reject criteria, an alternative way of demonstrating the benefit of this combined approach would be to ask the following question: using this combined approach, what size manufacturing flaw, a_m, would yield a life that is equivalent to the life defined by assuming the smaller NDI threshold flaw size, a_i, and the slow growth approach alone? This is illustrated in fig. 6, where

$$L_{sgai} = L_{tham} + L_{sgam} \tag{11}$$

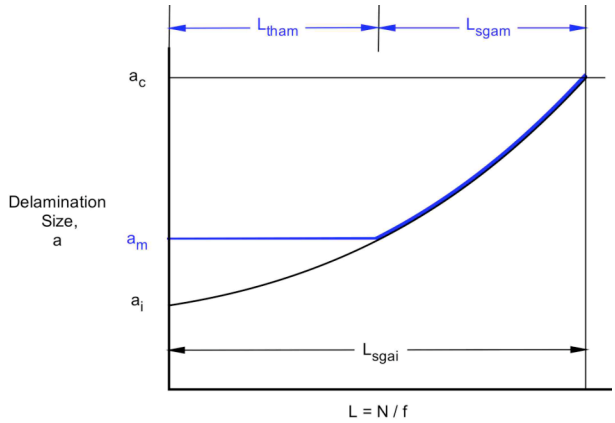

Fig. 6. Equivalence of slow growth life for NDI flaw and total growth life for manufacturing flaw

Integration of eq.3 from a_i to a_c, yields the slow growth life, $L_{sgai}=N_{sgai}/f$, as

$$L_{sgai} = \frac{1}{f}\left(1 + \frac{1}{A}\int_{a_i}^{a_c}\left[\frac{G_{\max}(a)}{G_R(a)}\right]^{-n} da\right) \tag{12}$$

Similary, integration of eq.3 from a_m to a_c, yields the slow growth life, $L_{sgam}=N_{sgam}/f$, as

$$L_{sgam} = \frac{1}{f}\left(1 + \frac{1}{A}\int_{a_m}^{a_c}\left[\frac{G_{\max}(a)}{G_R(a)}\right]^{-n} da\right) \tag{13}$$

For simplicity, if we were to assume a flat R curve such that $G_R=G_c$=constant, and we further assume, as in our earlier example, that G_{max} is a linear function of a, as in eq.7, then eq.12 becomes

$$L_{sgai} = \frac{1}{f}\left(1 + \frac{1}{A}\left[\frac{CP_{\max}^2}{G_c}\right]^{-n}\int_{a_i}^{a_c} a^{-n} da\right) \tag{14}$$

which, upon integration, yields

$$L_{sgai} = \frac{1}{f}\left(1 + \frac{1}{A(1-n)}\left[\frac{CP_{\max}^2}{G_c}\right]^{-n}\left[(a_i)^{1-n} - (a_c)^{1-n}\right]\right) \tag{15}$$

Similarly, integration of eq.13 from a_m to a_c, yields the slow growth life, $L_{sgam}=N_{sgam}/f$, as

$$L_{sgam} = \frac{1}{f}\left(1 + \frac{1}{A(1-n)}\left[\frac{CP_{\max}^2}{G_c}\right]^{-n}\left[(a_m)^{1-n} - (a_c)^{1-n}\right]\right) \tag{16}$$

The threshold life for the larger manufacturing flaw, L_{tham}, is obtained from eq.8 as

$$L_{tham} = \frac{1}{f}\left(\frac{G_c}{CP_{\max}^2 a_m}\right)^{\frac{1}{m}} \qquad (17)$$

Substituting eqs.15-17 into eq.11 yields the following algebraic equation that may be solved for a_m

$$0 = Q\left[(a_m)^{1-n} - (a_i)^{1-n}\right] + R\left(\frac{1}{a_m}\right)^{\frac{1}{m}} \qquad (18)$$

where

$$Q = \frac{1}{A(1-n)}\left[\frac{CP_{\max}^2}{G_c}\right]^{-n} \qquad (19)$$

and

$$R = \left(\frac{G_c}{CP_{\max}^2}\right)^{\frac{1}{m}} \qquad (20)$$

Hence, using this combined delamination onset threshold and slow growth methodology, a manufacturing flaw size, a_m, that is greater than the maximum size based on an NDI technique threshold, a_i, may be determined that could reduce the number of rejected parts. In general, for complex part geometries with geometrically non-linear structural response, $G_{max}(a)$ will need to be determined numerically. Therefore, for these more complex structural cases, we would substitute L_{tham} from eq.6, L_{sgai} from eq.12, and L_{sgam} from eq.13 into eq.11 to implement this methodology.

Summary

The benefits of using a Delamination Onset Threshold (DOT) approach in combination with the Modified Damage Tolerance (MDT) approach to establish more accurate expected life was illustrated. This combined threshold and slow growth approach may be used to establish accept/reject criteria that require less conservative initial manufacturing flaw sizes, and hence, reduces the number of rejected parts.

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