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Short Cracks in Aerospace Structures

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ABSTRACT The practical engineering significance of short fatigue cracks in aerospace structures is examined with respect to the design and operating requirements of safety and durability. It is shown that this significance is presently limited to the safety of some engine parts, notably discs and blades, and the durability of metallic airframe structures.

Introduction

Short crack growth is the subject of much recent research into fatigue of metallic materials and composites. The study of short cracks is undoubtedly important for improved understanding of the fatigue process and development of materials with better resistance to fatigue. However, the practical engineering significance of short crack behaviour appears to be limited (**1**). This will be illustrated and explained with respect to aerospace structures in the present paper. To do this, it is first necessary to consider the design and operating requirements of safety and durability of fatigue-critical aerospace structures.

Safety and durability of fatigue-critical aerospace structures

Structural fatigue design philosophies

Initially the only philosophy for designing against fatigue of aerospace structures was the safe-life approach, which means designing for a finite service life during which significant fatigue damage will not occur.

In the 1950s the fail-safe philosophy evolved and was first applied to civil transport aircraft. The fail-safe approach requires designing for an adequate service life without significant damage, but also enabling operation beyond the actual life at which such damage occurs. However, it must be shown that the damage (cracks or flaws) will be detected by routine inspection before it propagates to the extent that residual strength falls below a safe level.

Since 1970 the United States Air Force (USAF) has developed the damage tolerance approach (**2**). This philosophy differs from the original fail-safe approach in two major respects:

(1) the possibility of cracks or flaws already in a new structure must be accounted for;

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(2) structures may be inspectable or non-inspectable in service, i.e. there is an option for designing structures that are not intended to be inspected during the service life.

Inspectable structures can be qualified either as fail-safe or as slow flaw growth structures, for which initial damage must grow slowly and not reach a size large enough to cause failure between inspections. Non-inspectable structures, according to the USAF, NASA, and ESA (**2**)–(**4**), may still be classified as damage tolerant provided they can be qualified for slow flaw growth, which in this case means that initial damage must not propagate to a size causing failure during the design service life. However, this classification is debatable: civil aviation authorities place non-inspectable slow flaw growth structures in the (undesirable) safe-life category (**5**).

All these design philosophies are in use, not only for different types of aerospace vehicle, but also for different areas in the same structure. An attempt at a general classification is given in Table 1. Although this situation is rather confusing, the important point is that there is a trend to try and increase damage tolerance design in all structural areas.

Definitions of safety and durability

So far, safety has been discussed without qualification. However, actual design balances performance requirements against economic factors such that the probability of failure during the design life is less than some acceptable value. Since all structures deteriorate in service, i.e., the probability of failure increases with time, there is a safety limit. This is the time beyond which the risk of failure is unacceptable unless preventive actions are taken.

For safe-life and non-inspectable slow flaw growth structures the necessary preventive action is – in theory – retirement from service. In fact, the situation is more complicated. It may be possible to extend the service life by structural audit. This involves inspection or reassessment of known 'hot spots' and repair or replacement of damaged or suspect areas. This approach is made possible usually by advances in non-destructive inspection (NDI) techniques and improved understanding of the accumulation of fatigue damage in the structure. The result is that an originally safe-life design becomes, to some extent, amenable to assessment using damage tolerance principles.

For inspectable fail-safe and slow flaw growth structures the preventive action is, in the first instance, repeated inspection, followed by repair or replacement if required and feasible. Only when repair or replacement are not feasible, or when the frequency of inspection becomes uneconomic, need the structure be withdrawn from service.

Consideration of preventive action for ensuring safety leads to the requirement of durability. The necessity for a structure to be durable means, primarily, that the economic life (including any inspections, repairs, or replacements) should equal or exceed the design life. Current practice generally bases the

Table 1 Current application of structural fatigue design philosophies

Design approach		*Defects assumed for new structure*	*Structural fatigue design category*	*Structural items/Types of vehicle*				
				Airframes	Engines	Landing gear	Pressure vessels	Bolts
Safe-Life	Non-inspectable or no planned inspections	No	Original Safe-Life	• most general aviation and military aircraft • helicopters	all	all		all except STS* payloads
Damage Tolerance	Planned inspections	No	Original Fail-Safe	• pre-1980s civil transports • some helicopter components				
		Yes	Fail-Safe or Slow Flaw Growth	• modern civil transports and military aircraft • space shuttle orbiter	some gas turbine discs			$\phi \leqslant 8$ mm for STS* payloads
	Non-inspectable or no planned inspections	Yes	Slow (Safe) Flaw Growth Life	• some areas on F-16, B-1 and space shuttle orbiter • most STS* payloads	some turbine items (blades, discs)	space shuttle orbiter	space shuttle orbiter and STS payloads	$\phi > 8$ mm for STS* payloads

* STS = Space Transportation System.

economic life on full-scale and component test results, in particular the frequent occurrence of cracking. However, analyses are being developed, notably by the USAF (**6**)(**7**), to enable quantifying the economic life at the design stage. The most advanced analyses are concerned with the widespread initiation and growth of small cracks at fastener holes in metallic airframe structures, since such cracks are one of the most common maintenance problems. The upper limit of crack size that determines durability is defined on the basis of economic repair, e.g., the largest radial crack that can be cleaned up by reaming a fastener hole to the next fastener size. This is followed by installation of an appropriate oversize fastener.

Significance of short fatigue cracks

It must be stated right away that short fatigue cracks have no practical engineering significance for composite structures now or in the foreseeable future. The presence of short 'cracks' and their growth and coalescence during fatigue to form macroscopic defects in composites are of fundamental importance to development of more fatigue resistant composite materials, but there is no way in which such early damage accumulation may be quantified for engineering use.

On the other hand, short fatigue cracks are, or may be, practically significant for metallic structures. As is well known, there is considerable evidence that short fatigue cracks in metals grow at faster rates and lower nominal ΔK values than those predicted from macrocrack growth data (**8**). These apparent and unfavourable anomalies are found typically for cracks with governing dimensions less than 0.5 mm. Notable exceptions are cracks in some large grain size engine materials, e.g., (**9**).

The practical engineering significance of short fatigue cracks in metallic aerospace structures is the subject of the remainder of this paper.

Short fatigue cracks and the safety of metallic aerospace structures

Figure 1 gives an overview of the potential relevance and importance of short fatigue crack growth for the safety of metallic structures. The flow chart logic takes into account the structural fatigue design categories, non-destructive inspection (NDI) capabilities, and types of service load histories.

Broadly speaking, short fatigue cracks are potentially significant for safety only if a sufficiently high level of NDI is feasible, i.e., possible and economically justifiable. In more detail this means:

(1) For new damage tolerance structures pre-service NDI must be capable of detecting short cracks or flaws with high reliability. This is a necessary minimum requirement because in-service NDI usually has lesser capabilities.

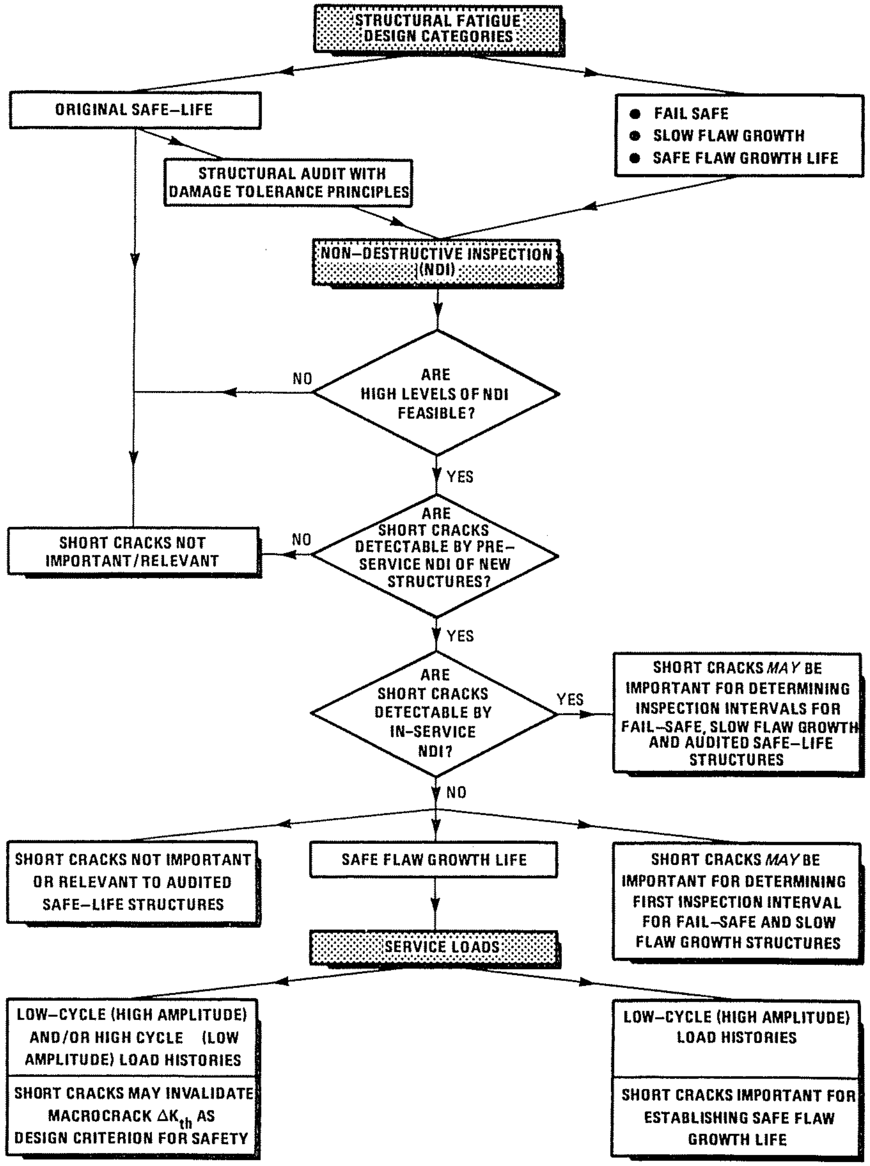


Fig 1 Short fatigue crack growth and safety of metallic structures

(2) For safe-life structures audited using damage tolerance principles in-service NDI must be capable of detecting short cracks or flaws with high reliability.

In fact, the current situation is that, except for a few special cases in engines – particularly military gas turbines – the feasible levels of NDI for aerospace structures correspond to relatively large flaw sizes that must be assumed immediately after inspection **(2)**–**(4)**(**10**). This is illustrated for airframes, the space shuttle orbiter, and Space Tranportation System (STS) payloads in Table 2. All initial damage sizes are beyond 0.5 mm, which is about the limit of the short crack regime for most materials.

Table 2 does not include aircraft landing gear and engines, which are traditionally designed and operated according to the original safe-life approach. For aircraft landing gear this situation is likely to continue for the foreseeable future. But for engines there is considerable effort to introduce the damage tolerance approach, e.g., (**11**).

Blades and discs are generally the most fatigue-critical items in engines. Short cracks are important for safe damage tolerance design and operation, but for different reasons. Fatigue loads on blades are mainly large numbers of low amplitudes. Thus ΔK_{th} (the threshold stress intensity factor range for fatigue crack growth) may be used as a design criterion for preventing high cycle fatigue failure due to, for example, thermal fatigue cracks in coatings, cooling holes, and other stress concentrations. However, the value of ΔK_{th} obtained from macrocrack growth data could be unconservative if the transition to high-cycle fatigue occurs in the short crack regime.

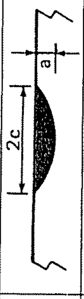
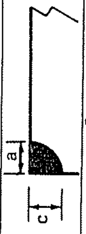
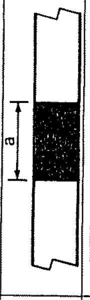
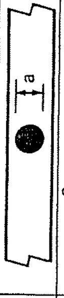
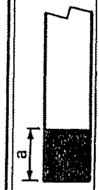
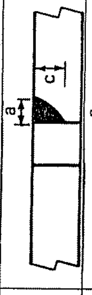
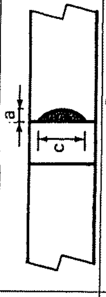
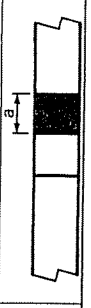
On the other hand, fatigue in engine discs is mainly a low-cycle, high amplitude problem. Critical crack lengths may be close to, or even in, the short crack regime. In such cases the behaviour of short cracks is of primary importance for application of damage tolerance principles to disc lifing.

Short fatigue cracks and the durability of metallic aerospace structures

When short cracks are important for safety they are also important for the durability of a structure. But even when short cracks are not important for safe damage tolerance design and operation they may be important for durability analyses.

As mentioned earlier, the most developed durability analyses concern the widespread initiation and growth of small cracks at fastener holes in metallic airframe structures. The way in which such analyses are done is illustrated schematically in Fig. 2. Crack propagation curves are obtained from visual and fractographic measurements on test components and specimens and are extrapolated analytically (using macrocrack-based crack growth models) to 'initial crack lengths'. These fictitious crack lengths are called Equivalent Initial Flaw Sizes (EIFS). The values and statistical distributions of EIFS define the initial fatigue quality and scatter in fatigue life, and these parameters are used

Table 2 Current well-defined safety requirements for assumed initial damage in aerospace structures (2)–(4)

Types of flaw			*Flaw size a(mm) to be assumed immediately after inspection*					
			New structures with pre-service inspection capabilities					In-service inspection of USAF airframes with special NDI
			USAF airframes with high standard NDI		Space shuttle orbiter except engines		STS payloads with high standard NDI	
Description	Geometry	*Aspect ratio (a/c)*	Fail-Safe	Slow Flaw Growth	High Standard NDI	Special NDI		
Surface flaw		1.0 0.2	1.27	3.18	1.9	0.635	1.9 0.65	6.35
Corner flaw		1.0 0.2					1.9 0.65	
Through crack			2.54	6.35			1.9	12.7
Embedded flaw					2.54	1.19		
Through edge crack						1.9		
Corner flaw at a hole		1.0 0.2	0.51	1.27	1.27	1.19	2.5	6.35 mm beyond fastener head or nut
Surface flaw in bore of hole		1.0 0.2					2.5 1.25	
Through crack at a hole			0.51	1.27	1.27		2.5	6.35 mm beyond fastener head or nut

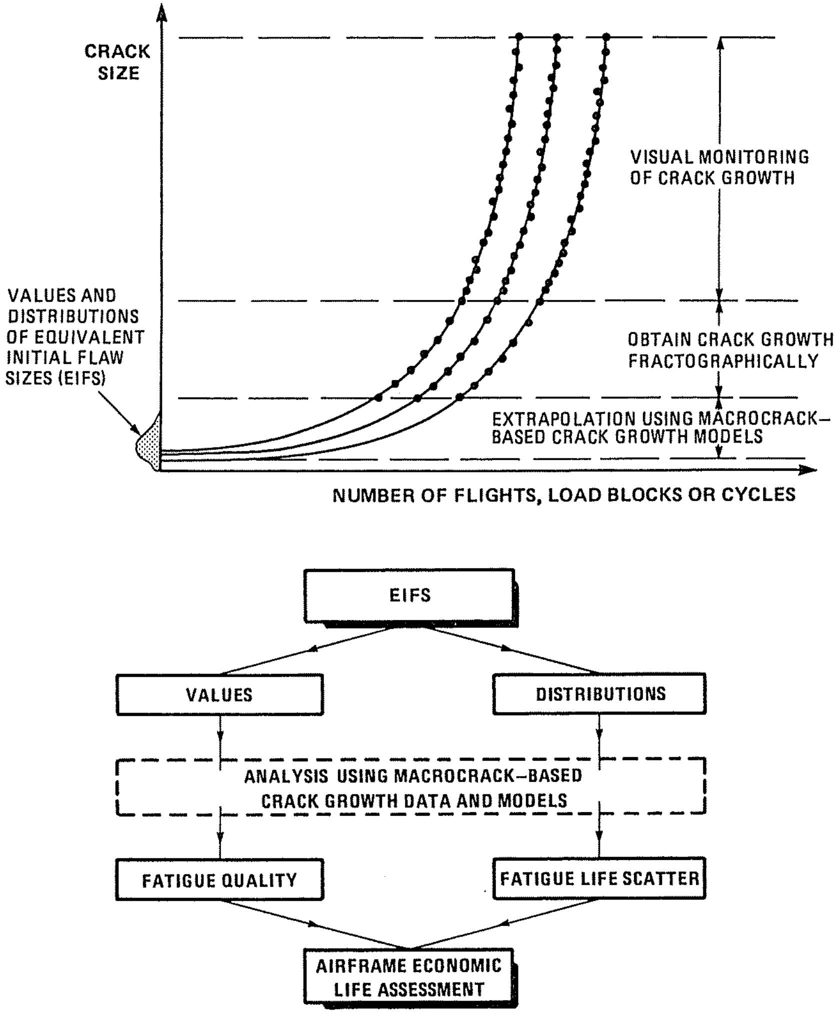


Fig 2 Schematic of the procedure for the EIFS concept of durability analysis

in assessing the economic life of the airframe. Details of the analysis procedure, which is quite complex, are given, for example, in **(6)(7)**.

Apart from the complexity of analysis the EIFS approach appears straightforward. However, extrapolation to initial crack lengths relies on macrocrack-based crack growth data and models, whereas the EIFS values are usually well within the short crack regime. The actual behaviour of short cracks is greatly influenced by a number of factors, including crack size, shape, and location **(12)**, local stress–strain fields at notches **(13)** and fastener holes, fretting **(14)**, load history **(15)**, fastener fit **(16)** and hole preparation (e.g., cold working), and material microstructure **(17)**. Present knowledge is inadequate to account for these factors quantitatively. This means that EIFS values and distributions apply only to the particular set of conditions for which they are derived.

A better understanding of the apparently anomalous behaviour of short cracks would enable modification of analytical modelling and extrapolation and provide a more certain basis for the EIFS approach. Some progress has been made but much remains to be done **(7)**. Thus it may be concluded that short crack growth is of primary importance for durability analyses of metallic airframe structures.

Conclusions

The practical engineering significance of short fatigue cracks in aerospace structures is limited. At the present time there are two areas in which short fatigue crack behaviour is of interest or importance:

(1) safe damage tolerance design and operation of some engine components, notably discs and blades;
(2) durability analysis of widespread cracking at fastener holes in metallic airframes.

Even in these areas the current importance of short cracks is mainly restricted to military aircraft, whose performance requirements place greater demands on structural integrity. This situation may change, but only gradually. If short cracks are to become generally significant for safety it will be necessary to achieve major advances in feasible NDI capabilities. With respect to durability, short cracks are potentially important for analysis of widespread cracking in both civil and military metallic airframe structures.

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