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Continued airworthiness assessment of evolving usage patterns in military transport aircraft

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Abstract

Safety of aircraft structure is assured through compliance with FAR/CS25.571 or military specifications, implying F&DT evaluation of PSE, and a maintenance program developed at the certification time, including replacement times and inspections, as well as a LoV of the program. All these activities are calculated based on assumptions of intended usage, and adequate safety factors to cover material and usage variability.

The reality is that aircraft usage, particularly military, deviates from the initial assumptions, which influences the kind of maintenance program, implying periodic re-assessments to keep adequate level of safety to comply with continuous airworthiness requirements.

1. Introduction

Fatigue and damage tolerance assessment of airframe structures is an essential task required for certification of aircrafts, complying with the requirements defined in FAR/CS 25.571 for civil environment, and various national specifications for military environment. The main outcome from this assessment is the definition of the structural maintenance program, which establishes replacement times for safe-life structures and threshold and repeat interval inspections for damage tolerant ones. The manufacturer or TC (Type Certificate) holder is the responsible of the edition of this maintenance program that, at the time of certification, is based on the initial assumptions of intended usage.

An efficient maintenance program requires further adaptation by the operators in order to schedule all the activities accounting for fleet size, rate of flight cycles and flight hours accumulation, usage severity, maintenance shops capabilities and other constrains or requirements. It is not intended in the paper to deal with the operator management. Instead it is focused on the possibilities and variety of maintenance program approaches that the manufacturer may offer to the operator for better accommodation to its specificities.

Among all the parameters that may affect the definition of a maintenance program, one of significant relevance is the usage variability. To better understand this, it could be first considered that all the a/c delivered to operators of a given type (as per TC) fly according to the intended usage assumed for certification. This means that each of them follow the types of missions (such as logistic, tactical, refueling, training, etc) and its relatives percentages. Also they follow the profile details of each mission (altitude, velocities), weights, number of manoeuvers, turbulence intensities, etc. In that case the definition of the replacement times and inspections would include adequate safety factor to cover material/assembly properties variability and other design analysis uncertainties.

The reality is that real operation differs from those design assumptions and so additional safety factors have to be applied to cover that usage variability or, in other words, to provide acceptable level of safety or reliability. The safety factors considered in this initial certification stage are values that have been historically applied on previous programs, normally with lack of a clear and rational relationship with reliability targets, but that experience have

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proved to be adequate. Nevertheless it is also acknowledged that some usage parameters show variability that it is not covered by those typical safety factors, and the manufacturers have developed maintenance programs that, either account explicitly for them based on usage data, or assume conservative assumptions for the fleet.

In the civil-like applications of military transport aircraft the most relevant parameters are the weight and the flight duration (flight hours per flight cycle), and several approaches have been considered to account for these effects, adapting the maintenance program accordingly. In these approaches the applied safety factor associated to usage covers other uncertainties, such as variations on flight profiles, number of manoeuvers or gusts, etc. Note that, alternatively, the maintenance program could be developed with increased safety factors to cover also the variability of weight or flight duration, but it would be very conservative for most of the fleet.

This exercise of adapting the maintenance program based on operational usage (e.g. flight duration) has the objective to comply with continuous airworthiness requirements, which accounts for this variability in usage throughout the life of the a/c in an efficient way. It is to note that additional evaluations are performed by the manufacturer, in order to detect other kind of deviations from initial assumptions, provide adequate modifications to the maintenance activities, and thus contributing to a continuous airworthiness under the acceptable levels of reliability.

The maintenance approaches described above, and other ones being developed, have been traditionally proved to be adequate to cover the usage variability of civil-like aircraft usage. In the military world the variability is significantly greater, starting from the categorization of the aircrafts (trainers, transport, mission, bombers, fighters). Due to this significant diversity, different maintenance approaches have to be developed for each of them in order to be safe and effective at the same time. An additional contributor to these military specificities is the evolution of the intended usage during the life of the aircraft systems, which accounts for factors such as geo-political situations, new systems and armaments developments or other kind of the operators interests. These aspects imply the convenience of regular revisions of the intended usage, and develop maintenance approaches that best fit the necessities of those operators and a/c system platforms, to effectively comply with the continuous airworthiness requirements under this evolution of the usage patterns.

Complying with the continuous airworthiness requirements is understood as keeping the adequate level of safety or structural integrity reliability throughout the life of the a/c. For this purpose it is necessary a link between the maintenance program criteria (including the safety factors) and a target reliability. It is acknowledged that this link is not widely shared in the airframe context. Several initiatives have been launched by a variety of organizations, with more or less complexity. In this paper it is explored a very simple approach, focused on fatigue life initiation, through a two variables reliability model based on reasonably accepted stochastic parameters, and calibrated to a certified deterministic approach. The scope of this initiative is not intended for the definition of the maintenance program, but to establish the criteria to assess the evolution of the usage patterns and its relationship with the applicability of the maintenance program or the necessity to develop an updated one.

2. Maintenance Programs for Military Transport Aircraft

The classification of the maintenance approaches to cover usage variability can be done based on fleet scope criterion, from the more general ones which provides the same maintenance program for all the a/c in the fleet, to those which allow adaptation to different usages within the fleet, or those which allow individual a/c adaptation, either based on mission type distribution, or simple usage characterization parameters (such as center of gravity g counter) or the more complete individual a/c severity assessment based on modern Structural Health Monitoring (SHM) systems (typically required for combat a/c). This paper will be focused on transport and mission military a/c, although some excursions can be made applicable to other military a/c categories.

2.1 Basic Maintenance Program

Starting from the most simple one, the replacement times or inspections are calculated including a standard safety factor to account for usage variability of individual a/c within the fleet. A priori this maintenance program approach assumes that there is small deviation from the design assumptions.

The safety factor depends on the criterion adopted, from fatigue initiation for safe-life structures, to fatigue initiation and/or crack propagation for damage tolerant structures threshold, and crack propagation for the interval (repeat inspection). For simplification and clarity, this paper focuses on fatigue initiation criterion, although it can be extended similarly to crack propagation.

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Regarding fatigue life initiation, typical military approaches (and also civil ones) agree with the criteria established in DEF-STAN-970, which considers a scatter factor of 1.5 to cover usage variability. When combined with the additional scatter to cover the other sources of variability (the *as-built* airframe, including material properties variability, manufacturing tolerances, etc), defines the overall scatter factor. The following figure shows this scatter and its relation with probability of failure (complementary of target reliability) of a theoretical fatigue life stochastic distribution.

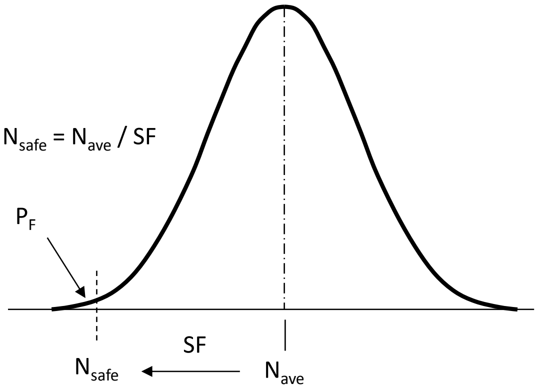

Figure 1: Relation between probability of failure and scatter factor

The spectrum developed for fatigue and damage tolerance analyses would normally include several mission types (logistic long or short, tactical with contour flying, surveillance, maritime patrol, training, etc), and a defined relative distribution of those missions within the total Design Service Goal (DSG), as declared in the intended usage. In order to comply with continuous airworthiness it has to be verified along the life of the system that usage is covered by the initial assumptions, both average and/or deviation. This is done with regular fleet surveys that evaluate the evolution of relative distribution of the missions, and possible deviations of each mission profile, and other characteristics such as weights, manoeuver statistics, etc.

The revision of usage data would allow definition of a new intended use, and develop a new spectrum with updated mission mix and individual mission profiles, which will finalize with an updated maintenance program.

Nevertheless an adequate compliance with the continuous airworthiness requirements would need to answer the following equivalent questions regarding the updated maintenance program:

- Is the target reliability (or probability of failure) kept?
- Do the applied scatter factors kept the same level of safety?

Really, an additional question could be raised after the fleet usage data revision:

- Is it necessary a revision of the maintenance program?

To answer these questions it is necessary an evaluation of usage severity (in this case in terms of fatigue initiation), accounting for variability among the a/c within the fleet, and compare with the adequate target reliability level. As explained before, standard airframe certification process does not explicitly consider this target reliability, making this comparison a difficult task.

Probabilistic Model

Several organizations have developed stochastic models to deal with airframe fatigue, which are complex and not always supported by well established probabilistic distributions of the relevant parameters. It is proposed here a simplified approach, using a two variables reliability model based on reasonably accepted stochastic parameters, and calibrated to a certified deterministic approach.

The rational for this model is detailed in the appendix, but a brief description is summarized here. The main aspects of the model are the following ones:

- Level II probabilistic model gathering all the parameters affecting the fatigue initiation in two groups:

  - As-built aircraft: covers variables such as material properties (s-n curves), manufacturing tolerances, etc.
  - Fleet usage: covers variables such as individual mission mix, loads (weight, center of gravity), statistics (gusts, manoeuvers, etc.).

- The mode of failure in this model is fatigue initiation, and the failure criterion is reached when the fatigue life is consumed (initiation of a crack)

- For the *as-built* variable, it is considered a log-normal distribution, with commonly accepted values of standard deviation (as indicated in FAA AC 23-13A, for instance $\sigma = 0.14$ for aluminum), although it is explored also a Weibull distribution with also commonly accepted parameters (for instance $\alpha = 4$ for aluminum).

- For the *usage* variable, it is considered a log-normal distribution. The value of the standard deviation is based on the assumptions taken in DEF-STAN-970 for material properties scatter factor and usage scatter factor of 1.5, which allow concluding $\sigma = 0.1853$ for usage variable.

- To complete the probabilistic model it is necessary to define the *target reliability* (complement of the accepted probability of failure) associated to the acceptable level of safety. This value is obtained through the *calibration* of the probabilistic model with the accepted deterministic one used for current certification, such that both of them provide the same level of safety. This assumption is substantiated with the in-service experience of the Airbus DS programs applying the deterministic methodology. The result depends on the distribution considered for the *as-built* variable. For the case of assuming log-normal distribution, the *target reliability* is 99.87%.

With this model it is possible to answer the questions raised above, particularly determine if the current maintenance program is still applicable or needs to be updated. The following plot shows two simple situations, while the real case would be a combination of both:

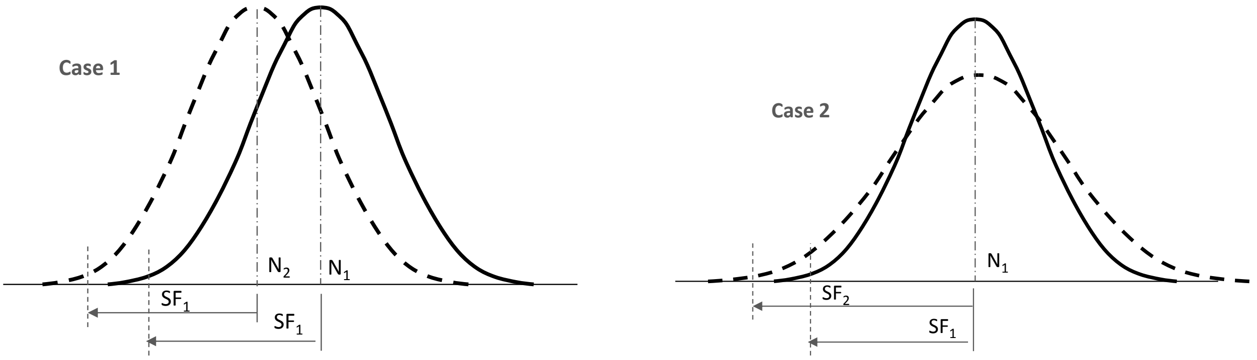

Figure 2: Deviation of usage distribution versus design assumption

- Case 1: the average life is reduced, maintaining the standard deviation, the scatter factor can be kept
- Case 2: the average life is kept, but the standard deviation increases, the scatter factor will increase

In the both cases shown it is concluded that the maintenance program needs to be updated in order to keep the same level or reliability and comply with the continuous airworthiness requirements.

The first case would be a typical one, in which the maintenance limitations are re-calculated with the new spectrum. For the second case, some alternatives to the increase of scatter factor are normally considered, such as taking a more conservative spectrum. In either case, the maintenance program becomes less effective from operational or economic point of view, since the limitations would be very conservative for a significant portion of the fleet. One of the reasons of such increase in scatter would be the evolution of the usage patterns, with different ones for different a/c within the fleet.

If this situation happens, it may be needed to consider alternative approaches to the maintenance plan in order to improve the effectiveness while at the same time keeping the adequate level of safety to comply with the continuous airworthiness requirements. Such alternative approaches are presented in the following paragraphs.

DOI: 10.13009/EUCASS2019-687

2.2 Maintenance Program Based on Regions

An evolution of the previous maintenance program when there are expected a few different usage patterns, is to develop a maintenance program for each of them, and allocate each individual fleet or even a/c to each program following established criteria. This approach could be applicable to cases where variability within each usage pattern is reduced, so that the scatter factor applied to that pattern in order to comply with continued airworthiness requirements allows an efficient maintenance program for all the fleet. This may be the case of strategic transport aircraft, which basically performs logistic missions, air-to-air refueling missions and training. Once an aircraft is allocated to one of the usage patterns, the approach would be similar to the one defined in previous section.

Nevertheless it is quite improbable that an a/c performs continuously the same mission pattern, and most probably there would be a mixture of them. For the military strategic transport aircraft, different usage patterns imply not only variability of weight and flight duration, but also the specific pattern of the military mission air-to-air refueling (altitudes, weights, speeds), and probably other specific military manoeuvers (evasion, low level flight).

The variety of military usage patterns is normally characterized through a combination or mix of typical types of flights (TOF). For instance, strategic transport mission TOF could be short logistic, long logistic, standard refuelling, severe refuelling (heavier and longer), or training. Individual a/c or fleet could fly different combinations of those typical missions. The following figure compares the situation of civil-like environment in which different operators fly different combinations of average flight times and weights, with a military environment in which different operators, fleets or individual a/c fly different mission mixes of typical TOF.

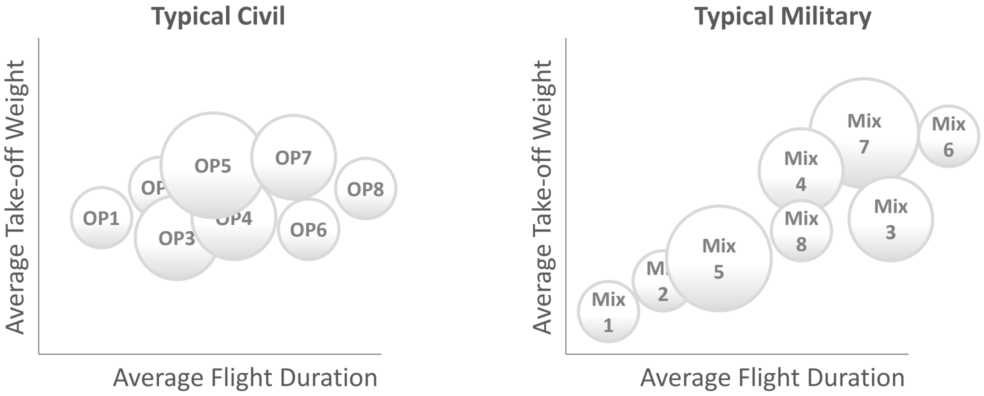

Figure 3: Typical civil and military usage patterns

Due to this significant variety of usage patterns and associated severities, it is not efficient to cover continuous airworthiness requirements with a single maintenance program and a big scatter factor. The alternative to develop individual maintenance programs for each individual mission mix is not practical either, since the a/c will be changing these mixes all along its life, making the approach complex and requiring additional tracking efforts.

This usage variability of strategic a/c, although significant, is in some way limited, since it can be assumed that the typical types of flights reasonably represent the fleet missions, whose inherent dispersion is considered covered by the standard scatter factors (nevertheless this assumption has to be verified through the periodic fleet surveys as explained in the previous section). To deal with the variety of mission mixes in a practical way, and at the same time complying with the adequate level of safety, Airbus DS is developing a maintenance program concept based on Usage Regions.

This new approach is depicted on the left side of the following figure. In this case it is selected two usage regions, one associated to standard usage (STU) and one associated to severe usage (SEU). This number is considered adequate for a strategic aircraft in order to cover continued airworthiness requirements and at the same time keep a relatively simple and easily manageable maintenance program.

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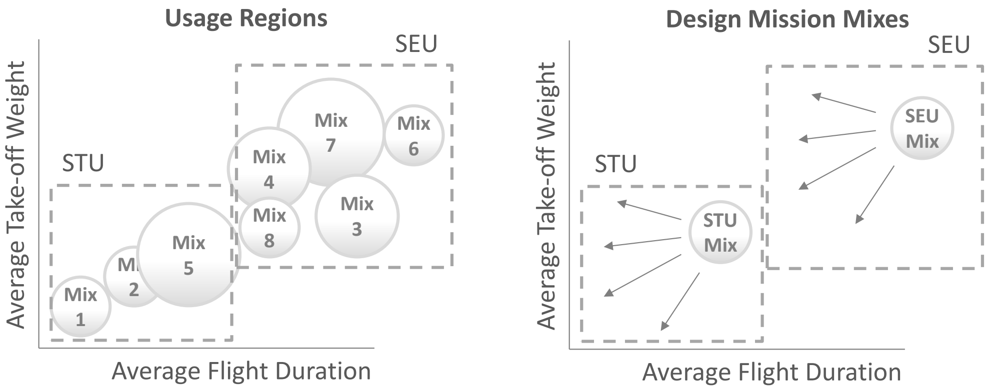


Figure 4: Usage Regions

The right side of the figure shows how the maintenance program is defined, establishing a typical mission mix for standard usage that covers its region, and a mission mix for severe usage that covers its region.

For a better representation of the different sensitivity of the airframe structure to mission parameters, really several mission mixes are defined in each region, typically on the order of 3. Regarding safety requirements, it has been commented above that the maintenance program (limitations or inspections) are calculated using standard scatter factors that cover the variability of usage within each mission or TOF. Hence, in order to comply with the continuous airworthiness requirements, it has to be shown that the reference missions and mission mix defined for each region conservatively covers the variety that can be expected in service. This assessment can be done at different levels, either with SHM (Structural Health Monitoring) data if the system is available in the fleet, or through other usage parameters if it is not. The following plot shows an example for two parameters (fuel at take-off versus payload), although other similar parameters which are considered contributing to fatigue damage would be also verified.

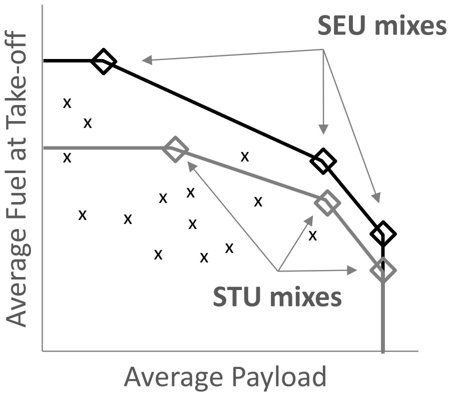


Figure 5: Usage Regions Mission Mixes – Conservative Coverage of Fleet

One important aspect of this approach is the transition from one region to another. This region transition is performed at individual a/c level, and implies an adjustment of the maintenance limitations (FC or FH) such that it accounts for the equivalent accumulation of FC or FH in the previous region. In this way, the operator has some capability to adjust the global maintenance program to their calendar schedule:

$$FC_{STU} = FC_{SEU} \text{ x } f_{SEU\_to\_STU}$$

Where: ff is the factor that converts SEU reference FC into STU reference FC

(Similar expression for FH, and the other way round to transfer STU to SEU).

The definition of STU and SEU may be dynamic, evolving through the life cycle of the aircraft in order to fit the in-service changing usage patterns, in order to guarantee continuous airworthiness safety levels.

This approach for maintenance program shows that there is some conservativism, since the mission mixes defined for each region have to cover the real in service fleet usage. This may be acceptable for operators, even more, the operator can choose to allocate all the a/c to the severe usage spectrum if it does not introduce unacceptable limitations, making the maintenance more simple. But it could happen that this conservativism is not acceptable. In that case a more complex maintenance approach is proposed in the following section, which increases the cost since it requires more maintenance information to be managed.

2.3 Maintenance Program Based on Individual Types of Flights

A further step in variability is the case when various operators or fleets fly similar mission types, but with very different percentage of each of them for individual a/c, and very different relative severity between the mission types (for instance logistic and tactical missions in the same mission mix). In that case it is introduced a first level of individual a/c tracking, in which it is recorded the number of each type of mission flown by each individual a/c, and accumulate the relative severity associated to each type.

This approach is an evolution of the previous one in which, instead of selecting several conservative mission mix in each region that cover all the fleet, it is evaluated the particular mission mix flown by each individual a/c to assess the accumulated severity, and then introduced a projection for the maintenance action in terms of FC, FH, or any other adequate parameter (which can be the case in military environment, such as Touch & go, SPS, LLF, etc).

In order to implement this approach, it is necessary to define the set of reference design missions (TOF, as in the previous approach), and compute the damage at each of the critical locations of the airframe associated to each TOF. The maintenance program is defined for the most critical mission (the TOF that provides lowest life limitations or inspections) plus some adjustment factors (which are the relative severity between each TOF and the critical TOF). The reason to provide data for each critical location of the airframe is due to the fact that each of them could have different sensitivity to each TOF. Figure 6 shows an example of the design and in-service data required, which is used to perform the adjustment with the following formulation for this example:

$N_{crit} = 25\,000$ FC	Critical life (for critical TOF) of this location
$f_i = 0.35, 1.00, 0.50$	Relative severities
$n_{AC} = 5\,000$ FC	Accumulated FC for this a/c
$p_i = 40\%, 25\%, 35\%$	% of FC for each TOF
$d_i = (n_{AC} \times p_i) / (N_{crit} / f_i)$	Accumulated damage for each TOF
$d = \sum d_i$	Accumulated damage for all the TOF
$N_{Adj} = n_{AC} / d = 44\,250$ FC	

Figure 7 shows graphically the adjustment performed. It is to note that the projection from the current status to the limitation can be done using the individual a/c usage rate, or a different projection rate (such as the design one, the fleet average, etc).

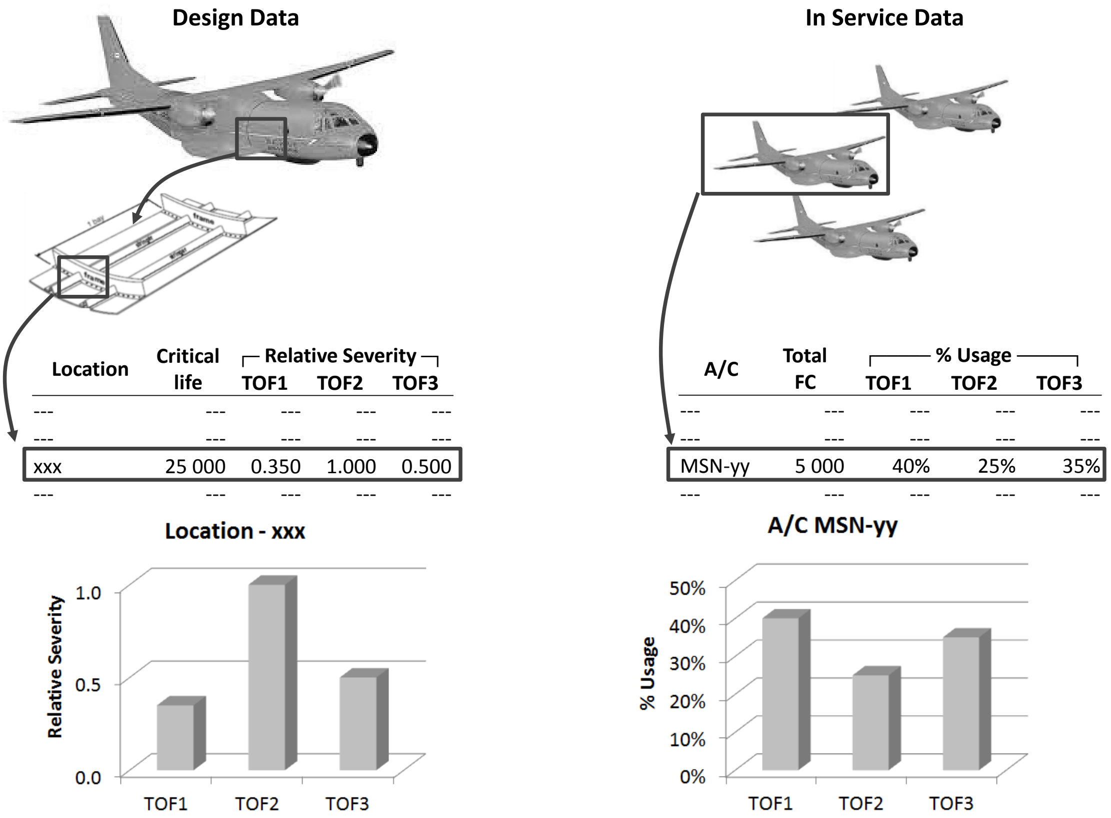
This approach introduces a much higher cost in managing maintenance data, since it requires:

- Identification, flight-by-flight and for each a/c, of the TOF code.
- Management of each critical location of the a/c, and update based on TOF usage for each individual a/c.

In case that this maintenance management is not of the interest of one operator, the maintenance data based on the design critical mission is used instead. This solution would introduce more conservativism that the approach based on usage regions presented in the previous section.

Regarding the impact on continuous airworthiness, this approach reduces the uncertainty related to the TOF that the individual a/c is flying. The usage variability associated to each individual type of flight is covered with the scatter factor philosophy, as explained in previous sections. Nevertheless it is still important, as for the approach based on usage regions, to verify through periodic fleet surveys that the selected missions conservatively cover the fleet.

In the case of tactical missions, including for instance contour flying or missile avoidance, the variability is normally increased, since the high maneuverability required for very specific scenarios makes it difficult to predict, and the same mission type may experience significant differences in severity. The continuous airworthiness of these fleets may be accomplished with regular in-service usage revisions, associated adaptation of maintenance programs, or even splitting the programs for individual fleets or squadrons. In any case, keeping the level of safety and reliability could require application of big safety factors that would make the maintenance program less effective. For that reason, the maintenance concept may need to change to an individual a/c tracking system.



Location	Critical life	Relative Severity TOF1	TOF2	TOF3
---	---	---	---	---
---	---	---	---	---
xxx	25 000	0.350	1.000	0.500
---	---	---	---	---

A/C	Total FC	% Usage TOF1	TOF2	TOF3
---	---	---	---	---
---	---	---	---	---
MSN-yy	5 000	40%	25%	35%
---	---	---	---	---

Figure 6: Maintenance program adjustment based on individual TOF

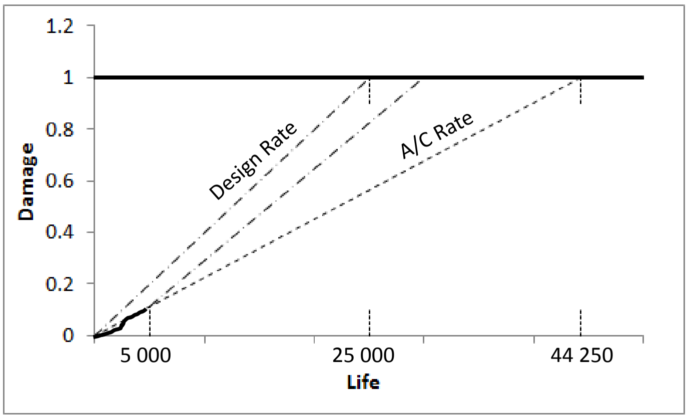


Figure 7: Adjustment of maintenance tasks based on TOF usage distribution

2.4 Maintenance Program Based on Individual A/C Tracking

As indicated above, particularly for tactical missions, the variability of specific military manoeuvres may not be covered by the standard scatter factors. In order to keep an efficient maintenance program, and at the same time an adequate level of safety, it is necessary to control in a deeper way the a/c usage, which is achieved through individual

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a/c tracking. These systems are considered necessary for fighter a/c, but they could also be necessary for transport a/c that performs tactical missions.

Regarding continuous airworthiness, one special advantage of this system is that it is reduced the uncertainty of in-service usage, which would allow removing the safety factor associated to usage variability. This aspect is explicitly addressed in DEF-STAN-970, which considers removing the scatter factor of 1.5 for monitored a/c.

Several alternatives are offered for individual a/c tracking, with top level classification in two groups (although there could be also mix approaches for different locations within the same aircraft):

- based on strain gauges measurements,
- based on flight parameters (parametric systems).

The parametric systems can be developed with different levels of complexity, from systems based on single parameters (such as center of gravity g counter) to full airframe evaluation using a high number of flight parameters (nz, speed, altitude, aoa, control surface deflections, etc) that are processed through either a correlated a/c loads model or neural network systems.

Each of them allows different level of accuracy in the prediction of the local stress spectrum, and different scope. The first type, using g counter, is adequate to monitoring components sensible to this parameter, such as the wing. Due to that, continued airworthiness requires complementing the usage variability assessment with additional fleet survey, typically done through installation of VGH recorders on a set of the a/c within the fleet These systems used to be implemented in older a/c models, particularly due to restrictions on data processing capability. On the other hand it is highly reliable.

The second type is the standard solution implemented nowadays, schematically depicted in the figure 8, in which the flight parameter system is compared with the one based on strain gauges. The aim of both systems is to provide a time-history of the local stresses at the critical locations of the airframe, from which fatigue damage is computed.

From continuous airworthiness point of view another advantage of these systems is that they allow capturing the behaviour of the evolution of the usage patterns. They are used, not only to obtain the local stress time-histories, but also to gather all the usage data on several parameters. Even the approach based on strain gauges is complemented with recording of this useful usage information. In any case specific considerations of reliability have to be considered for each of those approaches, which should imply adequate definition of the safety factors in order to keep the same level of safety.

Regarding strain gauges, the accuracy to determine the local stresses is very high. Nevertheless the amount of strain gauges installed in an a/c is limited from a practical point of view, and it is seldom possible to capture the time-histories at all the critical points that have been identified in the maintenance program. In practice the strain gauge reading is able to capture the usage severity at its specific location and orientation, and this usage severity is assumed to be the same around the area assumed to be covered by it. This fact introduces some uncertainty that needs to be evaluated and accounted for. Sensitivity analyses based on loads models will help in this task. Another aspect to consider is the reliability of the strain gauges, and the capability to provided data for a significant portion of time. For the flights with missing data it has to be defined filling factors which would be more or less accurate based on other usage information, but that has to be accounted for as the part of the general reliability of the system. Additionally, regular checking is required to detect any possible drift of the measurements for any reason (for example local adjacent wears, etc) that could yield to a distorted evaluation of the severity. Other important consideration is the calibration of the strain gauges against the flight events that they intend to capture. The accuracy of this process is not the same for all the locations of the a/c and for all the types of events, and this reliability has to be included in the overall assessment. All this aspects imply a significant effort of the maintenance of the system itself.

Regarding the parametric systems, they avoid the need of the maintenance of the strain gauges, although they introduce other considerations to be accounted for related to continuous airworthiness, which depend on the way the transfer function from flight parameters to local stresses is performed,

- Based on loads model, or
- Based on a neural network

The first type has the advantage over the approach based on strain gauges that it allows evaluating the local stresses directly at the location of the analysis, either using a global FEM model or with the aid of additional detailed FEM models in some cases. Since the loads model will be the same that has been used for the certification, a priori there won't be introduced additional uncertainties. In any case it will be needed regular revisions to verify that all the flight conditions that may be experience in the evolving usage environment are well capture by the model.

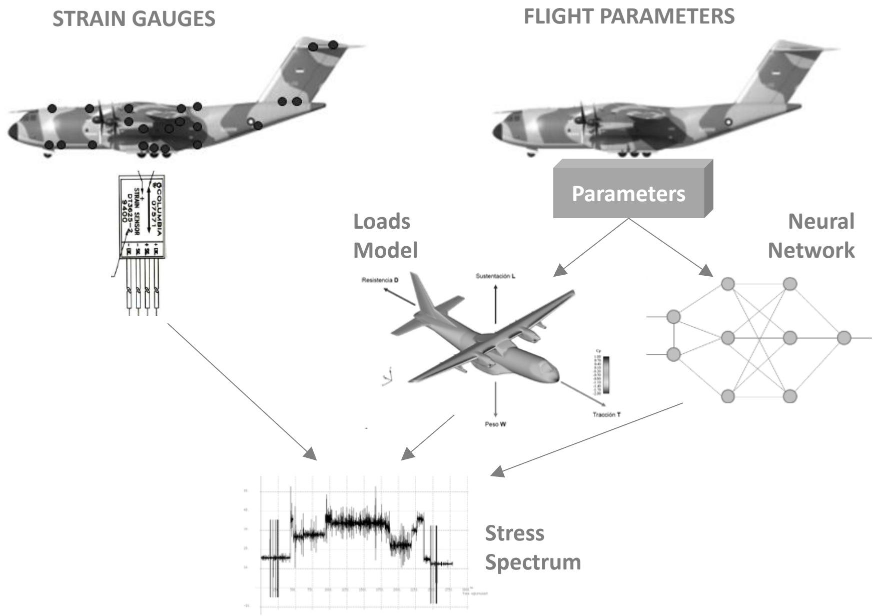

Figure 8: Individual aircraft tracking approaches

For the system based on neural network, basically it is calibrated at certain locations in which strain gauges where installed in the training phase of the network. So it has a similar uncertainty than the system based directly on strain gauges regarding the area covered by the strain gauge position. But additionally, during this training phase it can be seen the correlation between the measurement and the prediction by the network, which could imply the consideration of different reliability levels depending on the location.

The application of the individual a/c tracking systems depends on the specific maintenance program of the operator. For combat a/c design as safe-life structure, the maintenance program limitations may be directly expressed as a fatigue usage or index parameter instead of FC or FH. The outcome of the tracking system is then directly used for maintenance task activities.

For military transport aircraft it is not always the case, and the outcome of the tracking system in terms of usage severity at critical locations could be used as advisory information. Nevertheless it is of highly valuable in the context of continuous airworthiness, since allow more accurate evaluation of usage severities, in terms of mean values and standard deviations. With this information it is straight forward to apply the probabilistic assessments proposed in section 2.1. Complemented with the other recorded usage parameters that enable to identify possible usage pattern evolutions, contribute to a more rational criterion in the decision of the applicability of the current maintenance program, or the need to update it. Or even decide if the individual a/c tracking information in terms of fatigue usage needs to be incorporated directly as part of the maintenance program management.

In summary, although a priori the individual tracking systems allow removing the uncertainty in usage, with the possibility to reduced scatter factors while keeping the same level of safety than the un-monitored systems, particular consideration of the different aspects that contribute to the inherent reliability of the systems has to be accounted for when building the overall reliability model for the purpose of continuous airworthiness requirements.

3. Conclusion

Safety of aircraft structures is assured through compliance with certification regulations, by means of fatigue and damage tolerance analysis, from which it is derived a maintenance program that includes replacement times and threshold and interval inspections. For that purpose it is assume an initial intended usage.

The reality shows that this usage varies along the life cycle of the aircraft. In order to keep the adequate level of safety to comply with the continuous airworthiness requirements, the evolution of the usage patterns needs to be

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identified though periodic fleet surveys, and the maintenance program updated accordingly. It has been presented the variety of maintenance approaches that the industry offers to accommodate different usage deviation magnitudes and also operator specificities and interests:

- Basic Maintenance Program
- Maintenance Program Based on Regions
- Maintenance Program Based on Individual Types of Flights
- Maintenance Program Based on Individual A/C Tracking

The decision to keep or update the maintenance program within the evolving usage needs assessments to assure adequate level of safety or structural reliability based on continuous airworthiness requirements. In order to support the definition of criteria for this assessments, it is proposed a simple probabilistic model, using stochastic parameters commonly accepted, and with a target reliability calibrated with the level of safety inherent to the accepted deterministic model used for current certification.

4. Glossary

A/C	Aircraft	Pf	Probability of Failure
ADS	Airbus Defense and Space	PoD	Probability of Detection
da/dN	Crack Propagation Curve	PSE	Principal Structural Element
DSG	Design Service Goal	SEU	Severe Usage
EIFS	Equivalent Initial Flaw Size	SF	Scatter Factor / Safety Factor
FC	Flight Cycles	SHM	Structural Health Monitoring
F&DT	Fatigue and Damage Tolerance	S-N	Stress-Life Curve
FEM	Finite Element Method	SPS	Semi Prepared Strip
FH	Flight Hours	STU	Standard Usage
Kc	Fracture Toughness	TC	Type Certificate
LLF	Low Level Flight	TOF	Type of Flight
LoV	Limit of Validity	USF	Usage Severity Factor

Appendix A: Criteria for Assessment of Maintenance Program Applicability

From continuous airworthiness point of view, the basis for all these assessments identified in previous sections is to keep the adequate level of safety, or structural integrity reliability. In order to evaluate that, it is necessary to define that acceptable level of safety or reliability. It is considered here that the acceptable level of safety is the one assumed in the certification process of the airframe. The problem is that this certification process does not explicitly specify what is that level of safety. The typical approach for rational evaluation of level of safety or reliability is through probabilistic models but, as indicated, those models are not defined in standard certification of airframe structures. Nevertheless there is reliability data which can be considered commonly accepted that can be used in this respect. The purpose of this section is to figure out the probabilistic model that has been considered implicitly in Certification. With such a reference probabilistic model, it will be possible to use it and quantitatively compare with the actual fleet usage in the context of continuous airworthiness assessments to determine the validity of the assumptions for the maintenance program, and the necessity to update it.

There are many uncertain variables affecting the fatigue life of a specific location of an aircraft: design variables, material properties (S-N, da/dN, Kc, etc), manufacturing quality (EIFS, etc), detectability (PoD), loads and stress spectra (spectrum usage, limit load, etc), etc. The effect of those uncertainties is that the actual life will show a distribution like the one shown in figure 9. The probability that a particular a/c has a life lower than the calculated safe life (P_F) is small enough to be considered acceptable from a safety point of view. The criterion to comply the continuous airworthiness requirements in the evolving in-service usage means that the probability of failure in the actual fleet is lower than the probability of failure considered in the Certification.

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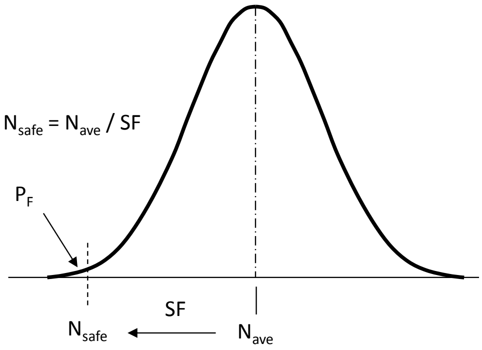

Figure 9: Actual distribution of fatigue life

The purpose of this appendix is to figure out the probabilistic model that has been considered implicitly in Certification, which will allow comparison with the actual fleet usage to determine the validity of the assumptions of the maintenance program.

Reliability model

The reliability model used normally in aircraft Certification, also generally by ADS, is a level I[1] type that uses a scatter factor that is considered to provide an acceptable level of reliability. As indicated above it is not clearly identified the basis for the definition of those scatter factors. This section attempts to figure out what are those implicit basis considering the information available from recognized references, and build a simplified reliability model level II or III:

- DEF-STAN 970 Leaflet 35, Fatigue Safe-Life Substantiation (ref. [3]) and R&M no. 3166, A Note on Test Factors, by N.I. Bullen (ref. [6])
- FAA AC 23-13A, Fatigue, Fail-Safe, and Damage Tolerance Evaluation of Metallic Structure for Normal, Utility, Acrobatic, and Commuter Category Airplanes (ref. [7])
- AFML-TR-69-65, Reliability Analysis Approach to Fatigue Life Variability of Aircraft Structures (ref. [8])

In this simplified reliability model all the variables affecting the fatigue behaviour of the structures are gathered into two main groups:

- As-built aircraft: covers variables such as material (s-n curves), manufacturing tolerances, etc. It will be referred with the sub-index MAT.
- Fleet usage: covers variables such as individual mission mix, loads (weight, center of gravity), statistics (gusts, manoeuvers, etc). It will be referred with the sub-index SEV (from usage severity)

In this model the fatigue life is evaluated using the following expression: $N = N_{MAT} / USF$

Where: N is the fatigue life at a particular location of an aircraft of the fleet
N_{MAT} is the fatigue life taking into account the variability of the material
USF is the Usage Severity Function that takes into account the variability in usage.

N_{MAT} would be the life of a particular location of a fleet aircraft associated to the Certification reference mission mix spectrum, considering the specific as-built condition of the aircraft and location.

USF is defined in the following way: $USF = d / d_{REF}$

Where:

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[1] Classification of reliability models by level according to JCSS (Joint Committee on Structural Safety): Level I using one characteristic value to describe each uncertain variable (Deterministic) with application of scatter factor in aircraft industry; Level II using two characteristic values to describe each uncertain variable; Level III using the joint probability distribution (FORM, SORM, Montecarlo); Level IV considers costs, construction, maintenance, repair, consequences of failure (assess target reliabilities for level III).

DOI: 10.13009/EUCASS2019-687

d_{REF} is the damage (for accumulated FC) at the particular location evaluated with the same methodology used in Certification (so reference as-built condition) and with the Certification reference mission mix spectrum.

d is the damage (for accumulated FC) at the particular location evaluated with the same methodology used in Certification but with the local spectrum experience by a particular aircraft in the fleet.

For convenience, USF can be expressed in a different way, taking into account that d = DSG / N:

$$USF = (DSG / N_{SEV}) / (DSG / N_{REF}) = N_{REF} / N_{SEV}$$

Where: DSG is the Design Service Goal

N_{ref} is the fatigue life at the particular location evaluated with the same methodology used in Certification and with the Certification reference mission mix spectrum.

N_{SEV} is the fatigue life at the particular location evaluated with the same methodology used in Certification but with the local spectrum experience by a particular aircraft in the fleet.

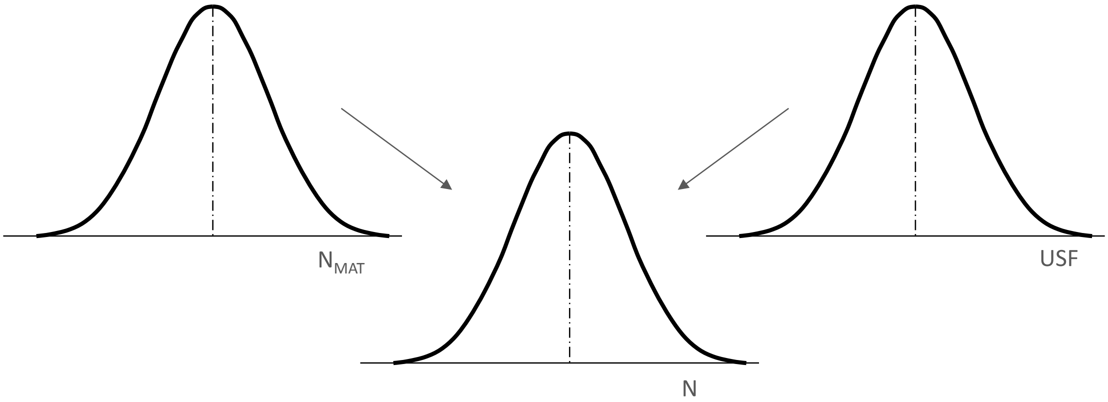

Figure 10: Actual distribution of fatigue life

So,
$$N = N_{MAT} / USF = N_{MAT} \times N_{SEV} / N_{REF}$$
$$N = N_{REF} \times (N_{MAT} / N_{REF}) \times (N_{SEV} / N_{REF}) = N_{REF} \times f_{MAT} \times f_{SEV}$$

Where f_{MAT} is the factor for material variability and f_{SEV} is the factor for usage severity variability

The following steps are:

Define the distribution functions of the random variables (N_{MAT} and N_{SEV} or USF, or f_{MAT} and f_{SEV}).
Define the target reliability (or the acceptable P_F).

Probability Distribution for N_{MAT}

The N_{MAT} random variable is the uncertainty that takes into account the variables associated to the as-built aircraft, such as material, manufacturing tolerances, etc. Several references have proposed probability distributions for this variable, normally adjusted to the two following distribution types:

- Weibull distribution (two-parameter α and β).
- Log-normal distribution[2], with variable $x = \log(N)$ and $z = (x - \mu) / \sigma$.

The following references are listed in this document:

- AFML-TR-69-65 (ref. [8]) proposes adjustment of thousands of fatigue test results with two different distributions for aluminum:
  - Weibull distribution (two-parameter) with shape parameter $\alpha = 4$ (section III paragraph 4) (Freudental in ref. [9] provides values for other materials)

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[2] In this document log-normal distribution is understood as a normal distribution of the variable $x = \log_{10}(N)$, where N is the life.

DOI: 10.13009/EUCASS2019-687

  - Log-normal distribution with standard deviation $\sigma = 0.14$ (section III paragraph 6)

- FAR AC 23-13A ref. [7]) proposes the following adjustment:
  - Log-normal distribution with standard deviation $\sigma = 0.14$ for aluminum (other materials available)

- DEF-STAN 970 Leaflet 35 (ref. [3]) explains the derivation of scatter factor taking into account probability of failures, which implicitly assumes the following distribution (calculated using also ref. [6]):
  - Log-normal distribution with standard deviation $\sigma = 0.1297$

In this document it will be preferably used the log-normal distribution, although assessments with the Weibull distribution will also be performed. For the log-normal distribution, it will be selected the value from AFML and FAA, $\sigma = 0.14$. Particularly the FAA information allows assessment of various materials, not only aluminum.

Probability Distribution for N_{SEV} or USF

The N_{SEV} random variable is the uncertainty that takes into account the variables associated to the individual aircraft usage, such as mission mix, loads (weights, center of gravity, etc.), statistics (gusts, maneuvers, bumps, etc.), etc. It has not been identified explicit information for usage variability distribution, but some conclusions may be derived examining the available references, particularly DEF-STAN 970. The two following characteristics have to be defined:

- Shape or type of the distribution (log-normal, Weibull, etc).
- Parameters of the distribution (σ for log-normal, α for Weibull, etc).

The type of the distribution is selected based on the usage monitoring data gather by ADS from other transport military fleet. Some of these data is presented in Annex B, from which it is considered that N_{SEV} follows a log-normal distribution. The parameters of this log-normal distribution assumed in the Certification are evaluated analyzing the information provided in DEF-STAN 970 Leaflet 35. For safe-life substantiation based on full-scale test, DEF-STAN proposes the following:

- Scatter factor: SF = 3.3333 · 1.5 = 5
- SFMAT = 3.3333 accounts for as-built variability, associated to a reliability 99.9% or PF = 10-3 with log-normal distribution s = 0.1297, as explained in the previous section.
- SFSEV = 1.5 accounts for usage variability, when the loads are not monitored.

It is understood that the addition of the SF = 1.5 when loads are not monitored tries to provide the same reliability that the initial SF = 3.3333 (which assumes that the loads are monitored). In other words, the global SF = 5 when loads are not monitored tries to get also a reliability 99.9% or $P_F = 10^{-3}$. As explained in section 0 our reliability model formulation is:

$$N = N_{MAT} \cdot N_{SEV} / N_{ref}$$
$$\log(N) = \log(N_{MAT}) + \log(N_{SEV}) - \log(N_{ref})$$

Changing to the variable: $x = \log(N)$: $x = x_{MAT} + x_{SEV} - x_{ref}$

Where: x_{MAT} is a normal distribution with $\sigma_{MAT} = 0.1297$.
x_{SEV} is a normal distribution with σ_{SEV}
x_{ref} is a constant, or a normal distribution with $\sigma_{ref} = 0$

In the Certification analysis x_{MAT} and x_{SEV} are assumed to be a variation from the average, which is taken as the reference, so the mean values are $\mu_{MAT} = \mu_{SEV} = \mu_{ref}$. The central limit theorem establishes that the linear combination of normal distributions is also a normal distribution with the following parameters:

$$\mu = \mu_{MAT} + \mu_{SEV} - \mu_{ref} = \mu_{ref}$$
$$\sigma = (\sigma^2_{MAT} + \sigma^2_{SEV} + \sigma^2_{ref})^{0.5} = (\sigma^2_{MAT} + \sigma^2_{SEV})^{0.5}$$

The following table shows a summary:

DOI: 10.13009/EUCASS2019-687

Table 1: Probabilistic model calculation

Distribution	**SF**	**σ**	**P_F**
As-built, MAT	$SF_{MAT} = 3.3333$	$\sigma_{MAT} = 0.1297$	$P_{F,MAT} = 10^{-3}$
Usage, SEV	$SF_{SEV} = 1.5$	$\sigma_{SEV} = ??$	
Combined	$SF = 5.0$	$\sigma = (\sigma^2_{MAT} + \sigma^2_{SEV})^{0.5}$	$P_F = 10^{-3}$

All the parameters shown in the table are not independent, so the parameter σ_{SEV} can be calculated (see Annex section **¡Error! No se encuentra el origen de la referencia.** for formulations). Combined distribution:

$P_F = 10^{-3} \rightarrow z = \Phi^{-1}(P_F) = 3.0902$
$SF = 10^{z \cdot \sigma} = 5 \rightarrow \sigma = \log(SF) / z = 0.2262$

Usage distribution: $\sigma = (\sigma^2_{MAT} + \sigma^2_{SEV})^{0.5} \rightarrow \sigma_{SEV} = (\sigma^2 - \sigma^2_{MAT})^{0.5} = 0.1853$

Target Reliability

In previous sections it has been determined the probability distribution for the random variables MAT (as-built) and SEV (usage). In order to complete the reliability model, it is pending to determine the target reliability, that is, the level of reliability that is considered acceptable from a safety point of view. As indicated above this acceptable level of safety is established by the scatter factors used in Certification, from which the maintenance program is derived.

Once the random variables distributions have been determined in previous sections, it is straightforward problem to determine the target reliability, with the aid of the Figure 9. In a general case the solution to this problem will require specific tools such as FORM, SORM of Montecarlo analysis. In the particular case of normal distributions, a simplified approach based on simple formulations can be used:

Material distribution: log-normal ($\sigma_{MAT} = 0.14$)
Usage distribution: log-normal ($\sigma_{SEV} = 0.1853$)
Combined distribution: log-normal

$\sigma = (\sigma^2_{MAT} + \sigma^2_{SEV})^{0.5} = 0.2322$
$SF = 5.0$
$SF = 10^{z \cdot \sigma} \rightarrow z = \log(SF) / \sigma = 3.0097$
$P_F = \Phi(z) = 1.31 \cdot 10^{-3}$
Target reliability = 1- P_F = 99.8692% → 99.87%

In the general case when both distributions are not normal another methods have to be applied.

An attempt is also made considering the Weibull distribution for the as-built random variable proposed in AFML document (ref. [8]). In this case it is not possible to use the central limit theorem, and Montecarlo is used instead, with $\alpha_{MAT} = 4$, $\beta_{MAT} = 54798$ (median = 50000, arbitrary number), and the same usage distribution:

n = 100,000 simulations → Target reliability = 99.57%
n = 1,000,000 simulations → Target reliability = 99.55%

Appendix B: Usage Severity Probabilistic Distributions

The N_{SEV} random variable is the uncertainty that takes into account the variables associated to the individual aircraft usage, such as mission mix, loads (weights, center of gravity, etc.), statistics (gusts, maneuvers, bumps, etc.), etc.
In order to define the shape or type of this random variable, it has been analysed the information gather from several SHM systems.

For this purpose is has been defined a not dimensional usage variable, $x = \log(N_{SEV} / N_{REF})$, and depicted in a normal distribution probability plotting paper.

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The following chart shows the probability plotting paper for about 1 500 flights of a medium & light mission a/c at a wing location (left) and about 4 000 flights of big tactical a/c at a location sensible to intensity and duration of manoeuvers, where only the most severe flights are shown (right):

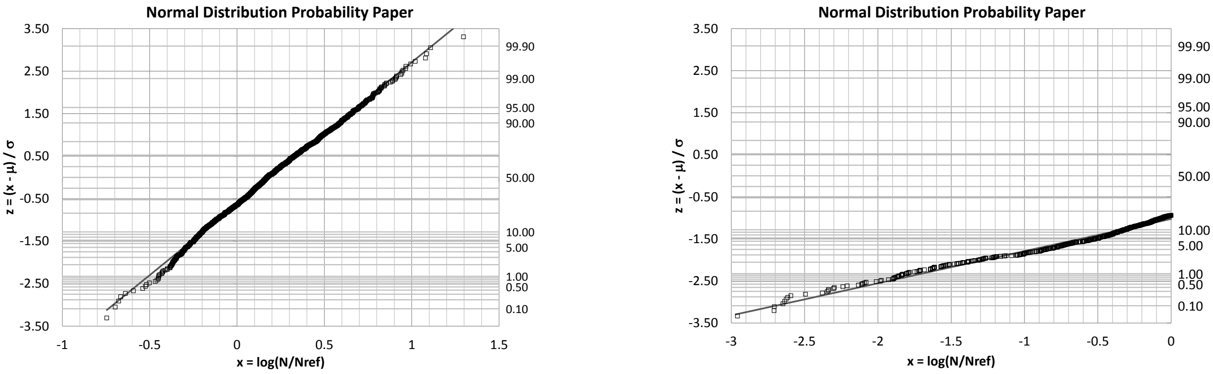

Figure 11: Usage severity distribution on normal probability paper

This next chart shows the probability paper for about 700 flights of big strategic a/c at a wing location.

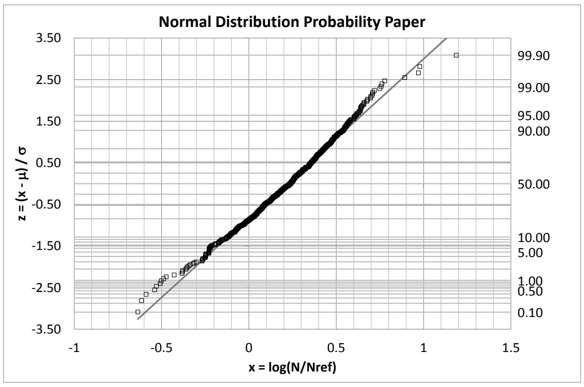

Figure 12: Usage severity distribution on normal probability paper – strategic a/c

The data presented in the previous plots would allow concluding that usage severity could be reasonably characterized by a normal distribution of the log(life). Note that this exercise has been performed for the usage severity of individual flights, in order to have a significant number of data for adjustment purposes. More adequate data should be derived from the severity of accumulated flights of individual a/c, which a priori would provide less dispersion.

References

[1] FAR 25.571, Damage-tolerance and fatigue evaluation of structure
[2] CS 25.571, Damage-tolerance and fatigue evaluation of structure
[3] DEF-STAN-970. Design and Airworthiness Requirements for Service Aircraft. Section 3, leaflet 35 Fatigue Safe-Life Substantiation. Ministry of Defense.
[4] MIL-STD-1530C. Aircraft Structural Integrity Program (ASIP). Department of Defense Standard Practice
[5] MIL-HDBK-516C. Airworthiness Certification Criteria. Department of Defense Handbook
[6] R&M no. 3166, A Note on Test Factors, by N.I. Bullen
[7] FAA AC 23-13A, Fatigue, Fail-Safe, and Damage Tolerance Evaluation of Metallic Structure for Normal, Utility, Acrobatic, and Commuter Category Airplanes
[8] AFML-TR-69-65, Reliability Analysis Approach to Fatigue Life Variability of Aircraft Structures
[9] AFML-TR-74-198, Reliability Assessment of Aircraft Structures Based on Probabilistic Interpretation of the Scatter Factor, Alfred M. Freudenthal, 1975