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# STRATEGIES FOR ENSURING ROTORCRAFT STRUCTURAL INTEGRITY

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## OVERVIEW

The views presented in this paper are those of the author and should not be construed as representing official Federal Aviation Administration rules interpretation or policy.

Part 29.571 of reference [1] contains several strategies that, with certain qualification, applicants are allowed to adopt to ensure adequate structural integrity throughout the operational life of a rotorcraft. There has been a continuing debate concerning the merits of the various strategies. Much of the discussion has centered on the damage tolerance versus the flaw tolerance philosophies and the pros and cons of each. Additionally, the appropriate role of the traditional safe-life philosophy has been debated at length.

This paper begins by considering what the objective of Part 29.571 is and then examines each of the strategies and their strengths and weaknesses. Following this a recommended strategy is proposed which is believed to offer the most rational path at the present time to achieving the stated objective.

## INTRODUCTION

The primary objective of Part 29.571 is to mitigate catastrophic failures due to fatigue by maintaining a minimum level of structural integrity throughout a structure's operating life. The level of structural integrity that a newly delivered rotorcraft must be shown to have is defined in Part 29.305 of reference [1]. In short the structure must be able to support limit loads without detrimental or permanent deformation and ultimate loads without failure where ultimate loads are 1.5 times limit. Compliance is generally shown by a combination of analysis and testing of structure that is as representative as possible of the production design and free from any known defects. This level of structural integrity will be referred to as the "baseline integrity" that each structure is required to begin life with. It is also one of the basic type design requirements. Additionally, Part 21.183 of reference [1] implies that for an aircraft to be considered airworthy it must always conform to type design.

Based on the above it is believed that maintenance of baseline integrity must always be considered when evaluating philosophies aimed at precluding catastrophic failures due to fatigue. Consistent with this has been the FAA's "flyable cracks" policy which has always included a requirement to show ultimate load capability, with a known crack, as a fundamental prerequisite before considering continued operation without repair. Also consistent with this line of thinking is the requirement to apply the basic type design requirements of Part 29.305 of reference [1] to any repairs or modifications to operational aircraft regardless of age. There are, in short, no provisions for relaxing structural integrity requirements as a structure ages.

## THREATS TO STRUCTURAL INTEGRITY

For a new structure whose design is certified and which possesses an airworthiness certificate the probability of catastrophic failure due to fatigue should be zero. This follows from the fact that the probability of meeting the strength and deformation requirements of Part 29.305 of reference [1] should be 1.0 and that it has not experienced any cyclic loading. However, once it is put into service there are many mechanisms that can give rise to fatigue cracks and eventually lead to catastrophic failure. For the following discussion these mechanisms, or threats to structural integrity, are divided into two categories. The first category will contain those mechanisms which will lead to "normal" fatigue. The second category will contain those mechanisms which could lead to "anomalous" fatigue.

### Normal Fatigue

Normal fatigue is the expected, inevitable (if we are operating above the endurance limit) fatigue that will occur if a structure was designed without error, manufactured as planned and operated and serviced as expected. Normal fatigue is predictable and the probability of it occurring is steadily increasing with time. Traditional fatigue testing is performed to characterize normal fatigue at the detail, component and aircraft level. If one defines a discrete endpoint to life, such as the appearance of a 1mm crack, the time to reach that endpoint typically follows a statistical distribution. Normal, Log Normal and Weibul distributions are typically used to characterize the behavior. Given a statistical distribution of life to a defined endpoint the degradation of failure strength capability with time can be conceptually depicted as shown in figure 1. This assumes the structure had some small margin of strength above the basic requirement. The cumulative probability of reaching a fatigue state such that the structure will fail at ultimate load is shown by a solid curve and the limit critical cumulative probability is given by the dashed curve. It follows that point A represents the average time to degrade to ultimate capability and point B is the average time to degrade to limit. This also illustrates that there is some period of time during which a structure can be considered to be virtually crack free and

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therefore expected to meet the baseline integrity requirements with high probably.

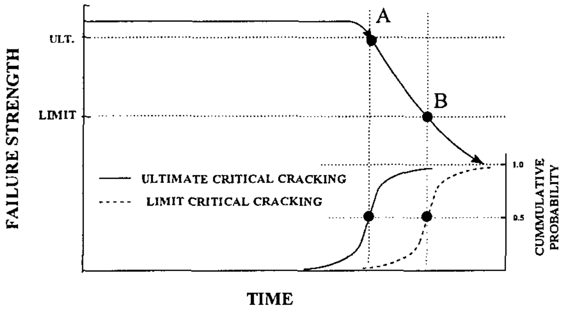

**Figure 1 Degradation of strength with time due to normal fatigue (50% probability)**

## Anomalous Fatigue

Anomalous fatigue occurs due to unexpected and unpredictable events. Sources of anomalous fatigue include but are not limited to:

- Design oversights/errors
    - underestimating external loads
    - underestimating internal loads
    - underestimating peak stresses
- Manufacturing errors/mistakes
    - omission of critical processes
    - introduction of defects
- Operational and service anomalies
    - severe usage (relative to expected)
    - service induced defects

Considerable effort is made during design and manufacture to mitigate the risk of anomalous fatigue. Likewise, controls are typically put into place once an aircraft enters service to minimize the risk of operational and service related anomalies. However, in spite of our best intentions, anomalous fatigue does occur and can result in increased maintenance costs at best and loss of aircraft and life at worst.

The degradation of failure strength capability due to anomalous fatigue can be conceptually depicted as shown in figure 2. Curve 1 is the degradation of strength due to normal fatigue and is included for reference. Curves 2 - 6 depict degradation due to anomalous fatigue. Since the time of occurrence of the anomaly and its severity are unpredictable by definition any reliable statistical modeling is questionable. The flat dashed curve is meant to depict the cumulative probability of anomalous fatigue occurring. As was discussed above concerted efforts are typically made to drive this to as near zero as possible. While it may be argued that there is some increase in cumulative probability with time (e.g. due to increased exposure to anomalous sources) it might be considered to be relatively low and virtually constant.

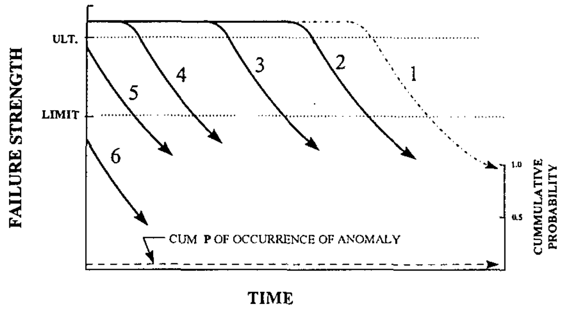

**Figure 2 Degradation of strength with time due to anomalous fatigue**

## THREAT STRATEGIES

Strategies employed to deal with the threat of normal and anomalous fatigue are discussed below. It is argued that the traditional safe-life philosophy and damage tolerance philosophy can be used to effectively deal with normal and anomalous fatigue respectively. The flaw tolerance philosophy is also discussed since it is currently included as an acceptable strategy in Part 29.571 of reference [1]. However, it is suggested that the flaw tolerance philosophy is unduly pessimistic relative to the normal fatigue threat and inadequate with respect to the anomalous fatigue threat.

### Safe-Life Philosophy

Before going further with this discussion it is considered necessary to clarify the author's definition of "safe-life" within the context of this paper. Two existing definitions are referenced for purposes of discussion. The first definition is given in reference [2] and is as follows:

> "Safe-Life means that the structure has been evaluated to be able to withstand the repeated loads of variable magnitude expected during service without detectable cracks."

The second definition is given in reference [3] and is as follows:

> "Safe-Life of a structure is that number of events such as flights, landings, or flight hours, during which there is a low probability that the strength will degrade below its ultimate value due to fatigue cracking."

The first definition correlates best with the words that currently exist in the safe-life rules of reference [1]. Here the focus is on the absence of detectable cracks. It is suggested that this focus can result in some ambiguity since what is detectable is a function of the inspection method. With inspection methods improving with time this definition is somewhat of a moving target and therefore less than adequate.

The second definition focuses on the baseline integrity discussed in the beginning of the paper. This focus is unambiguous and follows directly from the requirements of reference [1] for type design and airworthiness certification. Because of this it is suggested that it is the most appropriate and will be the definition used in the context of this discussion.

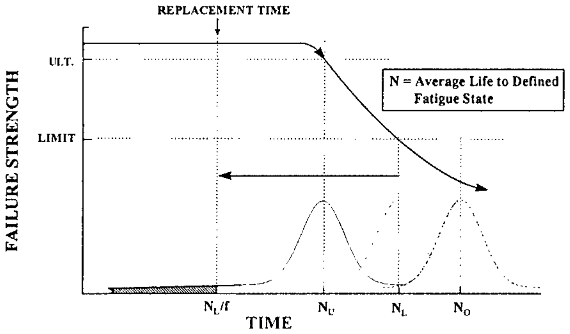

**Figure 3 Application of traditional safe-life philosophy**

Based on the second definition of safe-life discussed above and the nature of normal fatigue as depicted in figure 1 it is concluded that the traditional safe-life philosophy is adequate for dealing with the normal fatigue threat. This is conceptually depicted in figure 3. An average fatigue life is established based on analysis and test for a nominal part free from known defects. A factor is then applied to this life to establish a replacement time when the part is to be removed from service. Figure 3 illustrates the case of the replacement time being based on some fraction of the average time to develop cracking which would cause the structure to fail at limit load. Distributions of life to ultimate critical and sub limit critical are also depicted. It is believed that, in the past, average lives associated with fatigue states, that did not degrade the failure strength below ultimate, have often been used. In this case a replacement time based on $N_U/f$ would certainly result in "low probability that the strength will degrade below its design ultimate value due to fatigue cracking." For the scenarios where the average fatigue life corresponds to fatigue states where the failure strength is below ultimate the probability of having a fielded part's failure strength degrade below ultimate may be higher but still may be acceptably low depending on the value of f used. This is also illustrated in figure 3 for the case where $N_L$ is used. The retirement life is given by $N_L/f$ and the cumulative probability of failing below ultimate is small and represented by the fractional shaded area under the life to ultimate critical distribution curve.

A frequent deficiency of the safe-life philosophy as currently applied is the failure to quantify the fatigue state being addressed and its impact on failure strength. It is suggested that this should be corrected in the future so that there is no ambiguity relative to meeting the stated objective. Beyond this it may be desirable to quantify the cumulative probability of the strength degrading below ultimate at the replacement time.

Damage Tolerance Philosophy

Reference [4] discusses the adoption of a damage tolerance philosophy by the USAF. As discussed in the reference the primary motivation was the recognition that anomalous fatigue was a significant threat that had to be dealt with and that it wasn't being adequately taken care of by the safe-life philosophy which had been previously employed. The USAF requirements, which derive from their philosophy, were originally specified in reference [5]. It has been noted on numerous occasions, (e.g. see reference [6]), that anomalous fatigue due to manufacturing and in-service damage has been successfully controlled in the USAF fleet through the adoption of the damage tolerance approach in 1975. The common ground between the USAF damage tolerance philosophy and the one promoted herein is the requirement to assume a fatigue crack(s), perform a damage tolerance evaluation using fracture mechanics principles and establish inspection requirements consistent with the damage tolerance characteristics of the structure. Additionally, the USAF requirements specify crack sizes to be assumed and set minimum acceptable standards for crack growth life and inspection intervals. The key difference between the USAF philosophy and the one in reference [1] is that the USAF requirements result not only in a damage tolerance based inspection program but also a minimum acceptable level of tolerance to damage. In comparison, a design which is not inherently damage tolerant can still be found in compliance with reference [1] provided the inspection requirements match its damage tolerance characteristics (however good or marginal the characteristics might be).

The damage tolerance philosophy as advocated herein is based on (1) the assumption of a crack(s), (2) characterization of the growth and impact on strength of the crack(s), (3) assurance of a minimum strength equal to the highest loading that could be expected within the design operating envelop (e.g. limit load), (4) establishment of inspection requirements consistent with the damage tolerance characteristics of the structure and (5) implementation of inspections. It should be noted here that the setting of inspection requirements based on the assumption of anomalous defects, and insuring no failure at "limit" load, is only applicable to the period of time during which normal fatigue cracking is not expected to occur (i.e. low cumulative probability). Beyond this point additional action must be taken to deal with the constantly increasing probability of normal fatigue. As discussed above, replacement based on the traditional safe-life philosophy would be one way to deal with this.

It is believed that while no philosophy can be expected to precluded catastrophic failures due to fatigue with 100% certainty the damage tolerance philosophy provides the best protection against anomalous fatigue due to the kind of mechanisms previously noted. One of its strongest assets is that it deals directly with cracks which are, in the end, what cause the failure. The damage tolerance philosophy forces one to consider how a structure behaves with cracks and this insight can be used to modify the design such that there is at least a minimum level of tolerance to cracks. It also generates inspections that are geared to detect what actually causes a structure to fail (i.e. cracks). A damage tolerance philosophy can even be of benefit for anomalous fatigue due to design errors and severe usage that results in unexpected cracking. Even if the inspection intervals and inspections methods are not optimum for the subject cracking there will be some probability of precluding a failure because one is inspecting in the right location for the right thing.

Another ancillary benefit of a damage tolerance based inspection program is the additional protection from the normal fatigue threat that it provides. Since inspections are typically defined to detect cracks in fatigue critical areas premature "normal" cracking will have a measurable probability of being detected if it should occur before the replacement time is reached. In this case the replacement time could be reassessed to mitigate any potential risk to the fleet. Consistent with this it might be feasible to depart from tradition and be less conservative with the factor, f, used to determine the replacement time, provided that a damage tolerance inspection program is in place. This notion is discussed in more detail below.

### Flaw Tolerance Philosophy

The flaw tolerance philosophy is included as an alternative to the damage tolerance philosophy in showing compliance with Part 29.571 of reference [1]. This philosophy focuses on crack initiation from defects that might be envisioned to occur during manufacture or in the service life of the structure. Traditional safe-life methodology is employed using fatigue data for intentionally flawed test specimens. Replacement times are derived from test data for "barely detectable" flawed specimens and in-service inspection requirements are derived from test data for "clearly detectable" flawed specimens.

In general, the flaws to be considered are not cracks but instead include nicks, dents, scratches, fretting or corrosion that may occur during manufacture or during the service life of the structure. Application of the flaw tolerance philosophy requires the determination of the maximum probable undetectable and clearly detectable flaw sizes and critical locations based on a review of historical data and manufacturing processes. It is implicitly assumed that the impact on baseline integrity of these threats is conceptually the same as depicted for normal fatigue as shown in figure 1. That is, there is some quantifiable crack initiation phase followed by a crack growth phase and that the time to initiate a crack follows a statistical distribution which can be established based on fatigue testing of flawed specimens and/or flawed production components. The degradation of strength with time trend is conceptually illustrated in figure 4 for a production part without flaws, with barely detectable flaws and with clearly detectable flaws.

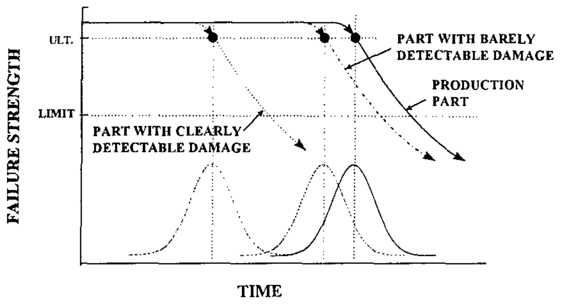

**Figure 4 Impact of flaw tolerant flaws (50% probability)**

It is the author's opinion that while the flaw tolerance philosophy could be considered an acceptable, but pessimistic, alternative to the traditional safe-life philosophy it should not be considered an acceptable alternative to the damage tolerance philosophy.

The flaw tolerance philosophy sets replacement times based on flawed part crack initiation life. The flaws considered are those that could go undetected during the manufacturing process and reduce the life below that of a "properly" manufactured part. This approach could easily yield replacement times that are less that those that would be set based on the traditional safe-life philosophy. This would appear to unduly penalize the majority of the population, make part replacement more of an economic burden than it is now and not significantly help mitigate the anomalous fatigue threat.

The flaw tolerance approach establishes inspection requirements based on precluding crack initiation from an in-service detectable flaw. The resulting inspections are aimed at detecting dings, bangs, scratches, corrosion, etc. and the intervals are based on the time to initiate cracks from these kinds of defects. While in-service inspections should be performed to look for these kinds of flaws this in itself falls short of what is required. It is difficult to imagine that potential flaw sources can be anticipated, flaw types characterized and severity quantified to a degree that is sufficient to bound all significant anomalous threats of this nature. It is also believed that the adequacy of the bounding will present a major dilemma for the regulators. The flaw tolerance philosophy does not produce inspections that have crack detection as their primary objective. This is a major deficiency since cracking is what ultimately results in failure The bottom line is that an inspector who is looking for cracks has a chance of finding them if they are there and will also detect and report any dents, scratches, corrosion, etc., if present. The converse is not necessarily true. Additionally, there are anomalous threats such as design oversights/errors and severe usage that can result in premature cracking without any tell tale "clearly detectable" flaws being present. The flaw tolerance philosophy does little to help mitigate failures due to these threats.

### A Proposed Strategy

It is suggested that an appropriate and effective strategy for meeting the objective of Part 29.571 of reference [1] would be to use a traditional safe-life philosophy to deal with the threat of normal fatigue and a damage tolerance philosophy to deal with the threat of anomalous fatigue. This strategy would have two primary elements which are summarized as follows:

1. Establish replacement times for all principle structural elements based on the traditional safe-life approach and remove them from service before there is any significant probability of developing cracks due to normal fatigue. Inherent with this would be a high probability that the baseline integrity would be maintained up to the time of replacement.
2. Establish in-service inspection requirements for all principle structural elements based on their damage tolerance characteristics determined from a damage tolerance evaluation (supported by analysis and test) unless it could be shown that this was impractical. If inspections tied rigidly to the damage tolerance characteristics of the structure were shown to be impractical detail inspections of critical areas for cracking would still be required using mutually agreed to NDI methods and intervals based on good engineering judgment. Additionally, extra precautions (e.g. more rigorous detail analysis, testing, loads monitoring, etc.) would be required for these parts to help mitigate potential sources of anomalies.

The proposed strategy is based on the concept of not allowing parts to operate beyond a point when there is a significant probability that the baseline integrity is compromised due to normal fatigue and rigorously inspecting the parts for potential cracking caused by anomalous fatigue up to that point. A rigorous inspection program must be derived from the results of a damage tolerance evaluation. Ideally the inspection location, method, threshold and interval would all correlate with the evaluation results. In some cases this might prove to be impractical however inspections for cracks in the appropriate areas should be imposed as a minimum. When a completely rigorous inspection program is practical, implementing it will also provide an additional safeguard against the normal fatigue threat. Because of this, traditional "safety factors" on life and/or fatigue strength might be reduced without reducing the level of safety achieved with traditional factors but without damage tolerance based inspections.

## SUMMARY

Part 29.571 of reference [1] contains requirements aimed at mitigating the risk of catastrophic failure due to fatigue. Structural evaluations must be performed and "inspections, replacement times, combinations thereof, or other procedures" must be defined to achieve the desired result. Three different philosophies are recognized in the rule. Either the flaw tolerant or damage tolerance philosophies must be used unless the applicant establishes that these philosophies cannot be practically applied. In that case it is acceptable to use the safe-life philosophy.

For new structure we can divide all potential fatigue cracking into two categories. One is "normal" fatigue which is unavoidable, inevitable and predictable. The second is "anomalous" fatigue which we try to avoid and whose potential occurrence is unpredictable. Given the different nature of each it is natural that two different strategies must be used to deal with each.

Part 29.305 of reference [1] contains basic structural integrity requirements for strength and deformation. These are basic type design requirements and per Part 21.183 of reference [1] they must be met if an aircraft is to be considered airworthy. These fundamental type design requirements must always be kept in mind when considering appropriate strategies to be used against the threat to structural integrity that fatigue presents.

The flaw tolerance philosophy should be dismissed as an inappropriate strategy for dealing with both normal and anomalous fatigue. It unduly penalizes the majority of a part population relative to the normal fatigue threat and does little to help mitigate the risks associated with the anomalous fatigue threat. The fact that it does not result in inspections that are devised to detect cracks is also a major deficiency.

An effective strategy for meeting the objective of part 29.571 of reference [1] and maintaining airworthiness per part 21.183 of reference [1] is to use both the safe-life and damage tolerance philosophies. Replacement times are specified based on the safe-life philosophy and parts are removed from service before the probability of normal fatigue and not meeting type design requirements becomes significant. Inspection programs are established, for the period of time during which normal fatigue is not expected to occur, based on the damage tolerance characteristics of the part. Implementation of these inspections would adequately mitigate risks associated with anomalous fatigue. A caveat to this strategy might be a reduction in the magnitude of traditional "safety-factors" used to define replacement times. This could result in significant economic benefits without reducing safety levels below those achieved with higher factors but without damage tolerance based inspections.

## REFERENCES

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