USING THE LEAD CRACK CONCEPT TO REDUCE DURABILITY TEST DURATION

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Abstract

Aircraft full-scale fatigue tests are expensive and time consuming to conduct, but are a critical item on the certification path of any aircraft design or modification. This paper outlines a proposal that trades cycling hours for increased detail in the teardown of the test article. A method for determining the equivalent demonstrated crack size (and crack growth curve) at the mandated test life utilising the lead crack framework is demonstrated. It is considered that the test duration can be significantly reduced whilst still achieving all desired outcomes of a certification program.

1. Introduction

Full Scale Fatigue/durability Tests (FSFTs) form the cornerstone in the structural qualification and certification of new aircraft types in both the civil and military sectors. Whilst the conduct of these tests consume enormous resources in time, effort and costs, they have thus far proved to be the most reliable, and in many cases, an essential means of establishing the evidence base for an aircraft's safety and durability.

Whilst there is a push towards a more analytical (or virtual test) basis [1], "FSFTs continue to produce premature fatigue cracking ([sic][2]), demonstrating the current inadequacies of the fatigue analysis process. Until a time is reached when FSFTs do not reveal significant premature failures or cracking, designers and regulators alike will not have enough confidence in analysis methods to allow deletion of full scale testing [1]". This paper proposes a means of accelerating the progress of the FSFT program, to lower the associated resource burden, whilst avoiding the current shortcomings that are associated with a fully analytical approach.

FSFT certification programs aim to (e.g. [3][4][5]):

1. Demonstrate the durability of the airframe (i.e. the period of service before structural impairment due to fatigue cracking could occur given a specific value for the allowable probability of failure);
2. Reveal locations prone to cracking (i.e. fatigue hotspots);
3. Provide data to correlate or correct design fatigue crack growth (FCG) codes;
4. Determine the residual strength (i.e. critical crack depths a_{CRIT}) of the airframe in the presence of fatigue cracks at end of testing;
5. Determine the potential influence of widespread fatigue damage (WFD);
6. Provide data to support sustainment, including the measurement of strain data;
7. Provide the baseline for individual aircraft fatigue life monitoring; and
8. Generation of Equivalent Pre-crack Sizes (EPS) to facilitate probabilistic analyses (e.g. [7]).

The data collection aspect described can be achieved early in the program, leaving the crack growth based items as factors driving the longevity of the test. There are many potential means of accelerating a FSFT (e.g. [9]). Briefly, these include: increased cyclic rates; smart spectrum truncation; autonomous non-destructive inspection (NDI); more sensitive NDI[1]; inducing artificial cracks in predicted hotspots [8]; inserting fracture surface-marking loads into the spectrum to aid quantitative fractography (QF) etc. Most of these require further development and this is recommended. This paper only considers an alternative method for determining the equivalent test demonstrated crack size (and FCG curve) at the mandated/desired test life utilising the lead crack framework. This methodology allows the test program duration to be significantly reduced whilst still achieving all desired outcomes of a certification program.

2. The Lead Crack Concept

A fatigue life prediction framework using a lead crack concept has been developed by the Defence Science and Technology (DST) Group for primarily metallic airframe components [11]. Developed initially for highly stressed, high performance aircraft structural integrity evaluations, its utility could be extended to other structural integrity problems. This framework builds on the observation that (near) exponential FCG is a common occurrence for naturally-nucleating lead cracks (i.e. those leading first to failure) in test specimens, components and airframe structures subjected to variable amplitude load histories [11]-[20].

2.1. Lead Crack Characteristics

Lead cracks have the following general characteristics (adapted from [11]):

1. They start to grow shortly after testing begins or after the aircraft is introduced into service from material or production discontinuities. Significantly, this implies that the threshold cyclic stress intensity factor (ΔK_{thr}) is small (i.e. close to zero), see [10][11][18]-[22] for more details. Other cracks where nucleation is time-dependant need separate consideration (e.g. in-service induced damage, poor repairs, corrosion nucleated). It should be noted that a conventional FSFT will also not provide information relating to such cracks.

2. Subject to several caveats (see [11]) they grow approximately exponentially with consistent loading history, i.e. FCG may be approximated by an equation of the form:

$$a = a_0 e^{\lambda t} \qquad \text{Equation (1)}$$

where:
- a = Crack depth
- a_0 = Initial crack size (or EPS) [12]- [17])
- λ = Growth rate parameter that includes the finite geometrical factor β
- t = fatigue life in terms of Cycles/No. of Load Blocks/Simulated Flight Hours

[1] If cracking could be detected at sub-mm depths, then repair options would be simpler than, say, component replacement due to significant cracking. It is also noted that a substantial portion of the FSFT program is consumed by inspection and (later) repair activities.

3. A significant portion of their lives is spent in the physically short crack regime (i.e. at depths less than approximately 1mm).

4. They grow in an optimum manner generally unaffected by such factors as crack-closure or material grain size etc.

5. The fastest possible lead crack is more likely to be revealed in a larger component than in a small coupon (i.e. the area or volume effect). Having a concurrent combination of ‘favourable’ grain orientation, local stresses and large initial discontinuities is more probable for a larger sample of material or a component containing multiple holes.

6. For a given material, spectrum and structural detail, the λ parameter of the exponential equation, e.g. the slope of the FCG curve shown in Figure 1, is approximately a constant for given spectrum, stress level and geometry.

7. The mean EPS for AA7050-T7451 plate is approximately equivalent to a 0.01 mm deep (semi-circular) surface fatigue crack [11]-[16]. In other words, in this material a 0.01 mm deep crack is a good starting point for estimating the average fatigue life using the lead crack framework, see Figure 1. This EPS value is well below the surrogate initial flaw/crack size usually assumed in the damage tolerant method for durability (i.e. 1.27 mm [4]).

8. The metallic materials used in highly stressed areas of high performance aircraft, where load shedding has not occurred, typically have a_{CRIT} of less than 10 mm, see [9][14][15][19].

9. The framework is designed to produce a conservative FCG curve (e.g. the quasi-static crack tearing close to end-of-life is ignored).

Exponential FCG represents an optimum path for the crack to reach a_{CRIT} for a given spectrum, stress level and detail — thus analyses based on the framework will tend to result in conservative fatigue life management outcomes (all else being equal).

3. The Lead Crack Based Method

Let us assume for illustrative purposes that the FSFT is ready to commence cycling and the program’s aim was to demonstrate structural durability via two life times of cycling. The lead crack framework predicts that cracks (with lives short enough to pose a meaningful risk of failure within the service life of the airframe) will commence growing from inherent material discontinuities shortly after the test starts.

The proposal is to terminate cycling early, for example after one life-time, and then perform a thorough teardown and detailed inspection of the test article (noting that the regulations already contain a requirement for a teardown inspection). The teardown is driven (but not limited) by a pre-knowledge of hotspots and from collected strain data to prioritise the order in which details are inspected. It is envisaged that the hotspots and surrounding details will be subjected to loads that would cause fracture to occur to reveal the largest crack (as well in many instances the surrounding smaller cracks). Many hotspots can be assessed in parallel subject to availability of resources. When cracking is detected QF is conducted to derive a FCG curve, see example in Figure 1. This step also confirms the appropriateness of the lead crack framework or informs the need for the use of an alternative model to predict the FCG at the hotspot under consideration. The a_{CRIT} can be calculated from material fracture toughness or separate tests.

The lead crack framework is then used to extrapolate (or interpolate) the FCG to a_{CRIT} or a_{RST} (RST = Residual Strength Test) depending on certification requirements, as shown in Figure 1. It will be important to examine some of the surrounding details (e.g. holes adjacent to the current hole with the biggest crack) to facilitate WFD investigations.

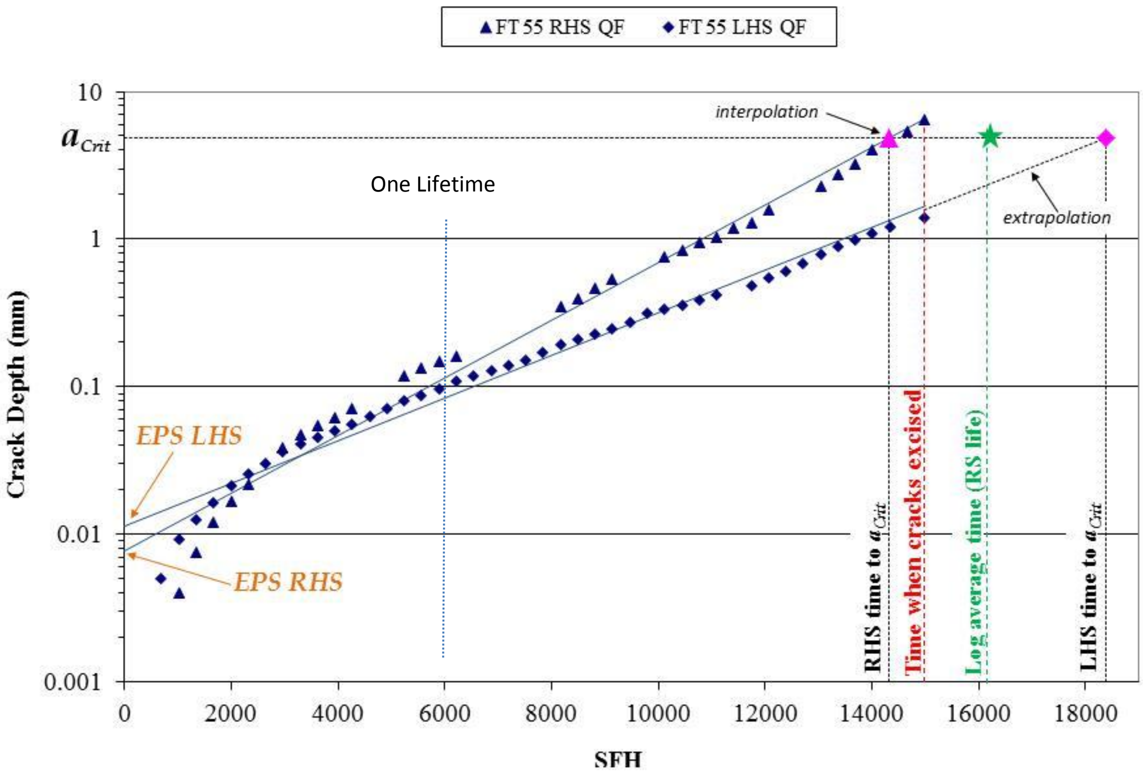

Figure 1. Schematic of typical (lead) crack growth (note: each point represents one spectrum block). This example from FT55 Fighter Aircraft FSFT [23] shows the crack depth (a) (log scale) versus time history (linear scale), as determined via quantitative fractography (QF). The growth curve for the LHS crack has been extrapolated to the estimated critical crack size for residual strength test (RST) loading conditions (a_{RST}), to estimate the achievable life to a_{RST}. For the RHS crack, the crack growth curve to the critical crack size has been interpolated back to a_{RST}. The demonstrated fatigue life was calculated from the geometric mean of the lives to a_{RST} for both sides. Note the approximately exponential crack growth, which was used to estimate the EPS values for each crack. The early departure from exponential is thought to result from the transition of a discontinuity into a crack.

Once FCG curves are available the certification requirements outlined above can be evaluated.

Given, that the QF of principal cracks can be conducted in a significantly shorter timeframe than the continuation of cycling etc. for another life-time, it is suggested that this approach could make the required certification data available to the regulator and the OEM at an earlier stage, enabling the introduction of any necessary modifications during production or at least more efficiently in-service. This facilitates a more agile approach to introducing new capability to service.

4. Conclusion

A method to reduce the duration of full-scale fatigue/durability test cycling required to achieve durability-based structural certification requirements based on the lead-crack framework has been proposed.. It is argued that by trading cycling time for more detailed inspection and fractographic examination, certification requirements can be met in a shorter timeframe with reduced costs. This would be a more cost effective and agile means of certification.

5. Copyright Statement

6. References

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