



3rd International Symposium on Aircraft Airworthiness, ISAA 2013

Discussion on Airworthiness Requirement of Widespread Fatigue Damage — Safe-life Methodology or Damage-tolerance Methodology

Feng Zhenyu^a, Mao Keyi^{a*}, Zou tianchun^a, Yang Yaning^a

^aTianjin Key Laboratory of Civil Aircraft Airworthiness and Maintenance, Civil Aviation University of China, Tianjin 300300, P.R.China

Abstract

Regulatory action and research conducted by FAA and industries to preclude widespread fatigue damage occurring in transport airplane fleet is introduced, especially the milestones in the rulemaking course. This article gives an interpretation of the current airworthiness requirement relating to widespread fatigue damage and limit of validity based on analysis of the widespread fatigue damage characteristics. The conclusion is made that the methodology of the current airworthiness requirement is a methodology both safe-life and damage-tolerance since that MSD/MED cracks are difficult to detect.

© 2014 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Selection and peer-review under responsibility of Airworthiness Technologies Research Center, Beihang University/NLAA.

Keywords: Widespread fatigue damage; damage-tolerance; safe life; airworthiness requirement; limit of validity

1. Introduction

WFD is a structural threaten which has never been recognized in structural design and verification till the Aloha accident happened. Learned from that accident, caused by the simultaneous cracking at multiple sites of the same structure (MSD) or multiple elements of adjacent structures (MED), WFD can lead to the structure no longer meet the required residual strength in a short period of time after the MSD/MED

* Mao Keyi. Tel: +86-022-2409-2312; fax: +86-022-2409-2311.
E-mail address: maoky_aw@163.com.

cracks become detectable by existing inspection method. Even worse, the MSD/MED cracks may be undetected the whole time even MSD/MED develop into WFD and led to catastrophic structural failure.

Section 25.571 Per-Amdt.25-132 requires that applicants for an airplane type certificate address the structural fatigue (other than sonic fatigue) technical issue by either damage-tolerance criteria or safe-life criteria. Damage-tolerance criteria, which is applied for most of the PSE, relies heavily on the inspection reliability. For certain structures, detecting MSD/MED cracking by existing inspection methods is impractical; fail-safe criteria is also a very important criteria merely not mentioned in Section 25.571, but it will lose its function as multiple simultaneous cracks developing in same structure or multiple elements of adjacent structures to certain extent.

Before Amdt.25-132 was issued, conservative damage-tolerance or safe-life evaluation was applied to preclude widespread fatigue damage and compliance with Section 25.571 on WFD requirement. For example more conservative factors were applied to divide the safe life and inspection threshold, higher fatigue stresses was used for analysis. As the latest revision to Section 25.571, Amdt.25-132 raised a systematic requirement to preclude widespread fatigue damage occurring in transport airplane fleet. It combined the structural-maintenance program with airplanes operation limit, makes that structural maintenance tasks, especial maintenance tasks address WFD, for an airplane are constant with time.

This paper will discuss the Amdt.25-132 rulemaking process, the theory Section 25.571 was based on, and analysis the key requirement of section 25.571.

Nomenclature

WFD	widespread fatigue damage
LOV	limit of validity
ISP	inspection start points
SMP	structural modification points
FSFT	full scale fatigue test
AAWG	Airworthiness Assurance Working Group

2. Milestone of Research and Rulemaking

On April 28, 1988, a Boeing 737-200 operated by Aloha Airlines, while en routing from Hilo to Honolulu, Hawaii at cruising altitude of 24,000 feet, experienced an explosive decompression and approximately 18 feet cabin skin separated from the airplane. Even the NTSB identifies that the probable cause for this accident was the failure of the airline's maintenance program to detect the significant disbanding (owing to the airline didn't management to supervise properly its maintenance force) and FAA to fail to require Airworthiness Directive 87-21-08 inspection of all the lap joints proposed by Boeing Alert Service Bulletin SB 737-53A1039, it also raised in the engineering design, certification, and continuing airworthiness of particular emphasis on multiple site fatigue cracking.

The first legislation precipitated by Aloha accident was in 1991 taken by congressional directing to FAA, namely Title IV of Public Law 102-143, the Aging Airplane Safety Act (AASA) of 1991. The act requires "the Administrator (FAA) to make such inspections and conduct such reviews of maintenance and other records of each airplane used by an operator to provide air transportation as may be necessary

to determine that such is in a safe condition and is properly maintained for operation in air transportation”, and specified that an operator must be able to demonstrate, as part of the inspection, “that maintenance of the airplane’s structure, skin, and other age sensitive parts and components have been adequate and timely enough to ensure the highest level of safety.” Although the Act didn’t define specifics of what had to be done, one clear intent was to avoid catastrophic failures caused by fatigue throughout the operational life of each affected airplane.

In response to the AASA, FAA rulemaking efforts resulted in the issuance of the Aging Airplane Safety Interim Final Rule on 2002, which was subsequently amended and finalized as the Aging Airplane Safety Final Rule. The overall safety objective of these rules is to assure continued airworthiness of fatigue critical structure. Two operational requirements were added to the regulations. The first was aging airplane inspections and records review in Parts 121, 129, and 135; the second requirement added was supplemental inspections in Parts 121 and 129.

The FAA has initiated rulemaking to revise FAR 25.571 in order to address shortcomings found as a result of the accident investigation twice so far. The first revisions dealt specifically with the addition of a requirement for fatigue test evidence for new certifications to address the possibility of widespread fatigue damage. The second and also the latest change in FAR 25.571 for WFD occurred in November 2011 with the issuance of Amdt.25-132, by which FAA require applicant to establish a LOV of the engineering data, stated as a number of total accumulated flight cycles or flight hours or both, that supports the structural maintenance program and must demonstrate that WFD will not occur in the airplane before it reaches LOV^[1,2].

3. WFD characteristics

3.1. MSD/MED initiation

MSD or MED begins as minute cracks which grow under the action of repeated stresses. This can happen because of normal operational conditions and design attributes or because of isolated situations or incidents, such as material defects, poor fabrication quality, or dings, corrosion pits, or scratches. These global damage may occur in a large structural element such as a single rivet line of a lap splice joining two large skin panels (MSD). Or it may be found in multiple elements, such as adjacent frames or stringers (MED).

It is hard to distinguish the main crack of MED/MSD cracking and local fatigue crack which is initiated in small areas or structural design details, since detecting the multiple slight cracks nearby is impractical. The MSD/MED initiation is mostly treated as MSD/MED detectable. And the time of MSD/MED initiation (in flight cycles, flight hours, or both) is the inspection threshold after which crack can be treated as MSD/MED cracking, even just one crack is detected. The aim is to achieve an efficient and economical inspection program.

Many OEM determine MSD/MED initiation time as the time required for the first MSD/MED crack reach adequate size to be detectable or 50% of the WFD sensitive structure details appear fatigue cracks. AC 25.571-1D proposes an alternative way to determine this Inspection Starting Point (ISP) as the $WFD_{(average\ behavior)}$ time divided by a factor of 3^[4].

3.2. MSD/MED cracks growth

MSD has the potential for strong crack interaction, and the effect of multiple cracks on each other needs to be addressed. MED, in most cases, does not have the same potential for strong crack interaction. But there is not a high probability that, after a crack initiates in an element, a second crack will initiate in

an element right next to it; and when an element fails completely, the load that has to be redistributed onto the non-failed structure. For where MSD/MED cracking inspection is practical, MSD/MED cracks growth must be monitored by special inspections if applicant wants to extend the operation of WFD sensitive beyond ISP. If so, the interval between inspections depends on the detectable crack size and the probability that it will be detected with the specific inspection method. This monitor period can't be extended indefinitely, if SMP is reached, repair, modification or replacement tasks must be applied to this WFD sensitive structure. If SMP is appropriately determined, a high percentage of airplanes would not have any multiple site damage or multiple element damage by the time the SMP is reached.

3.3. WFD average behavior

WFD (average behavior) is used to illustrate when WFD will occur. It is defined as “the point when, without intervention, 50% of the airplanes in a fleet would have experienced WFD in the considered area”. It is a point of time (in flight cycles, flight hours, or both number), and can be represent by a probability density function for certain structure configuration.

The WFD process includes both crack initiation and crack growth phase. Phase I in Fig.1 is the crack initiation period, during which generally spans a long period of time, there is little or no change in the basic strength capability of the structure. Moreover, probability analysis of MSD/MED detectable and WFD condition should also proof that WFD occurring in phase I is extremely impossible. At some time after the first small cracks start to grow, residual strength begins to degrade. Crack growth continues until the capability of the structure degrades to the point of the minimum strength required by Section 25.571(b).

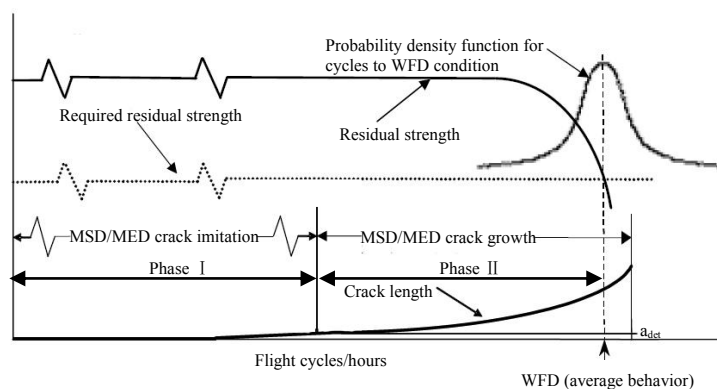


Fig. 1. WFD characteristics curve

4. Key requirement of precluding WFD

4.1. At least two times of Full Scale Fatigue Test

The requirement of FSFT was added by Amdt.25-96, which remain unrevised by Amdt.25-132. Amdt.25-96 requires that FSFT evidence is essential for demonstrating of widespread fatigue damage not occur in the airplane structure up to LOV. Furthermore, type certificate may be issued prior to completion

of full-scale fatigue testing, but airplane may not be operated beyond a number of cycles equal to 1/2 the number of cycles accumulated on the fatigue test article, until such testing is completed. That means FSFT is necessary, and the duration must be 2 times of LOV at least.

If one FSFT article maintains the minimum residual-strength requirements of Section 25.571(b) (maintains the minimum residual-strength requirement can be proofed by teardown inspections and a quantitative evaluation of any finding or residual-strength testing, or both) for test duration X , it can be conservatively assumed that the $WFD_{(average\ behavior)}$ of all WFD-susceptible structure is equal to X . accounting that ISP time is 1/3 of $WFD_{(average\ behavior)}$ time and SMP time is 1/2 of $WFD_{(average\ behavior)}$ time. It can be illustrated by fig.1, if X reaches 3 times of LOV, then the ISP is coincident with LOV, which means inspection is not essential for MSD/MED; if X reaches 2 times of LOV, SMP is coincident with LOV, which means predetermined modification or replacement task is not essential for the whole fleet (but may applied to MSD/MED cracking is found), but a monitor phase between ISP and SMP is needed. If any MSD or MED cracks were found, repair or alternative task should be applied. So the inspection should be practical, as AC 25.571-1D illustrated, if applicant would like to choose 2 times FSFT. FSFT duration can also between 2 times LOV and 3 times LOV, which a shorter monitor phase will benefit.



Fig. 1. (a) 3 times of FSFT schematic diagram; (b) 2 times of FSFT schematic diagram

4.2. WFD Evaluation

The WFD evaluation of susceptible structure is a process for determining when WFD is likely to occur in the structure, what maintenance actions might be necessary to prevent it from occurring before the LOV, and when those maintenance actions should be begun. For all the airplane structure with under the action of repeated stresses, WFD is unavoidable if the structure keeps operating without any repair, modification or replacement. Therefore, the WFD evaluation should applied to all structure (25.571 scope), as Appendix 3 of AC 25.571-1D addressed. If only it is demonstrated that the time of WFD occurring is far enough from LOV (5 times of LOV for example), WFD evaluation is not applicable.

A structure will come to one of three results below through WFD Evaluation: a. none additional maintenance actions are needed; b. MSD/MED cracking can't be detected reliably, the definite SMP and repair, modification or replacement plan; c. MSD/MED cracking can be detected reliably, the definite ISP, SMP and inspection interval, as well as the inspection method (semi-automated eddy current systems were recommended by AAWG) and repair, modification or replacement plan. For certain inspection, repair, modification and replacement plan, the purpose of WFD evaluation is to predict the ISP and/or SMP for the WFD sensitive structure. The ISP or SMP can be determined independently, or by divided by $WFD_{(average\ behavior)}$. Either the determination of ISP and/or SMP, or $WFD_{(average\ behavior)}$ should be based on service history, test data, fatigue analyses, damage-tolerance analyses, teardown inspections of high-usage airplanes, or any combination of these. The evaluation may accomplish either before FSFT or after

FSFT. Table 1 shows the subsequent treatment of WFD evaluation result for WFD evaluation is accomplished before FSFT. For demonstration purpose, ISP and/or SMP are determined by divide $WFD_{(average\ behavior)}$.

For situation 1 and 2 of Table 1, some design changes should be applied to relieve the sensitive of structure to WFD; for situation 2, proof that WFD will not occur up to LOV is an alternative way.

Table 1. Treatment of WFD evaluation result

No.	$WFD_{(average\ behavior)}$ determined by evaluation	Treatment	
		MSD/MED inspection is unreliable or impractical	MSD/MED inspection is reliable and practical
1	$\leq LOV$	Replacement task should be taken during FSFT and operation for several times; Demonstrate the modification will not led to WFD up to LOV.	MSD/MED monitor and replacement tasks should be applied during FSFT and operation; Demonstrate the modification will not led to WFD up to LOV.
2	$LOV \sim 2LOV$	Modification or replacement task should be taken during FSFT and operation; Demonstrate the modification will not led to WFD up to LOV.	MSD/MED monitor and modification or replacement tasks should be applied during FSFT and operation; Demonstrate the modification will not led to WFD up to LOV in addition.
3	$2LOV \sim 3LOV$	Modification or replacement task should be taken during FSFT and operation; Demonstrate the modification will not led to WFD up to LOV.	MSD/MED monitor and replacement tasks should be applied during FSFT; During operation, only MSD/MED monitor task is needed.
4	$\geq 3LOV$	Further consideration is unnecessary except extent of LOV; Structure is not sensitive to WFD if $WFD_{(average\ behavior)}$ time is enough times of LOV.	

4.3. Establishment of LOV for airplane

The LOV is the period of time (in flight cycles, flight hours, or both), up to which it has been demonstrated that WFD is unlikely to occur in an airplane's structure by virtue of its inherent design characteristics and any required maintenance actions. An airplane may not operate beyond the LOV, unless an extended LOV is approved.

The LOV, in effect, is the operational life of the airplane consistent with evaluations accomplished and maintenance actions established to prevent WFD. Although the LOV is established based on WFD considerations, it is intended that all maintenance actions required to address fatigue, corrosion, and accidental damage up to the LOV are identified in the structural-maintenance program. All inspections and other procedures (e.g., modification times, replacement times) that are necessary to prevent a catastrophic failure due to fatigue, up to the LOV, must be included in the Airworthiness Limitations section of the Instructions for Continued Airworthiness, as required by Section 25.1529, along with the LOV.

The process for establishing an LOV involves identifying a "candidate LOV", identifying WFD-susceptible structure, performing a WFD evaluation of all susceptible structure and finalizing the LOV. Even the "candidate LOV" is not the final LOV, it is what the FSFT duration time is based on. And only the "candidate LOV" is determined, if the structure is sensitive to WFD can be subsequently knew. Finalizing the LOV is adjustment to the "candidate LOV", which is based on how many of these

inspections and modifications or replacements does applicant would like to perform considering the corresponding LOV will be benefited.

5. Analysis of WFD airworthiness requirement

The ISP and SMP can be understood as the inspection threshold and the safe-life of structure respectively. For the structure which MSD/MED inspection is unreliable or impractical, the SMP is determined by WFD (average behavior) divided by a factor of 3. For fatigue evaluation, the minimum base scatter factors applicable to test results to determine safe-life (BSF_1) is 3^[3]. For WFD-susceptible structure for which monitor phase is applied, the ISP is determined by WFD (average behavior) divided by a factor of 3. For damage-tolerance evaluation, the minimum scatter factor applicable to the justified life in full scale fatigue test is 3. SMP, which is determined by WFD average behavior divided by a factor of 2, is for the purpose of providing the same safety level equal to two times FSFT. A series of test on panel with holes in SMAAC project showed that, the MSD initiation time is 0.659 of WFD (average behavior) averagely, which support that 2 times of FSFT and WFD average behavior divided factor of 2 can preclude widespread fatigue damage occurring in transport airplane fleet during LOV effectively.

6. Conclusion

The flowing conclusions are made:

- a. Two times of FSFT or WFD (average behavior) being divided by factor of 2 can preclude widespread fatigue damage occurring in transport airplane fleet during LOV effectively.
- b. For certain WFD-susceptible structure, the MSD/MED inspection may be impractical, so the methodology of the current airworthiness requirement is a methodology both safe-life and damage-tolerance.
- c. AMC25.571 addressed that “in those cases where inaccessible and uninspectable blind areas exist, and suitable damage tolerance cannot practically be provided to allow for extension of damage into detectable areas, the structure should be shown to comply with the fatigue (safe-life) requirement in order to ensure its continued airworthiness” is applicable to WFD situation. Equal consideration to FAR 25.571 should be applied for compliance with CS 25.571.

References

- [1] FAA. NPRM (Docket No. FAA-2006-24281; Notice No.06-04). 2006.
- [2] FAA. Final Rule (Docket No. FAA-2006-24281; Amendment Nos. 25-132, 26-5, 121-351, 129-48); 2010.
- [3] FAA ANM-115. Advisory Circular No. 25.571-1D, Damage Tolerance and Fatigue Evaluation of Structure; 2011, p. 17–19
- [4] FAA ANM-100 and AFS-300. Advisory Circular No. 25.571-1D, Establishing and implementing limit of validity to prevent widespread fatigue damage; 2011, p. 51–60