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NEW FATIGUE AND DAMAGE TOLERANCE EVALUATION RULES - ARE WE FIT FOR THEM?

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ABSTRACT

This paper shows the history and background of the motivation for the new rules concerning the evaluation of fatigue and damage tolerance of metallic and composite rotorcraft structures and the most significant modifications which were made compared to the existing rules.

Starting point is a “White Paper” written by industry dealing with the methodology of fatigue evaluation of helicopter structures. Based on that, working groups consisting of world wide helicopter industry and authority members were set up to establish modernized rules and associated advisory material for the fatigue and damage tolerance evaluations.

One of the most significant changes is the separation of the evaluation of metallic and composite structures in §27/29.571 and 573 respectively to account for the particularity of metallic and composite structures. Another important feature is the introduction of a requirement for the residual strength up to limit or ultimate load after repeated loading of the structure. The residual strength includes damage tolerance aspects as well. Replacement times and inspection intervals are to be calculated with the help of test results and analyses. The key elements of the new requirements are presented, compared among them and evaluated against the previous rule.

What are the repercussions of the new requirements on new certifications? A few examples of past and current fatigue substantiations show where Eurocopter stands related to the future requirements.

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1. HISTORIC BACKGROUND

In the late 1980s a severe incident led to the initiation of the TOGAA (Technical Oversight Group for Ageing Aircraft) working group. The target of this group was to look into the consequences of ageing aircraft structure, to propose related actions and this finally led to the introduction of the damage tolerant idea into the certification requirements of fixed wing aircraft.

The scope of the TOGAA group was then extended to the field of engines and in 1993 also to helicopters.

European and American helicopter manufacturers as well as the respective authorities created the RCWG (Rotorcraft Community Working Group) to find solutions to the requirements of the TOGAA. One outcome of this discussion was a methodology for fatigue and damage tolerance evaluation of metallic structure which was laid down by the helicopter industry in a so called “White Paper” and presented to TOGAA for comments.

Starting on this basis the Aviation Rulemaking Advisory Committee (ARAC) initiated the 29WG (Working Group to address the Federal Aviation Rule FAR29.571). This group was assigned to work on a new Advisory Circular (AC) for the FAR29.571 existing at that time and a new joint FAR/JAR rule 27/29.571 with an associated AC. In 1999 the decision was taken to initiate another group inside 29WG to separately deal with the specific issues of composites and to propose a new joint FAR/JAR rule 27/29.573 for composite structure and associated ACs.

The results of the working groups were given to ARAC in 2001 and finally led to the publishing of the following proposed new rules:

- January 2010
  NPRM No. 09–12 (Notice of Proposed Rulemaking) for FAR 27/29.573
  "Damage Tolerance and Fatigue Evaluation of Composite Rotorcraft Structures" [3]
- March 2010
  NPRM No. 10-04 for FAR 29.571
  "Fatigue Tolerance Evaluation of Metallic Structures"[4]
- April 2010
  NPA (Notice of Proposed Amendment) No. 2010-04 for CS-27/29.573: "Damage Tolerance and Fatigue Evaluation of Composite Rotorcraft Structures" [5]
- May 2010
  NPA No. 2010-06 for CS-29.571:
  "Damage Tolerance and Fatigue Evaluation of Metallic Rotorcraft Structures" [6]

2. MAIN DIFFERENCES BETWEEN EXISTING AND NEW RULES

A result of the working groups was the finding that currently the rule contains methodologies to be applied like flaw tolerant safe-life, fail-safe, and safe-life, the understanding of which may not be the same for everybody. It is recognized as being more appropriate to focus rather on the objectives and specific results than on the methods to be used. Therefore the key element is the complete fatigue evaluation process under consideration of crack initiation, crack growth, and final failure.

Another aspect is the fact that in the past some authorities required special conditions to be fulfilled by substantiations. Those special conditions were targeted to take into account new technologies and methodologies mainly in the field of composite applications. However, they contained quite detailed descriptions of substantiation methods which are rather appropriate for advisory material than for a rule. It was the goal of the working group to more clearly separate the "what" in the rule from the "how" in the advisory material.

For the comparison of the existing and new rules the following approach is used to reduce the complexity of the considerations and the designations. Referenced as the "existing rule" are the paragraphs of the current

FAR 29.571 Amdt. 29-28, 1989 [1] and
CS-29.571 Amdt. 2, 2008 [2].

The text of the both is practically identical; therefore the FAR is taken as the representative of the "current rule".

Looking at the "new rules" we have

FAR 29.571 NPRM No. 10-04 with
CS-29.571 NPA No. 2010-06

for the metallic components. In this case, again, the text of FAR and CS is matching except one statement which will be explained later in Chapter 2.4. So the FAR NPRM is taken as representative of the "new rule" for metallic structure.

For the composite components there is

FAR 29.573 NPRM No. 09-12 with
CS-29.573 NPA No. 2010-04.

The order and numbering of the subparagraphs in FAR and CS are not the same. However, the content of each of them can be matched despite some slight differences in the wording. There is the same exception as for the metallic components explained in Chapter 2.4. Based on the above, the FAR NPRM can be taken as representative of the "new rule" for composite structure (Fig. 1).

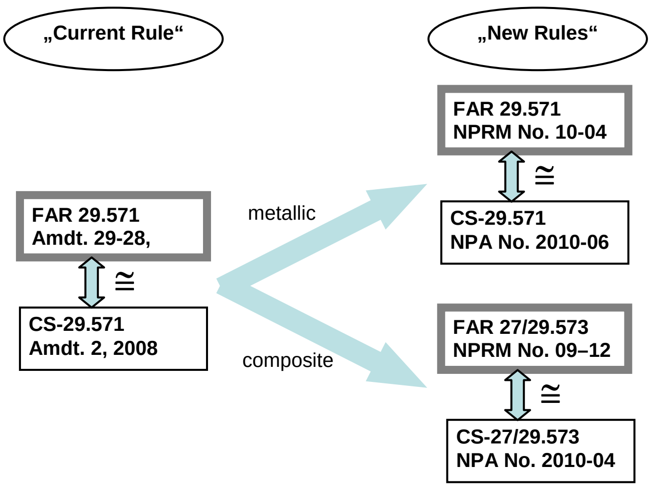

Fig. 1: Relation of "current and new rules"

As can be seen from the proposed new rules, one significant difference to the existing rule is the separate treatment of metallic and composite structures regarding their substantiation requirements. The reason for this is the unique behavior in fatigue and tolerance to damage of composites.

For example, on the one hand damage growth can be very small, but on the other hand impact damage can immediately lead to a significant reduction in the residual strength. Target of the new rule for composites is to provide improved tolerance to flaws and defects by application of methodologies which are practical and appropriate to helicopters.

2.1 Residual Strength Requirement

The term "residual strength" is used in the existing rule in connection with the Fail-Safe substantiation approach which is one option that can be chosen for the certification.

Existing rule:

(b) (2) ***Fail-safe*** *(****residual strength*** *after flaw growth) evaluation. It must be shown that the structure remaining after a partial failure is able to withstand design limit loads without failure within an inspection period ... .*

In the new rule there is a general requirement for showing residual strength capabilities independent from the individual approach which is used for substantiation.

New rule for metallic structure:

(f) A ***residual strength*** *determination is required to establish the allowable damage size. In determining inspection intervals based on damage growth, the residual strength evaluation must show that the remaining structure, after damage growth, is able to withstand design limit loads without failure within its operational life.*

New rule for composite structure:

(d) (1) … ***Each*** *damage tolerance* ***evaluation*** *must include:*

(d) (1) (v) An assessment of the ***residual strength*** *and fatigue characteristics of all Principal Structural Elements (PSEs) that supports the replacement times and inspection intervals established under paragraph (d)(2) of this section.*

2.2 Fatigue Tolerance vs Damage Tolerance

Currently the rule focuses on a Fatigue Tolerance Evaluation which looks - primarily - at damages under the influence of fatigue loading. In addition effects of environmental factors, flaws and damages occurring during manufacturing or service have to be considered.

Existing rule:

(b) … The fatigue tolerance evaluation must include the requirements of either paragraph (b)(1), (2), or (3) of this section, or a combination thereof, and also must include a determination of the probable locations and modes of ***damage caused by fatigue****, considering environmental effects, intrinsic/discrete flaws, or accidental damage. …*

Now the proposed rules require a general threat assessment which puts the effects of fatigue, environmental factors, flaws and damages occurring during manufacturing or operation on damage creation or propagation on the same level.

New rule for metallic structure:

(e) Each fatigue tolerance evaluation required by this section must include: …

(e) (4) For each PSE identified in paragraph (d) of this section, a threat assessment which includes a determination of the probable locations, types, and sizes of ***damage, taking into account fatigue, environmental effects, intrinsic and discrete flaws, or accidental damage that may occur during manufacture or operation****.*

New rule for composite structure:

(d) (1) … Each damage tolerance evaluation must include:

(d) (1) (iv) A threat assessment for all PSEs that specifies the locations, types, and sizes of ***damage, considering fatigue, environmental effects, intrinsic and discrete flaws, and impact or other accidental damage (including the discrete source of the accidental damage) that may occur during manufacture or operation****; …*

2.3 Replacement Times and Inspection Intervals

To date, the fatigue evaluation mainly results in a definition of a service life limitation for a part which is sometimes infinite. Less often there is a mandatory inspection interval which is as well listed in the Airworthiness Limitations Section (ALS) of the maintenance manual. The rule also allows of course the definition of both.

Existing rule:

(a) (2) Based on the evaluations required by this section, inspections, replacement times, ***combinations thereof, or*** *other procedures must be established as necessary to avoid catastrophic failure. …*

In the new rule both, inspections and retirement times, have to be defined and published in the ALS.

New rule for metallic structure:

(a) A ***fatigue tolerance evaluation*** *of each principal structural element (PSE) must be performed, and* ***appropriate inspections and retirement time or approved equivalent means must be established*** *to avoid catastrophic failure during the operational life of the rotorcraft.*

(h) Based on the requirements of this section, inspections ***and*** *retirement times* ***or*** *approved equivalent means must be established to avoid catastrophic failure. …*

Even though the metallic and composite new rule was elaborated in parallel there is a difference in requirements which is not attributed to the differentiation between metals and composites. The wording of the new composite rule lists replacement times, inspections and other procedures as equivalent alternatives.

New rule for composite structure:

(d) (2) Each applicant must establish replacement times, inspections, ***or*** *other procedures for all PSEs to require the repair or replacement of damaged parts before a catastrophic failure. …*

2.4 Methodology Approval

Current practice in certification shows that the authorities implicitly approve the way the applicant performs the fatigue evaluation. However, there is no formal requirement in the rule. In the new paragraphs of the FAR this requirement is introduced which is not the case for the CS. An interesting fact is, that this requirement is already existing in the Part 27 rules FAR / CS-27.571.

Existing FAR / CS-27.571:

(a) (1) The procedure for the evaluation must be approved.

New rule for metallic structure:

(c) The methodology used to establish compliance with this section must be submitted and approved by the Administrator.

New rule for composite structure:

(b) The compliance methodology of each applicant, and the results of that methodology, requires approval by the FAA.

2.5 Supplemental procedures

As of today's requirements the safe-life evaluation is allowed as a stop-gap project, in case the flaw tolerant options are not reasonably achievable.

Existing rule:

(b) ... Compliance with the flaw tolerance requirements ... is required unless the applicant establishes that these fatigue flaw tolerant methods for a particular structure cannot be achieved within the limitations of geometry, inspectability, or good design practice. Under these circumstances, the safe-life evaluation ... of this section is required. ...

(b) (3) Safe-life evaluation. It must be shown that the structure is able to withstand repeated loads of variable magnitude without detectable cracks for the following time intervals—

(i) Life of the rotorcraft; or

(ii) Within a replacement time ... .

The new rules - as already mentioned above - abandon the mentioning of specific methodologies in the favor of formulating a target of the substantiation. Here they call for supplemental procedures to accompany the definition of a retirement time for metallic materials, or to replace both retirement time and inspections for composites. This in fact opens up the range of the applicable solutions which however have to be duly justified to be accepted. Any type of monitoring system with on-board of off-board evaluation can be envisaged as an example for this purpose.

New rule for metallic structure:

(i) If inspections for any of the damage types ... cannot be established within the limitations of geometry, inspectability, or good design practice, then supplemental procedures, in conjunction with the PSE retirement time, must be established to minimize the risk of occurrence of these types of damage that could result in a catastrophic failure during the operational life of the rotorcraft.

New rule for composite structure:

(e) Fatigue Evaluation: If an applicant establishes that the damage tolerance evaluation described in paragraph (d) of this section is impractical within the limits of geometry, inspectability, or good design practice, the applicant

must do a fatigue evaluation of the particular composite rotorcraft structure and:

(e) (1) Identify all PSEs considered in the fatigue evaluation;

(e) (2) Identify the types of damage for all PSEs considered in the fatigue evaluation;

(e) (3) Establish supplemental procedures to minimize the risk of catastrophic failure associated with the damages identified in paragraph (e) of this section; and

(4) Include these supplemental procedures in the Airworthiness Limitations section of the Instructions for Continued Airworthiness required by § 29.1529.

3. EXAMPLES OF EUROCOPTER SUBSTANTIATIONS

This chapter shows some examples of past and current fatigue substantiations of components for Eurocopter helicopters.

3.1 Main Gear Box Strut Attachment Fitting of the NH90

Fig. 2: NH90 Tactical Transport Helicopter Version with High Cabin

The NH90 is a military 11 ton class twin engine helicopter. It features Fly-By-Wire controls, a corrosion free and crashworthy carbon fiber fuselage, and is offered with 2 cabin sizes (standard (1.58 m) and high (1.82 m)). Out of the 529 ordered helicopters 74 are already delivered and are performing tactical transport, naval as well as search and rescue missions.

The main gear box (MGB) of the NH90 is supported by four struts (Fig. 3). The struts are connected to elements of the anti-resonance system which are in turn fastened to the attachment fittings.

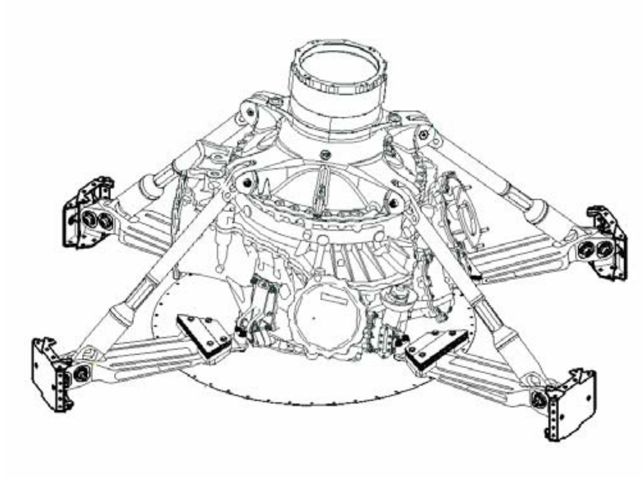

Fig. 3: NH90 Main Gear Box with Struts

The fittings have been subjected to fatigue tests in an as-manufactured condition to determine the critical location and damage type to be expected from fatigue (Fig. 4). As the load applied during the test was higher than the limit load, it is proven that during any time before the crack started the part was able to transmit at least limit loads.

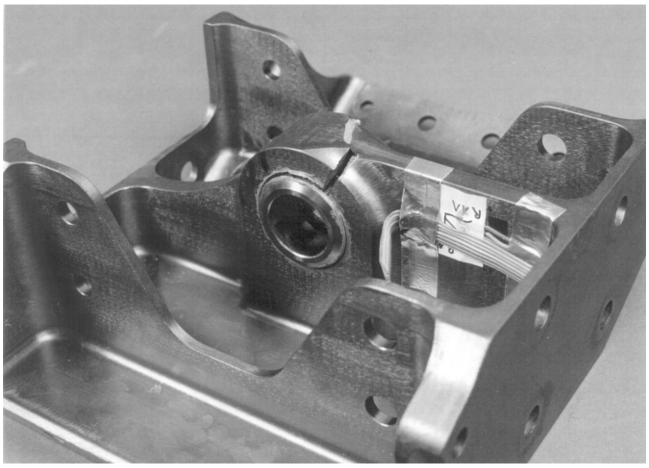

Fig. 4: NH90 MGB Strut Fitting after Test

The test results were used to establish an S/N curve for the time until crack initiation which was then transformed into a safe curve by applying a reduction factor. This safe curve is basis for the calculation of a retirement time which in this case is above a value of 10.000 hours considered as maximum helicopter service life.

For a part highly stressed in high cycle fatigue it is obvious that damage propagation cannot be mastered with reasonable inspection intervals. Therefore it was shown that damages like a scratch do not lead to crack initiation during an inspection interval before the scratch will be detected.

This was accomplished by applying an additional reduction factor to the safe fatigue curve which represents the stress increase due to the scratch. From this “safe fatigue with scratch curve” (Fig. 5) the time before crack initiation due to the scratch can be calculated which is then used as inspection interval for damage detection.

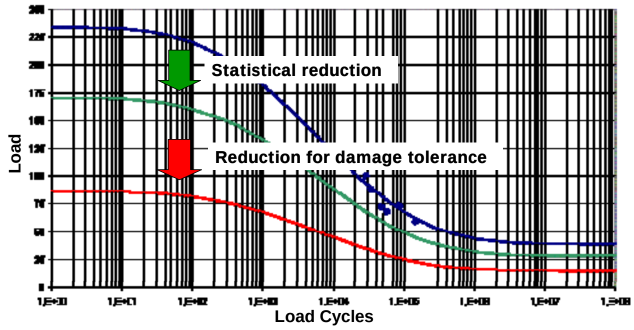

Fig. 5: “Safe Fatigue with Scratch” Curve

The major topics described in Chapter 2 of this paper are dealt with as follows:

2.1: The residual strength requirement is fulfilled with the proof of limit load capability for each applied load cycle. Furthermore, as the approach is following the flaw tolerant principle the static strength can be assumed as being the same as for the pristine part.

2.2: Damage Tolerance of the fitting is assured by assessing the potential threats like scratches or impact damages.

2.3: Catastrophic failure of the part is avoided by the defined retirement time of 10.000 hours and an inspection interval which ensures detection of a damage before it can initiate a fatigue crack.

2.4: The methodology was prepared by the four manufacturers participating in the NH90 project and presented to the respective military authorities who granted their approval.

2.5: Supplemental procedures were not applied.

3.2 Fenestron Drive Shaft of the EC135

Fig. 6: EC135 Multipurpose Helicopter

The Eurocopter EC135 (Fig. 6) is a twin engine helicopter in the 3 ton class and is – among others - used for Emergency Medical Services (EMS), police, and VIP missions. The certification of this modern designed helicopter was achieved in 1996, up to now 1000 helicopters have been delivered.

The tail drive train of the EC135 which connects the main gear box with the fenestron gear box contains two carbon composite drive shafts (Fig. 7).

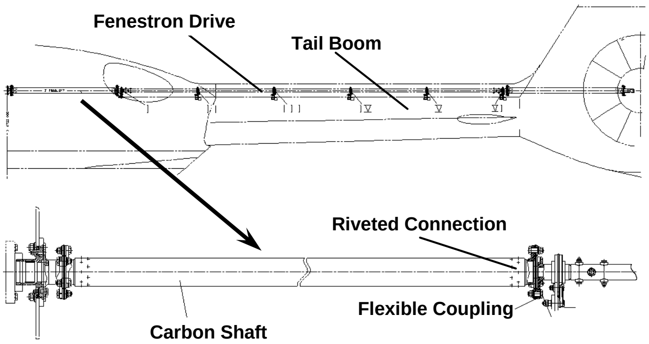

Fig. 7: EC 135 Tail Drive Train

Tests have shown that an impact energy level of 25 J creates damages which are just above the BVID (Barely Visible Impact Damage) threshold. As these damages might remain undetected the certification approach was to prove sufficient fatigue strength and residual strength to allow the presence of this kind of damage during the whole service life.

After applying the impacts on the test article the part was loaded under elevated fatigue loading. The fatigue test was finished with a residual strength test to show ultimate load capacity including the effects of temperature and humidity - implemented by a load factor - after damage and fatigue. Fig. 8 shows the drive shaft with three impacts on the test bench after completion of the fatigue and residual strength test.

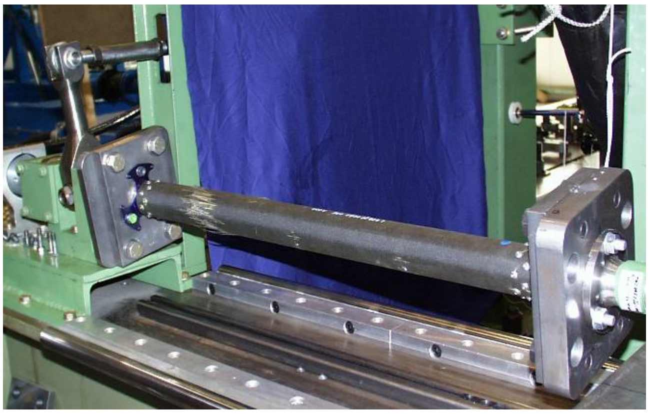

Fig. 8: CFC Drive Shaft on the test bench

The identical tests were performed with test objects containing manufacturing defects simulated by separation foils in between the composite layers. No detrimental effects on the strength of the parts could be observed.

Several tests were performed and the results are expressed in an “S/N curve” which is rather a “residual strength after fatigue curve”. This curve is used for the calculation of the retirement time of the drive shaft.

This certification was done in year 2000 where the working groups on the new rules were about to finish their proposals. The major topics described in chapter 2 of this paper are dealt with as follows:

2.1: The residual strength requirement is fulfilled with the static test at the end of the fatigue loading.

2.2: Damage Tolerance of the drive shaft is assured by assessing the potential threats like impact damage during handling and operation, manufacturing defects and environmental influence on strength properties.

2.3: Catastrophic failure of the part is avoided by the defined retirement time which is safe by taking into account fatigue, damages and environmental influence.

2.4: The methodology was not explicitly approved by the authority but during the certification process the approach and the justification for it was presented and discussed between Eurocopter and LBA (“Luftfahrtbundesamt” German National Authority).

2.5: Supplemental procedures were not applied.

<u>3.3 Tail Rotor Blade of the BK117 C-1</u>

Fig. 9: BK117 C-1 Helicopter

The BK117 C-1 is a twin engine helicopter with a maximum take-off weight of 3.350 kg. It is used in various missions like police, rescue, medevac and others. There are currently 367 helicopters of the BK117 Version A-1 up to C-1 in operation around the world.

The tail rotor blade of the BK117 is made of glass fiber reinforced composite material. Compared to the tail rotor blades of the former versions of the BK117 this blade has a higher chord and therefore higher thrust capabilities.

Among other tests the blade was subjected to dynamic flap and lead lag bending loads combined with the centrifugal force to determine the fatigue and damage tolerance behavior (Fig. 10).

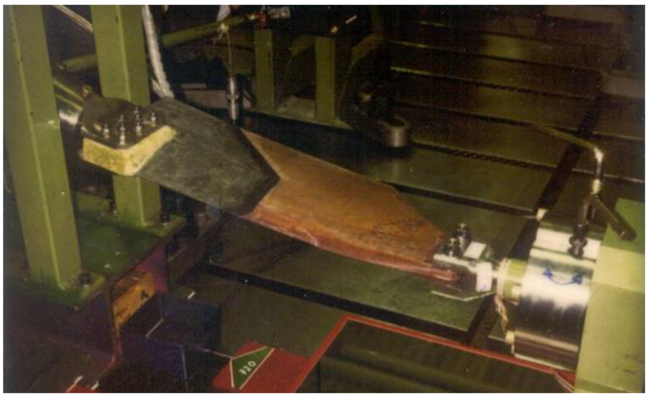

Fig. 10: BK117 C-1 Tail Rotor Blade in the test rig

During the test the initiation and the propagation of damages was closely monitored. As a result of the observations concerning the damage initiation and evolution, it was discovered that the damage first occurred in the form of a skin crack in the blade skin at the attachment area (Fig. 11).

Fig. 11: Damage of the Tail Rotor Blade after fatigue loading

In addition to the crack growth additional internal damages and delaminations occurred inside the blade structure. They were observed by means of Computed Tomography. Damage growth curves of three test specimen are shown in Fig. 12.

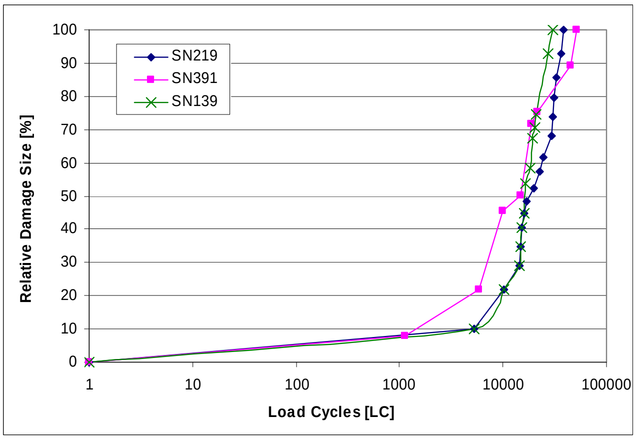

Fig. 12: Normalized Damage Size Versus Load Cycles

After the fatigue loading a residual strength test was performed to prove limit load capability including an amplification factor accounting for temperature and humidity influence (Fig. 13). During application of the increased limit load no additional damage growth was recorded.

Fig. 13: Limit Load Application

Resulting from these tests S/N curves have been derived for the time until crack initiation and for the time until limit load capacity. As a result of the analyses the lifetime until the initiation of first visible crack was determined as L1 = 940 hours. Similarly, the lifetime representing the duration up to limit load capacity was determined as L1 + L2 = 2050 hours.

With this data the determination of inspection intervals according to the scheme in Fig. 14 can be done.

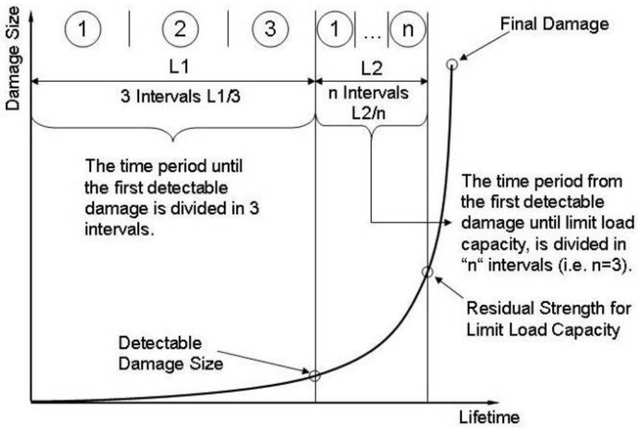

Fig. 14: Inspection Interval Determination

Dividing the calculated L1 of 940 h by 3 yields 313 h, which is rounded to 300 h for a practically applicable initial inspection interval. For L2 of (2050-940) h = 1110 h, dividing by n=3 would bring an interval of 370 h for the damage propagation time. As this interval is bigger than the initial one, 300 h is retained for the initial as well as for the repetitive interval.

The major topics described in chapter 2 of this paper are dealt with as follows:

2.1: The residual strength requirement is fulfilled with the static test at the end of the fatigue loading.

2.2: Damage Tolerance of the tail rotor blade is assured by analyzing the behavior for crack initiation and damage growth which is the predominant threat for the blade. The environmental influence on strength properties for the residual strength test was considered as well.

2.3: Catastrophic failure of the part is avoided by the defined inspection interval which is safe by taking into account fatigue, damages and environmental influence. In accordance with the new § 573 a retirement time has not to be given on top of the inspection interval.

2.4: The methodology was not explicitly approved by the authority but during the certification process the approach and the justification for it was presented and discussed between Eurocopter and LBA ("Luftfahrtbundesamt" German National Authority).

2.5: Supplemental procedures were not applied for the tail rotor blade.

4. CONCLUSION

The new proposed fatigue and damage tolerance evaluation rules develop more clearness and target focusing, rather than requiring specific methods. In contrary the advisory material discusses methodologies accepted in the frame of the rules. Clearly the aims of the rules are the same for metallic and composite materials but the ways to achieve them differs and justifies the introduction of a new paragraph for composites and their specific behavior.

In case of impracticality of the primarily required retirement time and inspection interval definition, the new rules open up the door for new methods existing today or being developed in the future.

This paper is focused on the pure definition of the fatigue and damage tolerance evaluation rules, without entering into the associated advisory material. This of course would highlight more details of the ways on how to comply with those new rules.

However, looking into examples of recent certification projects of Eurocopter shows, that compliance with the new rules is achievable and already partially implemented into the current practice.

Saying this, it must be kept in mind, that the examples presented here are just supplemental certifications. Comparing "old style" certifications with the new requirements - for a fully new aircraft -, results in significantly more effort to be invested in testing and substantiation work.

Improving the safety of our helicopters is one of the most prominent objectives of Eurocopter. One contribution is the application of damage tolerance principles in the substantiation like they are required in the new rules.

ACKNOWLEDGMENT

Special thanks to E. Ahci and H. Bansemir.

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