



# **Structures Bulletin**

**ASC/EN**  
**Bldg 28, 2145 Monahan Way**  
**WPAFB, OH 45433-7017**  
**Phone 937-255-5312**

**Number:** EN-SB-08-001, Revision A

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**Subject:** Revised Damage Tolerance Requirements and Determination of Fail-Safety Life Limits for Fail-Safe Metallic Structures

## **Background:**

The Air Force formally introduced damage tolerance requirements with the release of MIL-A-83444 in July of 1974. While this specification allowed the use of either fail-safe or slow crack growth design concepts, the primary focus was on the slow crack growth concept since most combat aircraft were designed with many single load path structures. With the slow crack growth concept, it is mandatory that material, manufacturing and/or service induced defects not be allowed to reach their critical crack sizes before they are detected and repaired. Initial crack sizes were specified in MIL-A-83444, and later in Joint Services Specification Guide JSSG-2006, for use in design and in establishing initial inspection intervals. These assumed initial flaw sizes were selected as surrogates for the myriad of manufacturing, material and in-service defects (i.e., rogue flaws) that can and occasionally do exist in aircraft.

At that time, commercial aircraft as well as some military transport aircraft were designed to the commercial aviation regulation, CAR 4b.270, fail-safe requirements. These requirements stated that the structure must be able to sustain 80% of limit load multiplied by a 1.15 dynamic factor after failure or partial failure (and crack arrest) of a load path. However, even then it was recognized that the shortcomings of this requirement were that it didn't address the issues of continuing damage in adjacent structure, safe periods of unrepaired usage after a load path failure and the fact that the fail-safety would be jeopardized later in life by the onset of widespread fatigue damage (WFD). The FAA later addressed these shortcomings in FAR 25.571 Amendment 96. The Air Force addressed some of these issues in MIL-A-83444 and later in JSSG-2006 by imposing slow crack growth requirements on multiple load path and crack arrest structures that were essentially the same as for single load path structures.

In retrospect, this approach had unintended consequences since it discouraged the airframe manufacturers from designing and certifying their structures as fail-safe. Although many manufacturers provided some fail-safety through the use of multiple redundant load paths (e.g., to comply with battle damage requirements), no aircraft has ever been designed and certified to the MIL-A-83444 or JSSG-2006 fail-safe requirements. Fail-safe design is the preferred concept since it provides large damage capability and is the only concept that protects against all forms of damage an aircraft may encounter in its lifetime. These include fatigue cracking, corrosion, accidental damage, manufacturing defects, discrete source damage, and maintenance induced damage.

**Purpose:**

The purpose of this bulletin is to provide revised fail-safe requirements (Table 1), which will encourage fail-safe design and certification of future Air Force aircraft. These changes could reduce the current inspection burden by focusing special nondestructive inspections (NDI) on only those safety-of-flight (SOF) locations which are not fail-safe. Additionally, this bulletin provides the criterion for the determination of fail-safe life limits for fail-safe design concepts. Requirements for slow crack growth designs have also been revised and are provided in EN-SB-08-002 (Table 1). Fail-safe assessments of current aircraft to identify those SOF locations which have inherent fail-safe capability are covered in Structures Bulletin EN-SB-08-003.

Table 1. – Revised Damage Tolerance Requirements

<b>Damage Tolerance Approach</b>	<b>Structures Bulletin</b>	<b>Summary of Significant Changes</b>
<b>Fail-Safe Multiple Load Path</b>	<b>EN-SB-08-001</b>	<b>Residual strength based on design limit load (DLL) Deleted 1.15 dynamic factor Deleted dependant and independent categories Added criterion to establish fail-safe life limit (FSSL)</b>
<b>Fail-Safe Crack Arrest</b>	<b>EN-SB-08-001</b>	<b>None</b>
<b>Slow Crack Growth</b>	<b>EN-SB-08-002</b>	<b>Residual strength based on DLL Changed initial flaw size assumptions for continuing damage Added guidance to determine operational life limit</b>

## **Discussion:**

### **Criterion**

Whenever it is negotiated between the program office and the manufacturers, aircraft SOF structures shall be designed to be fail-safe per the following:

It shall be shown by validated analysis that catastrophic failure or deformation which could adversely affect flight characteristics of the aircraft, will not occur after a load path failure (fail-safe multiple load path) or partial failure (fail-safe crack arrest) where rapid propagation is arrested due to damage containment features in the design, up to the fail-safe life limit (FSLL). The failure or partial failure shall be either readily detectable<sup>1</sup> or malfunction evident<sup>2</sup>. At the time of, and at any time subsequent to the failure or partial failure of the load path, the remaining structure shall be able to sustain limit loads without failure and be free of any effects (e.g. – flutter) due to reduced stiffness until the structure is repaired, replaced or modified.

If it cannot be shown that this criterion is achieved, then the structure cannot be considered to be fail-safe and thus it must meet the damage tolerance requirements for slow crack growth design.

### **Residual strength requirements for fail-safe designs**

Both MIL-A-83444 and JSSG-2006 specified the required residual strength in terms of being able to sustain  $P_{xx}$  and  $P_{yy}$  load levels after a load path failure or partial failure. The  $P_{xx}$  concept was based on the recognition that fighter aircraft often exceed their design limit load levels and it was thus believed that it was appropriate to base the required residual strength on load exceedance data. The  $P_{yy}$  load level included a 1.15 factor to account for possible dynamic magnification at the instant of a load path failure.

This Structures Bulletin revises and simplifies the previous requirement by requiring the residual strength be equal to design limit load (DLL) at the time of, and any time subsequent to, load path failure or partial failure. For those aircraft where the probability that DLL exceeds  $1 \times 10^{-7}$  occurrences per flight, the residual strength requirement shall be approved by the program office and ASC/EN. The 1.15 dynamic factor is no longer an Air Force requirement.

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<sup>1</sup> Readily detectable means that the failure or partial failure would be apparent from pre-flight or post-flight visual observations or they would be visually obvious during a scheduled maintenance action conducted within the predicted safe period of unrepaired usage.

<sup>2</sup> Malfunction evident means that the failure or partial failure would result in the malfunction of other systems, which would alert flight or ground personnel to the existence of the structural failure or partial failure (e.g., fuel leakage, control system problems, loss of cabin pressure, etc.).

The residual strength of multiple load path fail-safe structure is solely dependent on the strength of the remaining adjacent structure subjected to the redistributed internal loads that will exist after any load path failure. Thus, the adjacent load paths must not contain cracks larger than the associated critical sizes under the redistributed limit load. These critical sizes need to be calculated and an assessment made with regard to their probability of existing during the service life. Additionally, the load path failure should not affect the overall stiffness of the structure to a point where, for example, flutter modes may become an issue.

Residual strength analyses shall be performed for fail-safe designs, wherein each load path must be considered as the failed load path with the adjacent load paths acting as the remaining intact structure. For crack arrest fail-safe structure, analytical and test procedures for predicting crack arrest and residual strength that are used in the development of aircraft shall be approved by the program office and ASC/EN.

Additionally, fail-safe multiple load path structure will no longer be designated as either dependent or independent structure as specified in JSSG-2006 and in MIL-A-83444. Multiple load path dependent structure has been described as structure having a crack initiating from a rogue flawed fastener hole common to both the primary load path and the adjacent structure. With this scenario, crack growth can occur simultaneously in the adjacent members, and when one load path fails, the adjacent member could also fail. This structure may not be fail-safe for this cracking scenario and thus must be considered as slow crack growth structure (i.e., it is a multiple load path structure that acts like single load path structure) and must meet the damage tolerance requirements for slow crack growth designs. It does not comply with a basic requirement for fail-safety, which is that the load path failure will be detected and repaired prior to the failure of the remaining intact structure.

For multiple load path structure to have the potential of being fail-safe, the load paths must either not have a potential common damage origin (previously defined as multiple load path independent structure), or the design fail-safe damage size must encompass more than a single member (e.g., frame and skin bays).

### **Fail-safe design damage**

The design damage sizes for fail-safe design concepts often is an individual member or load path failure such as a wing or vertical stabilizer attach fitting, a wing carry through bulkhead, or a wing plank. However, for panelized construction the design damage normally consists of combinations of fuselage skin and stringer, fuselage skin and frame, wing skin and stiffener, spar cap and skin, and spar cap and web.

The goal of fail-safe design is to achieve sufficient damage capability to encompass damage due to discrete impacts from a variety of sources (e.g., engine burst, bird strike, hail, battle damage etc.) and local failures due to manufacturing, maintenance, accidental and/or environmental damage without loss of the aircraft. It is also a goal that the design damage sizes are large enough to be readily detected from the exterior of

the aircraft thus enhancing its visual detection and minimizing the possibility of an inspection miss. Some examples of typical design damage are as follows:

- Completely severed frame, tear strap and the two adjacent skin bays for the fuselage.
- Completely severed stringer and adjacent skin bays for the fuselage, wing or empennage skin and stringers.
- Completely severed stringer and at least one adjacent skin bay for the wing and empennage splicing stringers.
- Completely severed frame, tear strap and adjacent bays of the fuselage longitudinal lap splices.
- Severed lower cap on a wing carry through bulkhead.
- Severed fitting in system of wing attach fittings.

### **Inspections of fail-safe designs**

Inspections of fail-safe structure shall be visual for the purpose of discovering load path failures (fail-safe multiple load path) or partial failures (fail-safe crack arrest). These inspections are valid until the onset of WFD at which time the fail-safe capability will be degraded. The visual inspection intervals to detect failed structural elements or arrested cracks should be no longer than the predicted time for possible cracks that may exist in the adjacent intact structure to grow to their critical sizes under the redistributed loads. This time period is defined as the safe period of unrepaired usage. It is anticipated that this time period will decrease with an increase in flight hours as the sizes of cracks that may exist in the adjacent structure increases. However, a simplified approach has been developed to preclude updating the fail-safe analysis accounting for various crack size assumptions as explained below.

As noted in the definition of readily detectable, there are two cases, which may be considered: Case 1) where the damage will be detected during pre and post-flight visual inspections; and Case 2) where visual inspections must be scheduled to detect the damage.

**Case 1:** Obvious failures or partial failures (e.g., arrested cracks) that would be detected by a walk around inspection of the exterior of the aircraft. In this case, a visual inspection is performed before and after each flight and this is referred to as a “visually/functionally evident inspection.”

**Case 2:** Damage that requires a maintenance action to gain access to the structure (e.g., removal of a panel, use of ladders, etc.) to perform a visual inspection is referred to as a “scheduled visual inspection.”

Although not essential to protect structural safety of fail-safe structures, NDI to detect subcritical cracks and corrosion to preclude potentially expensive load path failures or partial failures of fail-safe structures may be performed at the discretion of the program office.

## **Fail-safety life limits**

As aircraft age there is an increased risk of encountering the onset of WFD involving both multiple element damage (MED) and multiple site damage (MSD). Aging processes (e.g., fatigue, corrosion, and wear) can seriously degrade the safety of fail-safe designs (and substantially increase the risk of catastrophic failure due to inspection misses in slow crack growth designs). MIL-STD-1530C requires analysis and full-scale durability testing to show that the onset of WFD will not occur prior to reaching the design service life. To ensure the onset of WFD does not jeopardize fail-safety, fail-safety life limits must be established. The operational life of fail-safe designs shall be limited to that point where the fail-safe residual strength is degraded to DLL due to the onset of WFD (i.e., the onset of MED for multiple load path concepts and the onset of MSD for crack arrest concepts). Approaches to establish fail-safety life limits for multiple load path fail-safe designs and crack arrest fail-safe designs are described below.

### ***Fail-safe life limit for multiple load path fail-safe designs***

With this design concept, the structure must retain its required residual strength for a safe period of operational usage after the failure of a load path. This failure may occur due to any reason (e.g., manufacturing or maintenance induced defect, accidental damage, environmental damage or discrete source damage) and at any time. The adjacent load path or paths provide the second line of defense against catastrophic failure. It is this adjacent structure that then controls the safe operational life limit for the aircraft. The specific type of WFD that affects multiple load path designs is multiple element damage (MED). MED is defined as “a type of WFD where the damage states of two or more structural elements can interact.” With the eventual occurrence of MED in the adjacent structure, its residual strength will be degraded.

Acceptable deterministic approaches to predicting when the FSLL will be reached are illustrated conceptually in Figures 1 and 2. Shown in these figures are predicted crack growth curves for the most critical adjacent structural component for two cases: “without load path failure” and “with load path failure at  $t=0$ ” under the redistributed internal loads. The load path failure assumed at  $t=0$  recognizes that the structure must be fail-safe for all threats to include discrete source damage that could occur at any time.

Consistent with JSSG-2006 durability requirements, the assumed initial flaw size,  $a_i$ , would be representative of the upper bound of normal material and manufacturing quality (i.e., a 0.01 inch initial corner flaw in a fastener hole) for both cases. As noted previously, a different  $a_i$  should be used if the risk analysis (required by MIL-STD-1530C) indicates that a different initial flaw size is required.

### Visually/functionally evident failure (Case 1):

The predicted critical crack size,  $a_{cr1}$ , is the size in the adjacent load path without failure of the load path under consideration and,  $a_{cr2}$ , is the predicted critical crack size with failure of the load path under consideration. Note that  $a_{cr2}$  is much smaller due to the increased internal loads. Projecting  $a_{cr2}$  onto the crack growth curve for “without load path failure” defines the fail-safety life limit for the structure assuming that the failure was pre-flight, post-flight ground or malfunction evident. This is shown as “fail-safety life limit for visually/functionally evident failures” in Figure 1. Beyond this point, the structure is no longer considered fail-safe because the adjacent load path could fail at the same time.

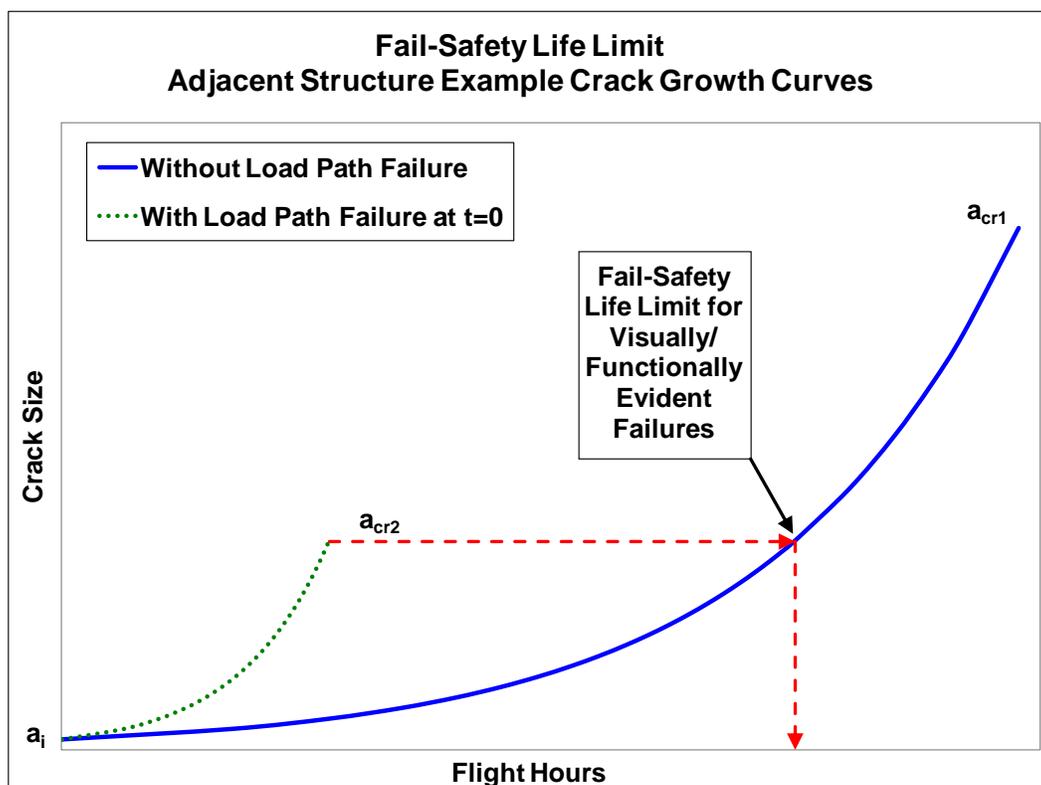


Figure 1. – FSSL for Visually/Functionally Evident Failures

## Scheduled visual inspections (Case 2):

If the failure of the load path were not immediately obvious, but required a scheduled visual inspection to detect the failure, then the fail-safety life limit would need to be reduced. The amount of reduction of the life limit would depend on the frequency of the scheduled visual inspection interval to inspect for the failed load path. This interval is determined by the program and would normally coincide with other maintenance actions. This visual inspection interval should not be confused with nondestructive inspections that are performed on slow crack growth designs!

As in Case 1, the predicted critical crack size,  $a_{cr1}$ , is the size in the adjacent load path without failure of the load path under consideration, and  $a_{cr2}$ , is the predicted critical crack size with failure of the load path under consideration. Assuming that the load path failed just after the last scheduled inspection, then the fail-safety life limit should be reduced to the time associated with the crack size that could have existed in the adjacent structure at the time of last visual inspection. This crack size is shown as  $a_s$ . Projecting  $a_s$  to the “without load path failure” crack growth curve then defines the fail-safety life limit for structures requiring scheduled visual inspections as shown in Figure 2. Alternatively, this approach can be used to determine an inspection interval for a required FSLL.

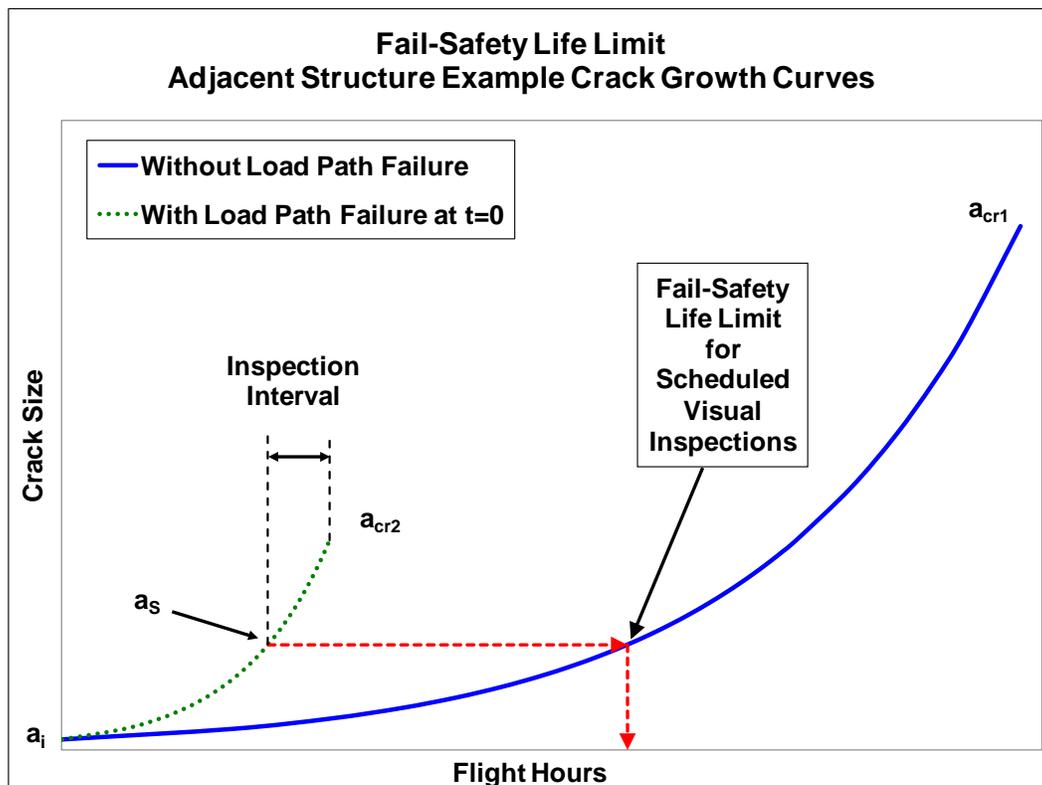


Figure 2. – FSLL for Scheduled Visual Inspections

### ***Fail-safe life limit for crack arrest fail-safe designs***

While the specific type of WFD that threatens multiple load paths is MED, the threat to crack arrest fail-safe structure is MSD. MSD is defined as, “a type of WFD characterized by the simultaneous presence of fatigue cracks in the same structural element (e.g., fatigue cracks that may coalesce with or without other damage leading to a loss of required residual strength).”

The prediction of the FSL for crack arrest fail-safe structure thus depends on not only predicting whether or not crack arrest will occur and predicting the residual strength without MSD present, but also predicting when the MSD will reach sufficient density and size where the lead crack or other large damage may not arrest and/or the required fail-safe residual strength can no longer be maintained. Some past fail-safe residual strength test results from mechanically fastened aluminum panels have shown that very small MSD in fastener holes (e.g., ~0.02 to 0.04 inch) ahead of the arrested crack can have a significant effect on the fail-safe residual strength (e.g., a 20 to 30% reduction). The prediction of the onset of MSD thus becomes one of predicting when such cracks will occur. Unfortunately, fatigue analyses (using either strain-life or stress-life methods) have been unreliable for predicting when MSD will occur.

The best measure of when the onset of MSD will occur is from the teardown inspection of the full-scale durability test article. This is particularly true for pressurized fuselages, since the cabin pressurization is the primary fatigue loading and the test spectrum generally represents the actual operational spectrum quite well. However, if the onset is to be quantified, the fatigue test duration needs to be sufficiently long so that MSD occurs. If it does not occur in the required two-lifetime durability test, then it can be assumed that the FSL is greater than the design lifetime when flown to the design usage.

For structure other than the pressurized fuselage that could rely on crack arrest fail-safety (e.g., wing and empennage skin and stringer panels), the teardown inspection of the full-scale durability test article is still the best source for developing the FSL. In this case, the MSD cracks can be analytically “backtracked” to develop an equivalent initial flaw size (EIFS) distribution as described in MIL-STD-1530C. The growth of this distribution should then be predicted using the same crack growth model for the actual usage spectrum. A risk analysis should also be performed to predict when the MSD would be of sufficient size and quantity to preclude crack arrest and/or cause the fail-safe residual strength to fall below DLL.

### ***Validation of predicted fail-safety life limits***

If the fail-safety life limit is reached and there have been no failures, several questions arise. Has the fail-safe capability really been lost by virtue of MED or MSD in the adjacent structure? What is required to validate whether or not MED or MSD has occurred? If MED or MSD has occurred, how can safety be protected until the aircraft is retired, or the structure is replaced or modified? And, if MED or MSD has not yet occurred, how can the operational limit be extended?

The answers to these questions require a teardown inspection of a high usage aircraft to determine whether or not the onset of MED or MSD has occurred when the predicted FSSL has been reached. This is particularly true if the predicted critical crack sizes under the redistributed loads for fail-safe concepts are very small and thus not detectable without fastener removal and optical inspections. If it is concluded that MED or MSD does exist, the short term alternatives are: grounding, operational restrictions, NDI, or proof testing (if practical) to guard against failure of any load path until the structure can be replaced or modified. In this case, a comprehensive risk analysis is required to formulate the appropriate course of action. If it is concluded that MED or MSD has not yet occurred, an evaluation should be performed to determine when it is likely to occur and the actions necessary (analysis, testing, additional teardown inspections, etc.) to ensure structural integrity is maintained if operations approaching this limit are anticipated.

## Summary:

### Criterion

It shall be shown by validated analysis that catastrophic failure or deformation which could adversely affect flight characteristics of the aircraft, will not occur after a load path failure (fail-safe multiple load path) or partial failure (fail-safe crack arrest) where rapid propagation is arrested due to damage containment features in the design, up to the fail-safe life limit (FSLM). The failure or partial failure shall be either readily detectable<sup>1</sup> or malfunction evident<sup>2</sup>. At the time of, and at any time subsequent to the failure or partial failure of the load path, the remaining structure shall be able to sustain limit loads without failure and be free of any effects (e.g. – flutter) due to reduced stiffness until the structure is repaired, replaced or modified.

If it cannot be shown that this criterion is achieved, then the structure cannot be considered to be fail-safe and thus it must meet the damage tolerance requirements for slow crack growth design.

### Residual strength

The required residual strength shall be DLL at the time of and any time subsequent to load path failure or partial failure. For those aircraft where the probability of DLL exceeds  $1 \times 10^{-7}$  per flight, the residual strength requirement shall be approved by the program office and ASC/EN. The use of the 1.15 dynamic factor is no longer required.

### Fail-safe design damage

Design damage should be extensive enough and sized so as to encompass damage that could occur due to discrete impacts from various sources as well as local failures due to manufacturing, maintenance, accidental and/or environmental damage. The goal shall be to have the design damage include failed internal members plus exterior skin so as to maximize their visual detectability from the exterior of the aircraft.

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<sup>1</sup> Readily detectable means that the failure or partial failure would be apparent from pre-flight or post-flight visual observations or they would be visually obvious during a scheduled maintenance action conducted within the predicted safe period of unrepaired usage.

<sup>2</sup> Malfunction evident means that the failure or partial failure would result in the malfunction of other systems, which would alert flight or ground personnel to the existence of the structural failure or partial failure (e.g., fuel leakage, control system problems, loss of cabin pressure, etc.).

### **Inspections of fail-safe designs**

Safety inspections of fail-safe structure shall be visual for the purpose of discovering load path failures (fail-safe multiple load path) or partial failures (fail-safe crack arrest). These inspections are valid until the onset of WFD at which time the fail-safe capability will be degraded. The intervals for visually inspecting for failed structural elements or arrested cracks should be no longer than the predicted time for possible cracks that may exist in the adjacent intact structure to grow to their critical sizes under the redistributed loads. This time period is defined as the safe period of unrepaired usage. It is anticipated that this time period will decrease with an increase in flight hours and the sizes of durability cracks that may exist in the structure. As noted in the definition of readily detectable, there are two cases, which may be considered: Case 1) where the damage will be detected during pre and post-flight visual inspections; and Case 2) where visual inspections must be scheduled to detect the damage before complete failure.

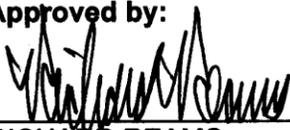
### **Determination of fail-safe life limits**

The operational life of fail-safe designs shall be limited to that point where the fail-safe residual strength is degraded to DLL due to the onset of WFD (i.e., the onset of MED for multiple load path concepts and the onset of MSD for crack arrest concepts).

The onset of MED will occur in multiple load path fail-safe structures when it is likely that a crack of critical size under the redistributed limit loads exists in the remaining adjacent load paths. An acceptable deterministic approach for predicting this limit is illustrated in Figures 1 and 2. A probabilistic approach (i.e., risk analysis) for predicting this limit is also acceptable, provided that a reliable crack population can be developed.

The onset of MSD will occur in crack arrest fail-safe structures when it is likely that the size and density of cracking ahead of the lead crack (or other damage) is sufficient to preclude the arrest of the crack at limit load. The prediction of this limit shall involve a risk analysis based on residual strength analysis, tests with and without MSD present, and predicted flaw populations versus time based on data derived from teardown inspections of full-scale fatigue tests.

Approved by:



RICHARD REAMS  
Technical Advisor, Structures  
ASC/ENFS  
WPAFB, Ohio

Approved by:



CHARLES A. BABISH IV  
Technical Advisor, ASIP  
ASC/EN  
WPAFB, Ohio

*Coordination*

<i>Name</i>	<i>Function</i>	<i>Email</i>	<i>Initials</i>
Mark DeFazio	Chief, Structures Branch	Mark.DeFazio@wpafb.af.mil	MSD
Juan Lado	Tech Expert, Durability and Damage Tolerance	Juan.Lado@wpafb.af.mil	JL