MASAAG Paper 116

Widespread fatigue damage in military aircraft

1 INTRODUCTION

This MASAAG Paper 116 presents recommendations for the assessment of the continued airworthiness risk posed by widespread fatigue damage (WFD).

This paper has been based on studies of the literature pertaining to widespread fatigue damage, covering both military and civil aircraft, and transport aircraft as well as combat aircraft. The damage tolerance design philosophy is mandated in the civil requirements but, in this Paper, allowance has been made for the application of other design philosophies, where appropriate.

It is intended that this Paper should form the basis of future policy applicable to the Project Teams (PTs) of the UK MOD and the Designers for any fleet likely to be affected by the recommendations. The purpose of the Paper is to provide all stakeholders in Structural Integrity (SI) management with a common understanding of the threat posed to SI by potential widespread fatigue damage, and to propose means of mitigating the risk.

2 What is WFD?

There has been awareness for many years that multiple cracks can develop in aircraft structure, such that its residual strength is compromised. Attention was focussed on the phenomenon by the Aloha Airlines accident in 1988; the “unzipping” of a fuselage lap joint whilst the aircraft was cruising at 24,000 ft precipitated a world-wide research effort and regulatory action to mitigate the risks posed by widespread fatigue damage.

It is thus well known that the presence of WFD and its manifestations as multiple site damage (MSD) and multiple element damage (MED) can lead to a combination of accelerated crack growth and reduced structural damage tolerance which can lead to significantly earlier failure of the aircraft structure than predicted in its absence.

A number of definitions were developed by civil regulatory committees to describe the terms associated with widespread fatigue damage in an attempt to standardise future publications. These definitions are reproduced below and are used throughout this Paper.

Damage Tolerance is the attribute of the structure that permits it to retain its required residual strength without detrimental structural deformation for a period of use after the structure has sustained specific levels of fatigue, corrosion, accidental or discrete source damage.

Widespread Fatigue Damage (WFD) in a structure is characterised by the simultaneous presence of cracks at multiple structural details that are of sufficient size and density whereby the structure will no longer meet its damage tolerance requirement (i.e. to maintain its required residual strength after partial structural failure).

Multiple Site Damage (MSD) is a source of widespread fatigue damage characterised by the simultaneous presence of fatigue cracks in the same structural element (i.e. fatigue cracks that may coalesce with or without other damage leading to a loss of required residual strength).

Multiple Element Damage (MED) is a source of widespread fatigue damage characterised by the simultaneous presence of fatigue cracks in similar adjacent structural elements.

The following terms have been used in the context of this paper, but may have other meanings elsewhere.

Usage refers to the general in-service life of the aircraft, in terms of whatever metric may be appropriate (flying hours, landings, pressurisation cycles, Fatigue Index, Equivalent Flying Hours, etc.); that is, the longer an aircraft remains in service (especially beyond its original design life), the greater the risk of developing WFD/MSD/MED becomes.

Fatigue qualified life: in the early stages of a fleet's life, this will be the certified design life (or design life goal, for civil aircraft), as demonstrated through the original fatigue substantiation programme. As the fleet moves through its life cycle, the qualified life will be compared with fatigue and usage consumption data (supported by validation exercises such as OLM programmes). Demonstration that WFD/MSD/MED will not occur prior to the end of the qualified life would typically involve an evaluation of the airframe using fatigue test evidence, analyses and aircraft usage data. The qualified life may already include specified modification action.

Degradation of structure not only includes the nucleation and growth of fatigue damage, but also the presence of fatigue, corrosion, fretting, galling, wear, creep, accidental damage, etc.

3 Why is WFD/MSD/MED a threat to SI?

As aircraft are increasingly retained in service for longer than their original design lives, widespread fatigue damage poses an increasing risk to the structural integrity and safety of these aircraft. The likelihood of WFD occurring in an aircraft structure increases with usage.

As defined above, WFD results from the development of simultaneous fatigue cracks at multiple structural details in one structural element (MSD) and/or several structural elements (MED) to an extent which causes the structure to no longer meet its residual strength requirements. WFD/MSD/MED may thus occur in similar structural details which are subject to similar high stresses, for example highly stressed fastener rows.

The potential risks presented by WFD/MSD/MED include the following:

- Multiple small cracks may coalesce to give a longer crack, leading to faster crack growth than expected;
- A long lead crack may grow more rapidly in the presence of short MSD cracks than when cracks are absent;
- The residual strength of the structure may be reduced by the presence of multiple small cracks;
- The presence of multiple short cracks may give a reduction in the crack stopping ability of the structure, e.g. cracks may extend across a greater number of fuselage frames than expected from analysis or test in the absence of WFD/MSD/MED.

The presence of WFD/MSD/MED may thus give a combination of accelerated crack growth and reduced structural damage tolerance – from the lower residual strength and crack-stopping ability – which can lead to significantly earlier failure of the aircraft structure than predicted in its absence. The potential risk from WFD/MSD/MED depends on a variety of factors, such as structural geometry, material properties, crack size, crack distribution, manufacturing quality and applied loading, but some typical examples from the literature are a reduction of the order of 37% in the fatigue life of a long lead crack in the presence of MSD and a residual strength reduction of 20 to 40% from MSD [5].

WFD can result from many cracks that are, in general, too small to be reliably detected using standard non-invasive non-destructive testing (NDT) techniques. In addition, structures susceptible to WFD may be difficult to inspect during routine maintenance tasks. An overview of available inspection techniques and their limitations is given in Annex C [6].

As explained above, the likelihood of WFD/MSD/MED occurring increases, the longer aircraft remain in service, especially where aircraft continue in service beyond their original design life. However, an earlier than predicted development of WFD/MSD/MED within the expected service life may result from an increase in loading severity (whether as a result of mass growth, change in aircraft role or changes in usage pattern) or raised stresses due to other reasons, e.g. material net section loss due to corrosion.

Therefore, WFD/MSD/MED clearly has important implications for the structural integrity and safety of aircraft and appropriate processes must be in place to minimise the risk of undetected WFD/MSD/MED.

4 What structures are at risk of WFD/MSD/MED?

The civilian Airworthiness Assurance Working Group (AAWG) identified a number of potential WFD/MSD/MED locations for transport aircraft structures. This list was reviewed and compared with arisings in the literature for transport aircraft, military transport aircraft and combat aircraft. The resulting categories of structures potentially susceptible to WFD/MSD/MED are identified in Annex A, for military transport aircraft (Table 1) and for combat aircraft (Table 2) (abridged from [5]).

In addition to the generic structures types identified in Annex A, there are a number of operational and other factors to be considered, that may increase the risk of WFD/MSD/MED. Examples of these factors are given in Annex B. As expected, the table shows that accumulated flights or hours (in other words, usage) are key factors in the potential for the development of WFD/MSD/MED. The degradation of the structure in service gives the potential for development of WFD/MSD/MED, typically at the design life. Life extension assessments must therefore include the consideration of WFD/MSD/MED, as required by Def Stan 00-970 (and civil regulations).

5 What measures can be taken to minimise the risks of WFD/MSD/MED?

As already noted, the risk of WFD increases with increasing aircraft usage. Consideration of WFD/MSD/MED is already required by Def Stan 00-970 (and civil regulations) and should be regarded as an integral part of SI sustainment activities. As such, a WFD assessment and mitigation programme should be carried out in conjunction with SI validation activities, such as Operational Load Measurement (OLM) programmes, Statement of Operating Intent and Usage (SOIU) updates, production concessions, corrosion records and ageing aircraft measures, such as life extension programmes, teardown, structural sampling, repair assessment programmes and ageing aircraft (structural) audits. It is in any case likely that information from these other activities will be necessary to support a WFD assessment and mitigation programme.

In general, WFD/MSD/MED would not be expected to occur within the fatigue qualified life (either the qualified design life, or the qualified life established by a life extension programme), unless loading severity has increased significantly, a change to the stress distribution has been introduced or material has been affected by corrosion. The possibility that loading severity/usage has increased with respect to design assumptions should be considered as a matter of course during OLM programmes and SOIU validation exercises.

It is necessary to have measures in place to preclude WFD from an aircraft fleet in a timely manner, to prevent SI being compromised and to obviate the need for unplanned SI recovery action. It is also necessary to consider the measures in place to preclude WFD in the context of other structural integrity issues such as ageing aircraft audits (which would be an opportunity to consider whether appropriate measures are in place), life extension (when the susceptibility to WFD would have to be assessed) and the Establishing SI phase, especially where second-hand aircraft are being procured.

The main thrust of the WFD assessment and mitigation programme will be to develop a package of measures to reduce the threat to SI. The combination of a variety of methods for the detection and assessment of WFD/MSD/MED is likely to be more effective than a single approach alone. The most generally used methods are full-scale fatigue testing, inspection and calculation where appropriate, supplemented by structural sampling and teardown where necessary. Application of these methods should result in supplementary inspection and maintenance programmes and refurbishment/modification as required. They should be used in conjunction with the results of other SI sustainment activities. The following activities should be considered:

a. **Assessment of susceptible areas.** The Fatigue Type Record should be reviewed and all Structurally Significant Items (SSIs) where WFD/MSD/MED is likely to be of concern should be identified (using Annex A and B as guidance). These may be, for example, similar features (i.e. with similar stress levels), those vulnerable to increases in loading severity and those susceptible to corrosion. Evidence from aircraft having a similar design pedigree (such as aircraft from the same designer and previous marks) should be considered for likely examples. Evidence from maintenance and repair arisings should also be included. For each area of concern, a threshold for WFD onset should be established, using accepted fatigue analysis techniques (for example safe life techniques to estimate crack nucleation time) and validated by test evidence, if available. Where an adequate threshold can not be demonstrated, these areas should be subjected to extensive inspection (preferably validated by test and/or teardown, see below).

b. **Teardown.** Teardown is normally required (although not mandated) as part of UK military SI management policy and has been shown to be important in finding WFD/MSD/MED. Teardown programmes enable detailed inspections not possible during normal in-service maintenance activities. Consideration should be given to retiring a high usage airframe, approaching its fatigue qualified life, for the purpose of teardown. As further aircraft in the fleet reach their fatigue qualified life, consideration should be given to carrying out repeat/additional teardown activity on samples recovered from these aircraft to validate the findings of the original teardown and confirm the efficacy of any inspection programmes. The teardown should be prioritised with respect to the identified susceptible features.

c. **Refurbishment/Modification.** Refurbishment is to be considered only as partial protection against the risk of WFD/MSD/MED as it will only be effective for certain types of structural feature, and if all incipient fatigue damage is removed. However, when coupled with an extensive inspection programme, refurbishment programmes may reduce the threat of WFD/MSD/MED somewhat (for example, if fastener holes are inspected, reamed and cold worked prior to reassembly). Modification or replacement of structure considered to be at risk (e.g. it has not been possible to demonstrate an adequate threshold for WFD onset) should be considered as the principal means of reducing the risk of WFD/MSD/MED to an acceptable level.

d. **Testing.** Full-scale fatigue testing (FSFT) has the potential, but cannot be relied upon, to identify those parts of the structure susceptible to WFD/MSD/MED and to indicate when this may occur; it is mandated for both original certification and for life extension in Def Stan 00-970 (and in civil regulations). The main concerns over the use of FSFT are that the loading may differ significantly from that experienced in service, and that the structure is normally in a pristine condition so that factors such as corrosion, damage or other degradation which may influence the onset of WFD/MSD/MED may not be present, so that the test results may be non-conservative. The FSFT must be sufficiently long to ensure that any potential in-service WFD/MSD/MED is identified. Civil and US military aircraft are typically tested to two lifetimes. UK military aircraft FSFT are normally taken to between three and five lifetimes, which makes the manifestation of WFD/MSD/MED more likely. Consideration should also be given to using a retired airframe for any life extension FSFT, such that corrosion and other damage are more representative of the fleet condition, and the consequent development of WFD/MSD/MED more likely than in pristine structure.

Once the point for the establishment (as described above) of a WFD programme has been reached, it is recommended that a Specialist Working Group should be established under the aegis of the Structural Integrity Working Group (SIWG) to scope and guide the development of the programme.

6 REFERENCES

1. Design and Airworthiness Requirements for Service Aircraft, Defence Standard (Def Stan) 00-970
2. Military Airworthiness Regulations, Joint Services Publication (JSP) 553
3. Military Aviation Policy and Regulation, Joint Air Publication (JAP(D)) 100A-01.
4. FAA, *Aging Aircraft Program: Widespread Fatigue Damage,* Docket No. FAA-2006-24821, Notice No. 06-04.
5. Brown, K. and Lucas, K. *Investigation into Lessons Learned from Past Experience of WFD/MSD/MED*, QINETIQ/CON/ACP/TR1000435/1.0, 1 March 2010.
6. Allen, B. P., Birt, E. A. and Shepherd D. P. *Investigation into Improved Practical Means of Inspection and Testing for WFD/MSD/MED,* QINETIQ/TS/AS/TR1000725, 1 March 2010.

Annex A – Structures likely to be susceptible to WFD/MSD/MED

Structure identified by AAWG as susceptible to WFD/MSD/MED
Longitudinal skin joints, frames, tear straps
Circumferential joints & stringers
Fuselage frames
Stringer-to-frame attachments
Shear clip end fasteners on shear tied fuselage
Aft pressure dome outer ring & dome web splices
Skin splice at aft pressure bulkhead
Lap joints with milled, chemi-milled or bonded radius
Abrupt changes in web or skin thickness, in pressurized or un-pressurized structure
Skin at run-out of large doubler, fuselage, wing or empennage
Window surround structure
Latches & hinges of non-plug doors
Over-wing fuselage attachments
Vertical stabiliser to fuselage attachment
Rib to skin attachments
Typical wing or empennage structure
Wing and empennage chord-wise splices

Table 1 Examples of structures where WFD/MSD/MED has been found for transport aircraft

Structure identified as susceptible to WFD/MSD/MED
Wings, especially at fastener holes
Bulkheads, especially wing-support
Fuel tank side skins
Engine inlet
Longeron
Fin root

Table 2 Examples of structures where WFD/MSD/MED has been found for combat aircraft

Annex B – Factors contributing to WFD/MSD/MED

Factor	Potential issues
Aircraft approaching Design Service Goal (DSG) or operation to Extended Service Goal (ESG) or “high-time”	Structural degradation during service leads to WFD/MSD/MED
Aircraft usage or loading more severe than originally anticipated	Increased usage or loading severity causes early onset of WFD/MSD/MED
Severe landings	Increased loading severity causes early onset of WFD/MSD/MED
Change in aircraft role	Modifications or change in loading lead to WFD/MSD/MED
Manufacturing and maintenance issues	Manufacturing or maintenance processes or errors lead to damage and/or increased local stresses which promote WFD/MSD/MED
Repair issues	Repairs cause local load re-distribution or are incorrectly applied, causing WFD/MSD/MED
Loose fasteners	Changes to load distribution and/or fretting may lead to WFD/MSD/MED
Corrosion	Thickness loss causing increased stress and/or crack initiation from corrosion may cause WFD/MSD/MED
Abrasion, chafing and wear damage	Damage promotes WFD/MSD/MED
Novel materials and/or processes	New materials or processes may lead to WFD/MSD/MED at unexpected locations or earlier than expected
Acoustic fatigue	Vibration of structure may promote WFD/MSD/MED

Table 3 Factors potentially contributing to WFD/MSD/MED for all aircraft

Annex C – Overview of NDT techniques for detection of WFD/MSD/MED

Technology	Subset	Detectable crack length	Comment
Dye penetrant	Fluorescent dye * †	150 nm	Operator dependant and susceptible to surface condition
	With structure under load (200 MPa) †	<1mm	In a comparative test found to be most sensitive for smooth surfaces
Eddy Current	Conventional high frequency (100kHz to 300 kHz)*	1 mm at surface	100kHz penetrates 0.4mm 300kHz penetrates

Technology	Subset	Detectable crack length	Comment
			0.2mm
	Conventional low frequency*	4.8 to 7.5 mm at 1.3 mm depth 10.5 to 13 mm at 7.6 mm depth	100 Hz to 10 kHz
	Magneto-Optic Imager (MOI) *	1.3 mm to 2.13 mm	Comparable eddy-current system achieved 2.38 mm
	Self-nulling eddy-current probe (Rivet Check System) *	1.3 mm in first layer of lap joint 12.7 mm at 12.7 mm depth	
	Meandering winding magnetometer *	2.8 mm in second layer	Potential to also detect pre-crack fatigue damage
	Transient or pulsed eddy-current *	1.5 mm crack at 1.5 mm depth. 6 mm crack at 6 mm depth	
	Remote field eddy-current ‡	3 mm crack at 11.3 mm depth	Laboratory experiment
	SQUIDs (Superconducting Quantum Interference Device) ‡	Not available	
Ultrasonics (open cracks)	Portable “immersion” technique ‡	2.5 mm in second layer	
	Angled phased array *	0.5 mm EDM notch in first layer and 1.5 mm EDM notch in second layer	Benefits from an automated data analysis technique
X-radiography	Film *	<0.5 mm	Highly dependant upon crack orientation
Laser ultrasonics	†	Not available	Susceptible to erroneous indications
Comparative Vacuum Monitoring (CVM)	‡	0.53 mm crack in a 1.0 mm thick and 1.1 mm crack in a 1.8 mm thick aluminium panel	Most sensitive test in a comparative life cycle study
Holographic interferometry	‡	<1 mm	Similar in performance to CVM in a comparative life cycle study
Positron annihilation	IPA-V system ‡	Multiple 10 micron cracks in 10 cm	Use of ionising radiation required

Technology	Subset	Detectable crack length	Comment
		depth	
	IPA-S system ‡	Multiple 10 micron cracks in 3 mm depth	Use of ionising radiation required
Phase contrast x-ray	‡	Not available	New technique still to be trialled
Advanced ultrasonics	Time-of-flight diffraction ‡	0.3 mm often associated with material thinning and corrosion	Primarily applied to pipes – interpretation difficult
	Surface acoustic waves ‡	6 mm crack in a bolted joint with 4 mm aluminium plates	Laboratory test only
Non-linear ultrasonics	Quantification of the acoustic non linear parameter (β) ‡	Primarily detects fatigue damage prior to crack initiation	Highly dependent upon specific application, little use in the field.
Structural health monitoring (excluding CVM)	Active monitoring (UGW) ‡	1 mm long crack when sensor within 1 cm of crack in plate structure.	Increased resolution with shorter range. Also depends on configuration, particularly propagation distance of guided wave.
	Passive system (AE) ‡	Not available	

Note: The techniques are identified according to their usage: * denotes in-service, † denotes laboratory technique (for teardown, for example) ‡ denotes technique under development.

Table 4 Summary table of NDE techniques for detection of WFD.