APPLICATION OF FLAW TOLERANCE METHODOLOGIES ON ROTORCRAFT METALLIC PRINCIPAL STRUCTURAL ELEMENTS

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ABSTRACT

The current airworthiness regulations require that a fatigue tolerant design is accomplished for metallic Principal Structural Elements (PSE). The goal is to avoid catastrophic failure due to fatigue cracking during the operational life of the rotorcraft, taking into account the effects of environment, flaws or accidental damage.
Several methodologies and guidelines have been recognized and discussed, supporting the establishment of replacement times and inspection intervals.
Airbus Helicopters successfully certified its H175 aircraft with EASA in 2014. This aircraft is compliant with the fatigue and flaw tolerance requirements of CS29. The substantiation of airframe fatigue tolerant design was achieved by a multiple load path approach including combined Safe-Life and Flaw tolerance methodologies. It leads to the definition of retirement times and/or mandatory inspection intervals for metallic principal structural elements.
Based on analysis mainly, this approach was used on each metallic PSE.

This paper presents this approach developed by Airbus Helicopters on each PSE made of metallic materials and presents the different aspects of this mean of compliance with fatigue and damage tolerance requirements.
It describes first the airworthiness regulations requirements regarding the fatigue and flaw tolerance for rotorcraft components. Then it details the methodology applied on H175 airframe PSE leading to determination of retirement times and inspection interval. The combination of fatigue analysis and flaw tolerance analysis is used based on probabilistic approach. Flaw tolerance analysis is leading to evaluation of design regarding different flaws that may be experienced in service, as e.g. corrosion, impacts or scratches.

INTRODUCTION

Airbus Helicopters implemented flaw tolerance methodologies on H175 to show compliance of design with airworthiness requirements CS29.571 and FAR29.571. The requirement is to evaluate the rotorcraft fatigue tolerance considering the effect of flaws or accidental damage. The substantiation of fatigue tolerant design is obtained by a combination of Safe-Life methodologies and Flaw tolerance approaches leading to the definition of retirement times and/or mandatory inspection intervals for every principal structural element.

Principal Structural Elements are those structural elements that contribute significantly to the carrying of flight or ground loads and the fatigue failure of which could result in catastrophic failure of the rotorcraft. First step is to identify these PSEs among the components supporting flight or ground loads by analysis of their failure consequences on rotorcraft.

Once these elements have been identified among the primary structure, a threat assessment is established to list the potential threats on components during manufacturing, transportation, maintenance and in service. The different types and sizes of flaws and their relevant locations are determined with respect to realistic occurrence during the life of the rotorcraft. The assessment takes into account the operational environment and previous company experience on identified threats to be as exhaustive as possible. The identified damages on metallic parts included corrosion, impact dents or scratches.

A fatigue evaluation is then performed considering the presence or not of redundancy in load paths. Metallic Principal Structural Elements are subdivided in Single Load Path PSEs and Multiple Load Path PSEs.
Single Load Path PSE flaw tolerance approach is based on demonstrating that, in presence of flaw, the time for a crack to initiate will be covered by an inspection to detect the flaw. It is a crack initiation method. Other methods are applicable and are detailed in ref [3].

Multiple Load Path PSEs will be identified when secondary load path can sustain flight limit loads in case of failure of primary load path. Proposed means of compliance in regulations are combining Safe-Life retirement, leading to retirement time, and Safe-Life inspection for a failed element, leading to inspection interval. This method is a crack initiation method. It results in an inspection for a completely failed load path. The interval is based on the crack initiation life of the adjacent structure. Internal load redistribution due to failure of the load path should be taken into account. The rationale behind this method is based on visual detection and disposition of the failed load path before the probability of initiation a crack in the adjacent structure becomes significant.

Both retirement times and inspection intervals are defining the PSE airworthiness limitations that are included in the Airworthiness Limitations Section of the Instructions for Continued Airworthiness.

These means of compliance for Single Load Path PSEs and Multiple Load Path PSEs were applied on H175 metallic PSE to evaluate fatigue and damage tolerance, and to show compliance with regulations. They were meaningful to preserve the design from additional weight and to ensure a high safety level in service.

1. DEFINITIONS

Specific acronyms and their definitions are provided in table 1. Other acronyms are listed at end of paper.

Acronym	Description	Definition	Source
PSE	Principal Structural Element	Principal Structural Elements are those structural elements that contribute significantly to the carrying of flight or ground loads and the fatigue failure of which could result in catastrophic failure of the rotorcraft	Ref [2] §d (1)(xvi)
CAT	Catastrophic	A catastrophic failure is an event that could prevent continued safe flight and landing	Ref [2] §d (1)(iii)
MLP	Multiple Load Path	Multiple Load Path is identified with a redundant structure of multiple and distinct elements, in which the applied loads would be safely redistributed to other load carrying members after complete failure of one of the elements	Ref [2] §d (1)(xv)
SLP	Single Load Path	One loaded element which cannot be identified as element of MLP	
BDF	Barely Detectable Flaw	Worst-case flaw that is expected to remain on the structure for its operational life	Ref [2] §d (1)(ii)
CDF	Clearly Detectable Flaw	Worst-case detectable flaw that would not be expected to remain in place for a significant period of time without corrective action	Ref [2] §d (1)(iv)

Table 1: Acronyms and Definitions

2. ACCEPTABLE MEANS OF COMPLIANCE OF AC29.571B

EASA Notice of Proposed Amendment (ref [6]) and FAA NPRM (Notice of Proposed RuleMaking) for 29.571 (ref [4]) were used as reference guidelines to define means of compliance for fatigue and damage tolerance evaluation of H175 metallic PSE. These guidelines have since been implemented in AC29.571B §29.571 (Amendment 29-55) FATIGUE TOLERANCE EVALUATION OF METALLIC STRUCTURE (Jan 2014) ref [2]. The proposed means of compliance have been approved by EASA for H175 certification.

2.1. Evolution of regulations regarding fatigue tolerance evaluation

FAR29 Amendment 28 made a requirement to consider damage when performing fatigue evaluations. It has been introduced afterwards within the CS29.

Substantial revision of §571 was issued in CS29 Amendment 3 (Dec 2012) ref [1]. This was the result of working group issuing NPRM for §571. A working group was set up jointly among FAA, JAA and the industry that developed proposals for criteria, to assess in a better way rotorcraft fatigue for metallic structures (see ref [7]). EASA Notice of Proposed Amendment ref [6] and FAA NPRM ref [4] have been harmonized in common guidelines in AC 29.571B Amendment 29-55 (ref [2]).

CS29.571 Amendment 2 prescribed two methods to account for damage:

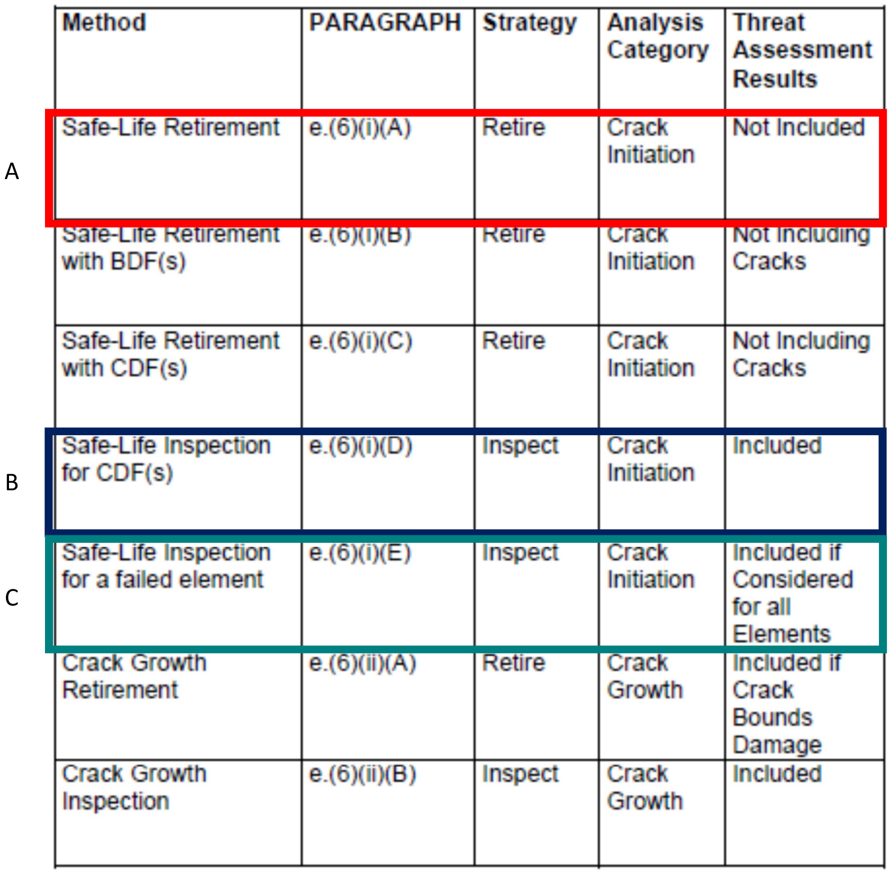
- Flaw tolerant safe life evaluation;
- Fail safe (residual strength after flaw growth) evaluation.

"Safe Life evaluation" method can be acceptable if the use of either of the two other methods is shown to be impractical.

In CS29 571 Amendment 3, Safe Life methodology leading to Safe-Life Retirement needs to be supplemented by other methods to account from damage. "Safe Life evaluation" methodology to substantiate the fatigue retirement time needs consideration of flaws in its determination, or complementary inspection intervals deduced from damage tolerance or any other supplemental procedure to minimize the risk of occurrence of identified flaws that could result in catastrophic failure during the operational life of the rotorcraft.

2.2 Last evolution of regulations regarding fatigue tolerance evaluation and H175 retained principles

The proposed means of compliance from ref [2] are listed in Figure 1 below:



Method	PARAGRAPH	Strategy	Analysis Category	Threat Assessment Results
Safe-Life Retirement	e.(6)(i)(A)	Retire	Crack Initiation	Not Included
Safe-Life Retirement with BDF(s)	e.(6)(i)(B)	Retire	Crack Initiation	Not Including Cracks
Safe-Life Retirement with CDF(s)	e.(6)(i)(C)	Retire	Crack Initiation	Not Including Cracks
Safe-Life Inspection for CDF(s)	e.(6)(i)(D)	Inspect	Crack Initiation	Included
Safe-Life Inspection for a failed element	e.(6)(i)(E)	Inspect	Crack Initiation	Included if Considered for all Elements
Crack Growth Retirement	e.(6)(ii)(A)	Retire	Crack Growth	Included if Crack Bounds Damage
Crack Growth Inspection	e.(6)(ii)(B)	Inspect	Crack Growth	Included

Figure 1: Figure AC 29.571B-1: Seven Fatigue Evaluation Methods

Each approach will support the establishment of retirement times and inspection intervals. Four methods are used to support safety-by-retirement strategies and they result in retirement times. The other three methods are based on safety-by-inspection strategies and the result is in-service inspection intervals.

Methods (A), (B) and (C) were applied as Means of Compliance for H175 fatigue evaluation of metallic airframe PSEs. There are crack initiation methods.

- (A) and (B) were applied for Single Load Path PSEs
- (A) and (C) were applied for Multiple Load Path PSEs

Method (A), “Safe-Life retirement” does not account for flaws. Application of this method results in a replacement time based on the time to initiate a crack in an as-manufactured part. This method needs to be supplemented by other methods to account for damage.

Method (B) “Safe-Life inspection for CDF(s)”: Application of this method results in an inspection task with an interval based on the time to initiate a crack from a CDF. The rationale behind this method is based on visual detection of the flaw before the probability to initiate a crack is significant.

Method (C) “Safe-Life inspection for a failed element”: Application of this method results in an inspection for a completely failed load path with an interval based on the crack initiation life of the adjacent structure. The analysis is accounting for internal load redistribution due to failure of the load path that is to be inspected.

3. IDENTIFICATION OF PSEs

Each metallic PSE must be identified according to ref [1] (d). All structural elements that contribute significantly to the carrying of flight or ground loads and the fatigue failure of which could result in catastrophic failure of the rotorcraft should be identified as PSEs. PSEs are structural elements or assemblies identified within dynamic and fuselage components of the rotorcraft.

Selection of PSEs

Failure mode and effects analysis are used to determine the metallic elements and group of elements, fatigue failure of which could result in catastrophic failure of the rotorcraft.

The selection of PSEs is then done with those elements which are contributing significantly to the carrying of flight or ground loads.

Example of PSE: Main Gear Box bars and main frames

Main gear box bars are shown in figure 2. Main rotor lift is transferred to main frames through main gear box bars. Bars and main frames are significantly loaded in flight due to rotorcraft load factor cycles. Fatigue failure of bars or main frames could result in unsafe event. Main gear box bars are PSEs, as main frames.

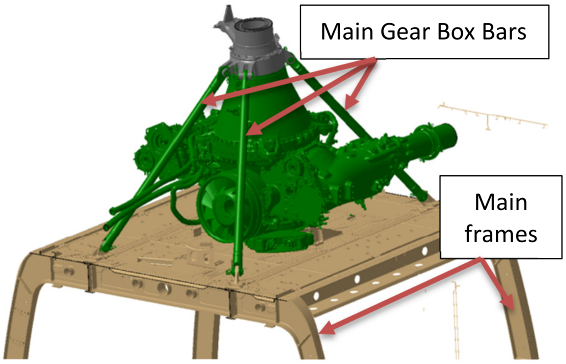


Figure 2: H175 Main Gear Box installation

Example of PSE: Suspension fittings

Suspension fittings are shown in figure 3. Main rotor torque is transferred to the fuselage through two fittings, significantly loaded in flight due to main rotor torque cycles. Fatigue failure of suspension fittings could result in unsafe event. Suspension fittings are PSEs.

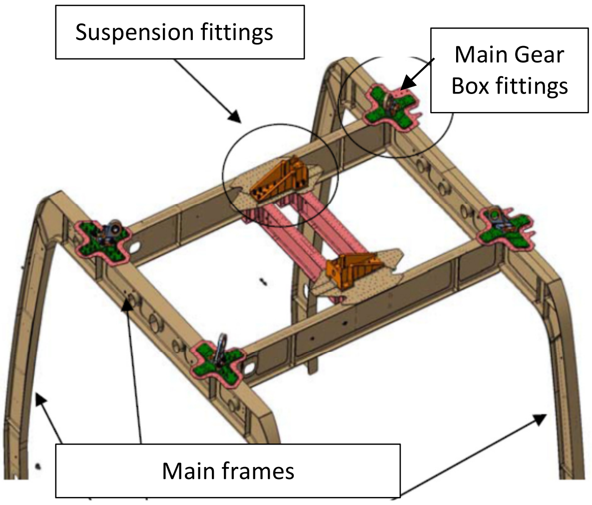


Figure 3: H175 main frames and suspension fittings

Once the PSEs have been identified, the following steps are remaining:

- Detailed threat assessment to define damage scenario;
- Safe life analysis by conventional fatigue methodology on as-manufactured part, following method (A);
- Flaw tolerance evaluation leading to inspection interval definition, following method (B) or (C);
- Definition of retirement times and/or inspection intervals to be included in Airworthiness Limitations Section.

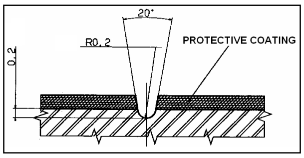
4. THREAT ASSESSMENT

A threat assessment must be established for each PSE according to ref [1] (e)(4).
The purpose of threat assessment is to define the helicopter potential damages that could occur during manufacturing, maintenance or in service and that could affect the fatigue strength of the metallic PSE.
As the retained means of compliance for H175 are based on combination of safe-life and flaw tolerance evaluation, threats like fatigue cracking and fretting phenomenon were already covered by the retirement times determined by conventional fatigue methods.
The threats identified were for typical flaws, maintenance and service induced damages, either Barely Detectable Flaws or Clearly Detectable Flaws. The retained threats for flaw tolerance evaluation were associated to a likely occurrence during the operational life of the rotorcraft.
Various types of threats may occur on helicopter during service life. Main sources are the following:

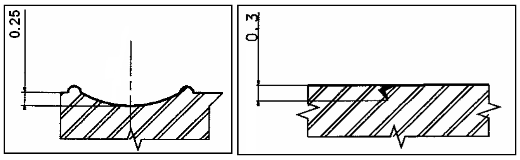
- Exposure to corrosion (including material, environmental conditions, contamination by corrosive fluids); It is supposed that the surface treatment is damaged and consequently, there are corrosion pits.
- Exposure to impact damages (including debris, dropped tools, hail, walk during maintenance)
- Exposure to wear and scratches
- Loss of tightening torque (for bolted connection)
- Incorrect storage, Transport, Handling, Assembly and Maintenance aspects of the component.

Feedback from in-service experience is an important mean to support likelihood of occurrence risk for a threat.

Flaw tolerance evaluation was done on previous programs (see ref [3]). Standard sizes for impacts, scratches and corrosion were defined to cover 90% of the flaw size distribution. A large campaign of fatigue tests was launched on coupons to characterize the effect of flaws on fatigue behavior for standard sizes. This database was helpful for flaw tolerance evaluation of design.
For each PSE location, flaw characterization (location, type and size) is provided, with assessment of detectability of flaw. Depending of the assessment results, the flaw is defined as BDF or CDF. Barely detectable flaw should be substantiated during the whole retirement life. Clearly Detectable Flaw should be substantiated during one inspection interval, up to application of corrective actions.



Scratch



Impact dent
Corrosion pits

Figure 4: Standard flaws (ref [3])

5. FLAW TOLERANCE EVALUATION OF METALLIC FUSELAGE COMPONENTS

5.1 Flaw tolerance evaluation of SLP PSEs

Single Load Path PSEs limitations are substantiated following (A) and (B):

- (A) Safe life retirement analysis by conventional fatigue methodology
- (B) Safe life inspection for CDF(s): Depending on the threat assessment results, a CDF is applied on PSE and the time to initiate a crack from the CDF is then computed to determine the inspection interval.

At the time of inspection, the CDF will be detected and some corrective actions will be applied to remove the flaw before the probability to initiate a crack becomes significant.
Safety factors are applied on mean fatigue curve to reach the requested failure risk.
Airbus Helicopters fatigue methodology is traditionally based on cumulative failure risk, defined at 10^{-6} at end of life. Safe life retirement analysis (A) is done considering as-manufactured part, and 10^{-6} failure risk at end of life.
Safe life inspection for CDF(s) (see ref [2] § f. (8) (i)) is done accounting for flaw at critical location for fatigue analysis. Time is computed to initiate a crack from critical area with flaw with a prescribed failure risk at time of inspection. Some fatigue tests up to crack initiation on component with flaws are supporting the analysis.
Higher number of fatigue test points on components is providing more confidence in mean fatigue limit and

deviation allowing then to define less conservative safety factors.

Result of fatigue analysis with flaws is leading to safe inspection interval to check the part.

The repetitive inspection consists of examination of structure for a presence of flaw using the substantiated inspection method. If no flaw is found the structure may be returned to service for another inspection interval period, up to the established retirement time. If the flaw is found, the structure is retired except if a repair procedure has been substantiated for the specific flaw.

5.2 Flaw tolerance evaluation of MLP PSEs by analysis

Redundancy of multiple load path structure can be managed to determine inspection interval for a failed load path, called primary load path.

The remaining life of the secondary load path after primary load path failure is used to determine the inspection interval.

As defined in ref [2] §f. (8) (iii) (A), "Safe life inspections substantiation for a failed load path provides a safe interval of operation between repetitive inspections for the failed load path. The substantiation is based on conventional Safe-Life methodology except that the configuration of the structure substantiated is with the primary load path inoperative and appropriate flaws imposed in the remainder of the structure, as determined by the threat assessment".

5.2.1 Substantiation conditions

Table 3 details the conditions for MLP PSE flaw tolerance evaluation (from [2] § f. (8) (iii) (B)).

Source	Conditions for Substantiation of Safe Life Inspection for a failed element	Comments
Ref [2] §f. (8) (iii) (B) (1)	The principal "flaw" is the failure of the most critical load path	A critical load path needs to be identified among existing load paths.
Ref [2] §f. (8) (iii) (B) (2)	The remainder of the structure may be representative of normal manufacturing quality unless the threat assessment indicates that a larger damage should exist.	Depending on the threat assessment results, a flaw should be considered on secondary load path.
Ref [2] §f. (8) (iii) (B) (3)	Any applied load changes or load distribution changes that occur as a consequence of the load path failure should be included	Once primary load path has failed, the secondary load path is extra loaded. This load redistribution should be considered to analyze the time to initiate a crack on secondary load path.
Ref [2] §f. (8) (iii) (B) (4)	Pre-existing fatigue damage in the remaining structure at the time the first load path fails should be factored into the analysis	Initial fatigue damage needs to be considered on secondary load path up to failure of primary load path
Ref [2] §f. (8) (iii) (B) (5)	The remaining structure after first load path failure must be shown to have limit load capability, considered as the ultimate loading.	The secondary load path (with inoperative primary load path) has to sustain limit loads.
Ref [2] §f. (8) (iii) (B) (6)	The inspection conducted is for the failed or missing load path	Inspection is to check integrity of primary load path

Table 3: Conditions of Safe Life Inspection for a failed element substantiation

The applicability of the method is defined by the residual fatigue damage evaluation on secondary load path. In case the load paths are fatigue damaged with an equivalent level, then the residual fatigue damage on remaining load path should be too low to compute any acceptable inspection interval after failure of one element. In this case, each load path would be considered independently. Inspection intervals are then determined considering each load path as SLP PSE.

The flaw tolerance evaluation method "Safe life inspection for a failed element" is based on analysis and/or tests. Analysis of initiation on secondary load path is based on crack initiation methods (e.g. using the S-N curve and the Miner's Rule).

5.2.2 Substantiation Principle

Two load paths can be considered in MLP PSE:
-one primary load path (path 1: a frame for example)
-one secondary load paths (path 2: lateral shells for example)
The probability of complete failure of the MLP PSE can be decomposed in

$$p = p1xp2$$

with:
-p1 the probability of failure of primary load path
-p2 the probability of failure of secondary load path

The analysis will be processed as follows:

1. Fatigue analysis with the two paths loaded in normal conditions (path 1 & 2 operative).
2. Multiple load path demonstration: The initiation in the secondary load path considered as failure will be analyzed assuming the effective failure of the primary load path.

A new equilibrium is set up and a fatigue analysis is performed with the load redistribution on path 2. This approach is leading to an inspection interval and is providing evidence that the failure of the load path 1 has no catastrophic consequence.
To demonstrate that the complete failure of the MLP (with 2 load paths) is extremely improbable, it is proposed that for the general case the analysis will be based on the risks:
- p1= 10^{-3} (at the end of retirement time) for the fatigue analysis
- p2= 10^{-3} (at the end of the inspection interval) for the fatigue analysis of path 2 and leading to the inspection interval.

In case a MLP is considered PSE, the probability of complete failure of the MLP will be equal to p1xp2.
p1xp2 probability is equal to 10^{-6}.
The cumulative failure risk at the end of life will be equal to 10^{-6}.

A crack initiation method:
Figure 5 is describing the crack growth situation for evaluation by analysis which is proposed in ref [2) §f. (8) (ii) (B) (3) (i) considering a crack growth in secondary load path. Time for the crack to propagate should be limited by the capability of secondary load path to sustain limit loads. This method is leading to a crack growth inspection. Safe-Life inspection for a failed element is an alternative method proposed in ref [2] §f. (8) (iii), based on time to initiate a crack (with a prescribed risk) in secondary load path after primary load path failure.

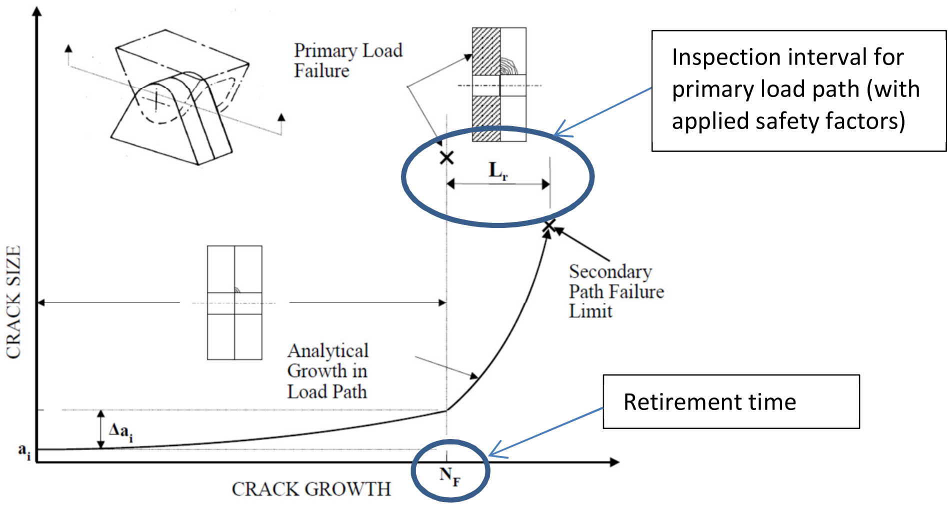


Figure 5 : Figure AC 29.571B-6 : Multiple Load Path Structure Analytical Evaluation to Support Inspection for a failed Load Path (ref [2] §f. (8) (ii) (B) (3) (i))

Remark: (from ref [2] §f. (8) (ii) (B) (3) (i)): Retirement time N_F should be equal to the retirement time for the structure being inspected, or equal to the rotorcraft design service life if the structure has no declared retirement time.

5.2.3 Steps of fatigue damage analysis for MLP PSE

MLP PSE limitations are defined with retirement time and inspection interval. Retirement time of MLP PSE is established up to crack initiation on primary load path. Safe life inspection is established up to crack initiation on secondary load path with failed primary load path.
Considering a MLP PSE made of two load paths, load path 1 & 2, the fatigue damage analysis of primary and secondary load path is done in two steps.
Fatigue damage analysis is done following Miner's rule and conventional fatigue method. Fatigue damage evolution can be represented as shown in figure 6.

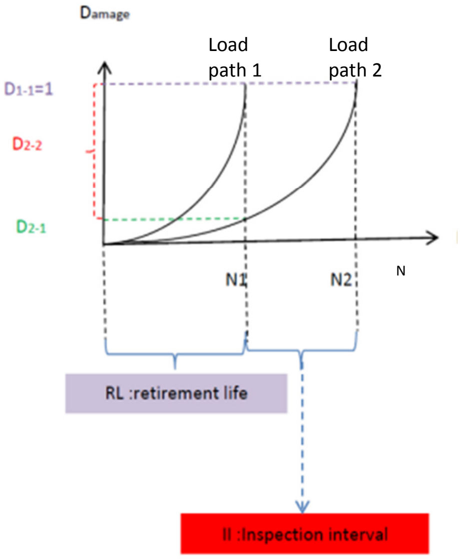


Figure 6: Fatigue damage evolution in the 2 load path PSE

Step 1: Analysis of Retirement time N1

1: Primary Load Path
2: Secondary Load Path

At beginning of life the situation is as shown in figure 7.

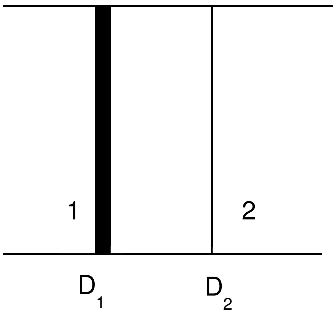


Figure 7: The 2 load paths at beginning of life

With:

- D_1 fatigue damage of Load Path 1
- D_2 fatigue damage of Load Path 2

At N1, considering Miner's rule, the fatigue damage is defined with:

$$D_1 = D_{1-1} = 1$$

$$D_2 = D_{2-1} << 1$$

D_{1-1} and D_{2-1} are computed considering a risk 10^{-3} at N1. D_{2-1} is computed for the mean time to initiate a crack on load path 1. Indeed N1 may be lower than the design service life of the rotorcraft. Initial damage on load path 2 should then be analyzed conservatively, considering the mean time to reach load path 1 failure. This time is limited to the rotorcraft design service life.

Step 2: Analysis of inspection interval for a failed element

The initial damage on load path 2 is D_{2-1}
D_{2-2} is the residual fatigue damage in load path 2.
At N1, the primary load path is failed as shown in fig. 8
The time to propagate the crack into load path 1 up to failure is conservatively neglected into the analysis.

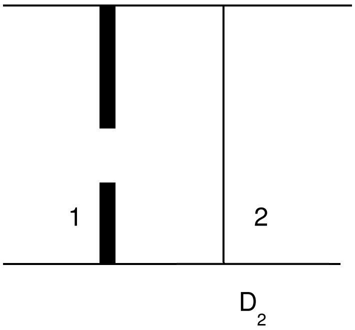


Figure 8: Load path 1 is failed. Load path 2 is extra loaded.

Considering Miner's rule, the fatigue damage at N2 is:

$$D_2 = D_{2-1} + D_{2-2} = 1$$

$$D_{2-2} = 1 - D_{2-1}$$

D_{2-2} is computed considering a risk 10^{-3} at end of inspection interval.
The inspection interval is then defined with ΔN:

$$\Delta N = N2 - N1$$

Final PSE limitations

Retirement time N1 and inspection interval ΔN are defining the PSE limitations.

5.2.4 Summary

The MLP PSE fatigue and flaw tolerance evaluation is summarized in figure 9.

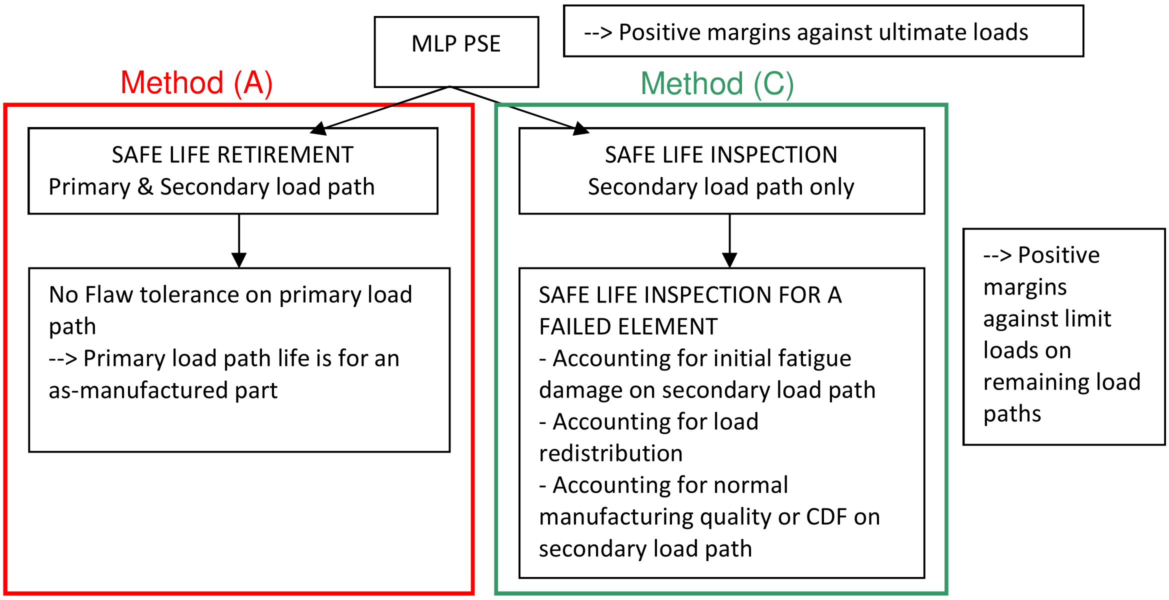


Figure 9: Summary of MLP PSE flaw tolerance evaluation

CONCLUSION

Proposed Means of Compliance for fatigue and flaw tolerance requirements were successfully approved by EASA for H175 certification. The fatigue substantiation was achieved by a combination of conventional Safe-Life methodologies and Flaw tolerance approaches leading to the definition of retirement times and inspection intervals for each PSE.

For metallic PSEs, two methodologies were proposed, depending on the identification of PSE as SLP or MLP PSE. MLP PSE flaw tolerance approach evidenced that failure scenario should be considered very early in development to design PSEs with fail-safe considerations. Fail-safe concept with MLP PSE fatigue methodology is, at the end, leading to fail-safe design, and optimized weight.

Defined means of compliance are leading to improvement of fatigue reliability of metallic PSEs and are supporting the inspection plan for the operative rotorcraft.

ACKNOWLEDGEMENTS

The authors would like to acknowledge all the people involved in the implementation of this methodology during H175 development.

ACRONYMS

EASA: European Aviation Safety Agency
FAA: Federal Aviation Administration
CS29: Certification Specifications for Large Rotorcraft
FAR29: Federal Aviation Regulations – Transport Category Rotorcraft
AC: Advisory Circulars
NPRM: Notice of Proposed RuleMaking
NPA: Notice of Proposed Amendment
JAA: Joint Aviation Authorities
RL: Retirement Life
II: Inspection Interval

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