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'WFD' – WHAT IS IT AND WHAT'S 'LOV' GOT TO DO WITH IT?

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Abstract. *Fatigue cracking of any kind can significantly reduce the load carrying capability of a structure. Because of this it is considered to be a major threat to structural integrity. Chapter 14 of the Code of Federal Regulations (14 CFR) includes specific requirements intended to preclude catastrophic failures due to fatigue. Fatigue cracking may be symptomatic or incidental, localized or at multiple locations. The 14 CFR requirements make no distinction. They are intended to mitigate the strength reducing effects of fatigue regardless of why or how it manifests itself. The Aloha Airlines incident of 1988 was caused by fatigue cracking at multiple locations that could be considered symptomatic. This incident precipitated an avalanche of activities related to symptomatic fatigue cracking at multiple locations. This included research, development and even new rulemaking. In many respects, this cracking was treated like a new phenomena. For many it was seen as a new and singular threat that needed special attention. Consistent with this a new term, "widespread fatigue damage" (WFD), was coined. Is WFD really something new? Does it need special treatment and maybe even its own rule? These questions are considered and it is concluded that WFD is not something new. It is also argued that WFD is and always has been within the scope of existing rules. However, one thing that is missing in the rules is the concept of a "limit of validity" (LOV) of an airplane's fatigue management program (FMP). The LOV is the cumulative amount of operation beyond which it has not been validated that the FMP will keep the threat of catastrophic failure due to fatigue sufficiently low. The LOV is very much dependent on the fatigue knowledge base that has been acquired at any given time. The lack of an LOV is a deficiency relative to fatigue management in general and not just for what has been labeled WFD. It is concluded that rulemaking is needed to require the establishment of an LOV for certain existing airplane models and future certified ones. Additionally, the existing requirement to provide full-scale fatigue test evidence should not be limited to addressing the threat of WFD but should be required to characterize the fatigue performance of all primary structure in support of establishing an LOV for the FMP.*

1 INTRODUCTION

Fatigue is a generally recognized threat to aircraft safety. This is especially true for metallic primary airframe structures. Because of this, design certification requirements have been in place for some time which are intended to preclude catastrophic failures due to fatigue. These requirements have not remained static, however. They have evolved over time to where they are today. This evolution has been driven primarily by service experience that has revealed perceived shortcomings in the requirements themselves or in the way they have been interpreted. The evolution of fatigue requirements in Chapter 14 of the Code of Federal

Regulations (14 CFR) for transport category airplanes has been previously discussed by Eastin[1]. The very first requirements were based on the "safe-life" philosophy and date back to at least 1945. In 1956 a "fail-safe" approach, that has been previously discussed by Eastin and Mowery[2], was added as an acceptable option. In 1978 the requirements changed significantly when the "fail-safe" approach was deleted and the "damage tolerance" approach was adopted as the approach that had to be used unless shown to be impractical. Subsequently, the requirements remained essentially unchanged until 1998 when the term "damage at multiple sites due to prior fatigue exposure" was deleted and replaced with "widespread fatigue damage" (WFD). Additionally a requirement was added wherein the designer must demonstrate "with sufficient full-scale fatigue test evidence that widespread fatigue damage will not occur within the design service goal of the airplane". More recently, in April 2006, a proposed "WFD rule" was published by the FAA[3] for public comment. Among other things, this proposed rule would require designers to establish limits of validity (LOVs) for the fatigue management programs (FMPs) for certain existing airplanes and all transport category airplanes certified in the future.

So what is WFD? And why, after a period of 20 years without any substantial changes to the fatigue requirements, was it decided that they were not sufficient to deal with it? Also, what is behind the proposed "WFD rule" that has been recently proposed?

2 FATIGUE TYPES AND MANAGEMENT STRATEGIES

Fatigue in the context of this paper is very generic. It is not limited to just initiation or crack propagation. It can be due to an anomalous defect or not. It can be cracking at a multiplicity of locations or not. This is the fatigue that that the civil aircraft certification requirements of 14 CFR address. There is nothing now in the rules, nor has there ever been, anything that allows a designer to ignore any specific fatigue type or cracking scenario. If fatigue cracking could lead to a catastrophic failure it must be addressed and inspections or other procedures established, as necessary, to prevent catastrophic failure.

Eastin[4] has suggested that all fatigue events are due to either "normal" or "anomalous" fatigue and that it is important to identify the type of fatigue involved when selecting the strategy to be used to deal with it. Schijve[5] advises that, "a first question of a failure analysis must be: Was the failure a symptomatic failure or was it an incidental case?" In the discussion that follows, Schijve's terminology will be adopted and the words "symptomatic" and "incidental" will be used to refer to normal and anomalous fatigue respectively.

As has been previously discussed by Eastin[6] the specific fatigue requirements of 14 CFR depend on aircraft category and there are only three basic fatigue management strategies that are recognized. The "safe-life" approach is based on replacing or retiring structure before the probability of cracking is significant and will be referred to as safety-by retirement (SBR). The "fail-safe" approach depends on designing the structure such that cracking will be obvious during the course of normal operation and maintenance before it becomes dangerous and will be referred to as safety–by-design (SBD). The "damage tolerance" approach relies on inspections that are developed based on quantified crack growth and residual strength characteristics and will be referred to as safety-by-inspection (SBI). This paper specifically addresses the fatigue requirements for transport category airplanes contained in part 25 of 14 CFR where the current fatigue management strategies are SBI and SBR, with SBI required unless shown to be impractical.

3 MSD AND MED

Both incidental and symptomatic fatigue cracking can proceed in many different ways. In both cases cracking may initiate at a single location and remain isolated. On the other hand cracking may initiate at multiple locations and involve large areas and multiple elements

Subsequent to the Aloha accident, which is discussed below, the terms “multiple site damage” and “multiple element damage” were coined to facilitate discussing symptomatic fatigue cracking at multiple locations. These terms are currently defined in reference [7] as follows:

> **Multiple site damage (MSD)** is a source of widespread fatigue damage characterized by the simultaneous presence of fatigue cracks in the same structural elements.
>
> **Multiple element damage (MED)** is a source of widespread fatigue damage characterized by the simultaneous presence of fatigue cracks in similar adjacent structural elements.

These terms are unnecessary and should be discarded. Only the type of fatigue and whether or not it is reliably detectable before it becomes dangerous is important.

4 WFD

Another term coined after Aloha is “widespread fatigue damage”. It is currently defined in reference [7] as follows:

> **Widespread fatigue damage (WFD)** is the simultaneous presence of cracks at multiple structural locations that are of sufficient size and density such that the structure will no longer meet the residual strength requirements of § 25.571(b).

Consistent with the definition WFD is a condition. It is when MSD and MED have advanced to the point where the residual strength is reduced to the level required by § 25.571(b). This term was necessary because of the way the Aviation Rulemaking Advisory Committee (ARAC) recommended approaching the problem. They concluded that MSD and MED could not be managed with SBI alone and therefore mandatory replacement/modification (i.e. SBR) would be required at some point. They recommended that in order to prevent WFD from occurring, the susceptible structure should be modified at some fraction of the average time it takes for WFD to occur in a fleet of aircraft.

The term WFD, like MSD and MED, could be discarded. However, if we must have it the following definition is proposed:

Widespread fatigue damage (WFD) is when symptomatic fatigue cracking at multiple locations has degraded the static strength of the structure to the level required by § 25.571(b).

5 THE DEMISE OF SBD

A discussion of WFD would not be complete without discussing some of the concerns that resulted in SBD being removed from the part 25 fatigue requirements in 1978.

SBD was added to the fatigue requirements for transport category airplanes as an option to SBR in 1956. It was a generally held belief at the time that it was a superior approach as compared to designing and managing a structure to be crack free. It was considered to be more straightforward to achieve. It did not rely on expensive and time consuming full-scale fatigue testing and airplanes certified accordingly were considered to have an indefinite life. Not surprisingly SBD became the preferred strategy for the vast majority of transport airplanes certified in the 1960's and 1970's.

However, as the time in service of these airplanes started approaching the design life goals originally set by their designers, there was a growing concern over the potential loss of fail-safety due to the ever increasing likelihood of concurrent cracking in the surrounding structure. This concern is central to Maxwell's[8] 1973 ICAF paper in which he concludes that, "it is considered that there is likely to be a finite life for fail-safe structures beyond which safety is impaired by the onset of many interacting cracks………"

Another 1973 ICAF paper by O'Brien, Benoy, Torkington and Douglas[9] also raised concerns with respect to the long term capability of structure. One of several concerns cited was the "possibility of a number of defects developing concurrently in adjacent structure with potentially serious consequences for the fail-safe performance of the component."

The threat to fail-safety that was of concern is symptomatic fatigue cracking at multiple locations and it fits the current definitions of MSD and MED that are identified as precursors to WFD. Thus, WFD was being discussed and was a serious safety concern many years prior to the Aloha incident of 1988. Mounting concerns over the reliance on the fail-safe approach to manage fatigue over the long term is what prompted the Civil Aviation Authorities in the United Kingdom to limit the operational life of fail-safe certified aircraft in the 1970's. Finally, hastened by the Lusaka accident in 1977, which has been discussed by Eastin and Bristow[10], SBD was removed from the requirements in 1978. In its place SBI was adopted as the preferred strategy for managing fatigue in certain existing transport category airplanes as well as all future ones.

6 THE ADOPTION OF SBI

6.1 The Supplemental Inspection Documents (SIDs)

The British authorities determined that in order for the airplanes that they had set operational limits for to be allowed to continue to operate, continuing structural integrity programs would have to be established and implemented. Guidance was provided and the fatigue that was supposed to be considered was not limited to incidental or symptomatic or single or multiple locations. The FAA followed suit and provided similar guidance in AC 91-56 [11]. Likewise, the intent of this AC was that fatigue in general should be considered and appropriate maintenance actions established to mitigate it as a safety threat. In this context it can be argued that MSD and MED were within the scope of threats to be addressed and that, in theory, implementation of the SIDs should have precluded WFD.

6.2 Amendment 45 to § 25.571

As previously mentioned, Amendment 45 to § 25.571 removed SBD and adopted SBI as the required fatigue management strategy unless shown to be impractical. Consistent with the guidance provided in AC 91-56 the new rule did not limit the type of fatigue that needed to be considered. In fact, the new rule included the following direction:

> *"Damage at multiple sites due to prior fatigue exposure must be included where the design is such that this type of damage can be expected to occur."*

Also, like the guidance of AC 91-56, the new certification requirements included a provision for maintenance actions other than inspections. A provision included in paragraph (c) of § 25.571 stated the following:

> *"Compliance with the damage-tolerance requirements of paragraph (b) of this section is not required if the applicant establishes that their particular application for particular structure is impractical."*

This provision is realistic in that it recognizes that there may be fatigue cracking sites and scenarios that must be addressed but do not lend themselves to SBI. Symptomatic cracking at multiple locations could be an example of this.

§ 25.571 at Amendment 45 can, and should, be interpreted as generally applicable and all inclusive relative to fatigue. Accordingly the steps to compliance should be as follows:

- Consider fatigue from all potential sources (e.g. incidental and symptomatic).
- Address all probable scenarios (e.g. local as well as cracking at multiple locations)
- Perform a damage tolerance evaluation to characterize crack growth life and residual strength characteristics.
- Consider the practicality of detecting the cracking before required strength is lost.
- If SBI is practical establish inspections.
- If SBI is impractical default to SBR and establish a replacement/modification time in service.

Based on the above, it can be argued that § 25.571 at Amendment 45 contained comprehensive requirements that, if complied with, would have ideally resulted in freedom from any catastrophic failures due to fatigue. There were a couple soft spots, however.

The notion of an indefinite life that had existed for fail-safe certified structure was carried over to damage tolerance certified structure. For example, the opening sentence paragraph (a) reads as follows:

> *"An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion, or accidental damage will be avoided throughout the operational life of the airplane."*

But the "operation life" was not bounded. A literal interpretation is problematic and results in an unrealistic requirement to establish all the "inspections or other procedures" needed to avoid catastrophic failures for an unbounded period of time.

Additionally, total reliance on SBI was the expectation. The rule itself asks for a SBI solution first but allows SBR if SBI is shown to be impractical. However, the advisory material of AC 25.571-1 [12] reads as follows:

> *"Typical examples of structure that might not be conducive to damage-tolerance design are landing gear, engine mounts and their attachments."*

The message here is that SBI is expected for virtually all airframe fatigue cracking that needs to be addressed.

7 THE ALOHA EXPERIENCE

The 737 was one of the first Boeing airplane models that was subject to a damage tolerance evaluation using the guidance of AC 91-56. A SID was voluntarily developed by Boeing and subsequently mandated by FAA airworthiness directive in 1984. Four years later a 737 enroute from Hilo to Honolulu, Hawaii suffered an explosive decompression and lost a significant portion of the fuselage. The airplane landed otherwise intact but one life was lost and 8 persons were injured. A subsequent NTSB investigation was conducted and the findings were published in [13]. Causal factors included fatigue cracking in a fuselage lap splice at multiple sites linking up and resulting in catastrophic failure of the fuselage structure. The intent of the SID effort was to identify and establish any supplemental inspections or other procedures needed to prevent this kind of event. So how did this happen?

Potential cracking in the fuselage lap splices at multiple fastener holes had been considered in performing the damage tolerance evaluation of the 737. In accordance with AC 91-56 it was recognized that what would become known as WFD was a threat and was intended to be addressed as part of the damage tolerance evaluation. However, for this mode of cracking it was determined that the cracking scenario would involve mid-frame bay link up of multiple local cracks followed by extension of the resulting lead crack until the tips approached the bounding frames wherein the crack would turn and result in the skin "flapping" and a controlled loss of cabin pressure. This was considered a safe and acceptable event since damage would be safely contained within a single frame bay and would be immediately evident due to loss of cabin pressurization. It was concluded that for this particular cracking site and scenario there would be no need for proactive modifications or any special directed inspections since potential fatigue could be safely managed within the scope of normal maintenance.

In the case of Aloha, cracks occurred in the lap splice at multiple fastener holes and proceeded to linkup as anticipated. However, the resulting lead crack was not contained within a frame bay. One bay skin flapping did not occur. Cracking apparently proceeded fore and aft over multiple frame bays and was probably facilitated by pre-existing cracks in the lap splice fastener holes in adjacent frame bays. This eventually resulted in rupture and loss of a significant portion of the forward fuselage. The resulting condition of the airplane was extremely unsafe although a landing was accomplished.

As a consequence of Aloha there was a renewed concern with maintaining the continued airworthiness of high time airplanes. The primary threat was the same one that Maxwell and others were concerned with: symptomatic fatigue cracking at multiple locations. Maxwell had cautioned that this could eventually render the fail-safe characteristics of a structure no longer something that could be depended upon for safety. Now the concern was that SBI might not be sufficiently reliable. This resulted in an unprecedented avalanche of activities that included millions of dollars of engineering research and development and years of joint Industry and Airworthiness Authorities working meetings.

8 WFD RULEMAKING

The Technical Oversight Group for Aging Aircraft (TOGAA) was chartered by the FAA in the wake of Aloha to oversee aging airplane activities and make recommendations. The TOGAA heavily influenced the direction of rulemaking and their thinking is clearly reflected in changes to 14 CFR § 25.571 that were made with Amendment 96 in 1998. The TOGAA's perception of the problem embodied the notion that symptomatic cracking at multiple locations was a concern because it could undermine a structure's originally certificated fail-safe capability. This view was consistent with concerns that had been expressed by Maxwell and others relative to airplanes that had been certified to the pre-Amendment 45 fail-safe requirements. However, the TOGAA's view becomes problematic with airplanes certified to the damage tolerance requirements of 14 CFR § 25.571 at Amendment 45 and later where there is no requirement to demonstrate fail-safety for certification. The TOGAA concluded that damage tolerance based inspections using existing non-destructive inspection technology could never be made reliable enough to allow complete reliance on SBI to maintain safety. (Note that this was counter to the premise discussed earlier that structure certified to the new damage tolerance requirements could be operated indefinitely based on SBI and the expectation that this should be practical for virtually all airframe structure.) Because of this, the TOGAA concluded that the designers should be required to demonstrate that WFD would not occur within the design service goal that was set for the airplane. They further argued that this should be done based on full-scale fatigue test evidence. The TOGAA philosophy found its way into the rules with [14]. But what if an airplane is operated beyond its DSG? The rule is silent on this issue and there was nothing added that explicitly changed the perception that a damage tolerance certified structure could be operated indefinitely based on SBI. Although Amendment 96 was a step in the right direction it did not go far enough.

Concurrent with the TOGAA's oversight activities the ARAC was tasked on a number of occasions to consider aging aircraft safety and make recommendations. Specific recommendations were made to the FAA relative to WFD. Although the ARAC working group's perception of the basic problem was not the same as TOGAA, they did eventually arrive at the same conclusion that symptomatic fatigue cracking at multiple locations could not be managed safely with inspection alone. They concluded that a proactive approach was necessary wherein a structure should be modified or replaced before significant cracking of this kind became probable. They reasoned that inspection should only be used as added insurance if it could be shown to be reliable. They also recognized that the reliability of prediction and characterization of symptomatic fatigue cracking is dependent on the available fatigue knowledge base. And since any fatigue knowledge base is finite it is unreasonable to expect anyone to develop a FMP that will adequately address symptomatic fatigue at multiple locations for an unbounded period of time. Out of this came a recommendation that a limit of validity (LOV) be established for the FMP developed. This would be the period of time during which it was demonstrated that WFD would not occur by virtue of the structure's inherent fatigue characteristics and any mandated maintenance actions required to mitigate WFD.

Based on the above, the ARAC recommended rulemaking for existing airplanes to require WFD evaluations and establishment of LOVs. For future airplanes they recommended that § 25.571 be modified to require demonstration that WFD would not occur prior to the LOV. Furthermore it was recommended that the LOVs for both existing and new airplanes be published in the Airworthiness Limitations Section (ALS) of the Instructions for Continued Airworthiness (ICA) as an operational limit. No airplane would be allowed to operate beyond this point without a re-assessment of symptomatic fatigue at multiple locations and a demonstration that WFD would not occur prior to the extended LOV. Once this was done the ALS of the ICA would be updated with a new LOV and the airplane would be allowed to operate until that one was reached. Thus the LOV as characterized by the ARAC in reference [15] was not a brick wall but a gate with a lock. The key to the lock was an engineering assessment conducted to justify an LOV extension. It was also envisioned that additional maintenance actions would most likely be required to allow extension and these would involve both inspection and modification.

Proposed changes to 14 CFR § 25.571 for new airplanes and new requirements for certain existing airplanes that were intended to embody the basic intent of the ARAC recommendations on WFD were published for public comment in reference [3] in 2006.

9 THE CASE FOR AN LOV

The concept of an LOV has been questioned by some. It is often argued that the current approach that allows indefinite operation based on SBI and relies on airworthiness directives (ADs) for correcting "unsafe conditions" has provided an acceptable level of safety and there is no reason to suspect that it will not continue to do so in the future. However, a review of past fatigue incidents for which ADs were issued does not help the "business as usual" argument.

A survey was recently conducted by the FAA and it was found that serendipity was responsible for an uncomfortable number of fatigue crack findings in primary airframe structure. In these cases the maintenance action that resulted in the finding was not a damage tolerance based inspection where the site and scenario had been properly anticipated and an effective inspection established proactively. Instead, the successful detection of the cracking before it became dangerous can be attributed to happenstance and an alert and dedicated mechanic or inspector who went above and beyond the bounds of his specific tasking.

Another disturbing AD survey finding was that a significant percentage of the ADs were implemented in an emergency mode. This happens when it is determined that there is very little time to react and the normal AD process that involves public notice and comment prior to mandating any action must be short circuited to insure adequate safety for the fleet.

The findings discussed above support the assertion that "business as usual" is not good enough. There have been too many surprises. How long will our luck hold out? Market trends and time are against us in this regard. As more and more maintenance is outsourced and the maintainer is more and more removed from the owner/operator, it is more likely that factors that facilitate serendipity (e.g. tribal knowledge, ownership, going the "extra mile") will be diluted or even absent. Consequently, as the fleets age and the probability of symptomatic cracking increases, the probability of our luck running out also increases.

So, how to proceed? In accordance with the existing rules all fatigue types and likely scenarios must be addressed using the damage tolerance approach as discussed by Eastin and Swift[16]. Symptomatic cracking must always be considered since it is inevitable without intervention. But it is unreasonable to address all symptomatic cracking that might occur if the airplane is operated indefinitely. Here is where the LOV comes in. It bounds the problem based on a finite knowledge base (e.g. limited fatigue testing, little or no service experience). Based on the knowledge base existing at any given time it can be determined if there is any potential symptomatic cracking that needs to be addressed prior to the LOV. If so, the corresponding fatigue cracking sites and scenarios need to be defined and "duration", "detectable" and "dangerous" need to be quantified. Using this information one can make a determination if SBI is practical. If not, SBR must be used. Resulting maintenance actions are then defined as appropriate to preclude any symptomatic cracking up to the LOV and these actions constitute a fatigue management program (FMP) that is sufficient or "valid" up to the LOV. As the knowledge bases increases over time (e.g. service experience, additional testing and analysis) it is reasonable to expect that the LOV can be increased provided the proper evaluations are performed to address the threat of symptomatic cracking prior to an extended LOV. In this sense, the LOV is the demonstrated "fatigue knowledge base horizon" out to which symptomatic fatigue cracking can be safely managed.

10 RULEMAKING NEEDED

For reasons previously discussed, the threat of WFD is considered to be within the scope of the “fatigue” that was/is intended to be addressed when complying with § 25.571 at Amendment 45 and later. Therefore, there is no need for rulemaking to require any kind of special WFD evaluations. The requirement already exists and “inspections or other procedures” should be established based on the results of evaluations required under § 25.571 to prevent any potential catastrophic failures.

However, § 25.571 at Amendment 96 needs changes to correct several deficiencies. As currently written, the operational life of a type design is indefinite. As previously discussed, this is problematic. Establishing all the inspections and other procedures needed to operate safely for an indefinite period based on a finite amount of knowledge is simply not possible. To remedy this the designer should establish a finite period of time (i.e. an LOV) up to which he demonstrates that his proposed FMP has a high probability of avoiding catastrophic failures due to fatigue. Furthermore, it should be required that full-scale fatigue testing should be performed to support the demonstration relative to symptomatic fatigue (both local and at multiple locations). Acceptable means to mitigate failures could include (1) demonstrating a low probability of symptomatic cracking prior to the LOV, (2) damage tolerance based inspections when reliable and (3) proactive modification prior to the LOV. To be complete the LOV established by the designer should be captured in the ALS of the ICA as an operational limit.

To be consistent with the changes suggested above for new type design certification there should be rulemaking for existing airplanes that requires establishment of FMPs that adequately address symptomatic fatigue out to a demonstrated LOV that is also captured as an operational limit.

11 CONCLUSIONS

- All postulated or actual fatigue incidents can be characterized as either symptomatic or incidental.
- The terms MSD, MED and WFD are unnecessary and should be discarded.
- § 25.571 (Amendment 45 and on) and AC 91-56 explicitly require consideration of fatigue in general (i.e. no particular types or scenario are exempted).
- Changes to advisory material should be made to remove the inference that all fatigue cracking in all structure except for landing gear can be reliably detected before it becomes dangerous. There should be a stated expectation that there will be areas and probable cracking scenarios where SBI will not be viable and eventual replacement or modification will be necessary.
- Changes to 14 CFR transport category fatigue rules are needed to require:
    - Establishment of LOVs for the FMPs for certain existing airplanes and all future ones,
    - Full-scale fatigue testing to support validation of LOVs for the FMPs for all future airplanes.

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