



Application of Damage Tolerance principles to the design of helicopters

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ABSTRACT

The design of helicopters against fatigue phenomena is a particularly important and complex problem, due to the peculiar load spectra, composed by a high number of low-amplitude cycles.

The fatigue design methodology most commonly applied by the helicopter community was based on the Safe-Life philosophy, applied anyhow with a particular approach. Since 1989, the Airworthiness Regulations evolved towards the application of Damage Tolerance principles also to rotorcraft. This change has forced the helicopter industries to review their design methodologies, and to face new problems, linked with fracture mechanics applications to their typical structures. Flaws, accidental damages and manufacturing discrepancies must be accounted for, in addition to the retirement life based on Safe-Life.

The paper reviews the current requirements and presents and discusses the methodologies that the helicopter industry adopts for demonstrating compliance with such regulatory requirements. In addition, recommendations are given on research and development activities required for refining the defined methodologies and for their better implementation.

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1. Introduction

Helicopters are very specific aircrafts, facing very demanding situations, particularly for what concerns the fatigue load environment, as a consequence of the high frequency dynamic loading, induced by the aerodynamic field of the rotor blades. The fatigue spectra have a very high number of cycles per flight, much more than in a fixed-wing aircraft, and so the methodologies used by the helicopter structure manufacturers are directly linked with such feature. Historically, the Safe-Life methodology has been the traditional design philosophy used to accomplish safe operation, defining a retirement life. Notwithstanding built-in conservatism and large scatter factors, fatigue failure sometimes occurred, before the designated safe life. Obviously in the years consideration has been taken for the possible presence of defects, which may strongly reduce the safety of the structure: a very specific design methodology, called Enhanced Safe-Life, has been defined, and will be described in the following. The manufacturers used to specify in-service inspections, which were defined on experience and judgment, not always laying on rational basis.

Under the impulse of the FAA, the regulatory change to FAR 29.571 was approved in 1989 (Amdt. 29-28), requiring tolerance to flaws and damages and opening the way to the application to rotorcraft of the Damage Tolerance (DT) design philosophy, devel-

oped for fixed-wing aircraft and successfully applied for a significant period of time ([1]). Three different options are addressed to demonstrate the safety of fatigue critical elements (principal structural elements, PSE) belonging to the helicopter mechanical parts and to the airframe. At the same time, interest for the application of Damage Tolerance (DT) principles comes also from the many operators of aging helicopter fleets (mainly military), who are increasingly facing fatigue related maintenance issues and the pressure for structural life extension programs. The DT approach could significantly contribute to the solution of these problems, conjugating safety with economy.

It is therefore important to describe the various options offered by the current regulations to perform the design against fatigue of any PSE, keeping also into account the effects of environment, intrinsic/discrete flaws, or accidental damage:

1. Flaw Tolerant Safe-Life or Enhanced Safe-Life, an approach that is adopted only in the helicopter community; it is based on a traditional Safe-Life design methodology, that uses special $S-N$ curves, obtained from specimens containing some defects (flaws). Such test results allow to estimate the life of components containing a defect, which may have been introduced during the manufacturing (scratch) or generated during the operation (impact, pitting), etc. i.e. not a fatigue crack. It must be shown that a PSE containing such defects will be able to sustain the prescribed fatigue load cycles for the whole design life or the replacement time, without any fatigue crack nucleation;

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2. Damage Tolerance, as it is called by the fixed-wing community, while it is more often called Flaw Tolerance by the helicopter community; and indeed the regulation uses the term “fail-safe (residual strength after flaw growth) evaluation”. It requires that the structure can retain, after a partial failure, the capability to withstand the limit load; it is based on the use of redundant solutions (fail-safe) or on the slow crack propagation approach (or, preferably, on the no-growth approach). The use of redundant solutions is often possible in stiffened shell structures, and sometimes multiple load paths can be easily introduced. Nevertheless, most dynamic components cannot be other than single load path. In this case, the slow crack growth (or the no-growth) option is the recommended one. Inspection intervals must be determined, in order to ensure that, if a defect is present, this is timely detected and consequent repair actions taken.
3. Safe-Life, i.e. the old, traditional design methodology based on the use of $S-N$ curves of pristine specimens, that defines a period of safe operation of a given component (retirement life). The high number of cycles that are typical of helicopter spectra are such to require a specific design procedure: the crucial point is that the experimental results necessary to trace an $S-N$ curve with adequate confidence level, particularly in the 10^7 cycles range, are difficult (and expensive) to obtain due the closeness with the endurance limit, which causes a number of lower value run-out results. The helicopter community has established a specific approach to the problem of defining a mean $S-N$ curve using a shape curve, i.e. a curve of a given shape that is fitted to the experimental data, in order to weight differently the data coming from long life test results with respect to those coming from the shorter life region.

The regulations state clearly that the Safe-Life approach can be utilised only after that the application of Damage Tolerance concepts has been demonstrated not to be possible for practical reasons (limitations due to geometry, inspectability, other valid reasons). Typical examples may be landing gear, drive system gears, main rotor and tail rotor shafts, etc.

In addition to the safety issues specified in the regulations, helicopter manufacturers must also consider the durability requirement, commonly applied by means of a traditional Safe-Life approach, which so defines a service life. Shorter retirement lives based on the Flaw Tolerance approach or inspections based on fracture mechanics analysis or tests are additionally mandated to manage tolerance to defects, environment or accidental damages.

The paper discusses the fatigue design methodologies and the application of damage tolerance principles to helicopter structures, limiting the attention to metallic components.

2. Towards Damage Tolerance

The debate about the introduction of the DT design philosophy to rotorcraft structures started many years ago. Lincoln [2] first showed some practical examples of how it was possible to apply Damage Tolerance principles, revisiting the traditional Safe-Life design of some components of the HH-53C and HH-60A helicopters. He concluded that application of damage tolerant design concepts required a re-design of the critical parts examined, with a re-assessment of the safety margins of the various components, measured with a different meter with respect to the standard Safe-Life design. In most cases, the stress levels must become lower, in order to have viable inspection intervals.

It should anyhow be considered that Lincoln conclusions were somewhat influenced by the success of the ENSIP (Engine Structural Integrity Program) program, that is based on the detectability

of very small defects, both in the pre-service and in-service phases. Typical sizes of initial crack for Damage Tolerance qualification of helicopter machined components are 0.125 mm for “initial quality” cracks and 0.38 mm for “rogue” cracks [1]. This accuracy is not necessarily attainable with the required reliability for helicopters [3].

The general objection from the helicopter community was that, due to the typical features of the helicopter spectra, the inspection interval was often (if not almost always) so short that unacceptable costs were charged to the operators, which made it an impractical solution.

Indeed, owing to the particular load spectra, the implementation of the DT approach is more difficult than for fixed-wing aircraft. In particular, recent research has shown that currently available models do not accurately predict fatigue crack growth under helicopter spectrum loading: they show large scatter and tend to be unconservative when applied to the prediction of crack growth lives in helicopter components [4]. Moreover, load interaction effects for the special characteristics of helicopter spectra (many high R -ratio cycles, sometimes interspersed by few underloads) are not properly accounted for [5–6]. In addition, various authors have pointed out that insufficient (or even inappropriate) crack growth data are used for the near-threshold regime in the ΔK vs. da/dN diagram, that is of decisive importance for the high-cycle (vibratory) fatigue that occurs in helicopters [7]. These problems must be studied in depth, since any DT-based design and maintenance concept needs reliable crack growth predictions. A considerable research effort is devoted in this direction, and some recent developments, based on the use of a strip yield model, have been presented [8–9].

A last, but obvious observation, is that also the load spectrum, i.e. the stress history in a given location of a PSE, must be known with higher accuracy and research in this direction is highly important. The following sub-paragraph presents some peculiarities of such spectra.

2.1. Load spectra

A few examples are appropriate in order to better describe the peculiarities of a rotorcraft spectrum. In the framework of preliminary load surveys on a new helicopter developed by Agusta-Westland, acquisitions were made of load acting on various parts. Fig. 1 shows the minimum and maximum stress of the various cycles on thin panels belonging to the rear fuselage, in a passenger transportation mission. In the early part of the flight, maneuvers are performed, with abrupt changes of mean and amplitude, followed by a long cruise segment.

Rotor components are subjected to other types of spectra, dominated by many high R -ratio low-amplitude cycles, interspersed with a number of low values minima, consequence of the start-stop cycle (equivalent to the ground-air-ground cycle for fixed-wing aircraft structures). Standard load sequences have also been defined, like Helix and Felix [10], test load sequences for articulated or semi-rigid rotors, respectively (Fig. 2). The R -values in Helix and Felix range between 0.4 and 0.6 (rotor blades and rotor roots); more recent work indicated that more than 80–90% of the total number of cycles have high R -values (0.7–0.9), which is reflected also in other recent standard sequences, such as Rotorix [11] and Asterix [12].

Great emphasis is being given to the development of Health and Usage Monitoring Systems (HUMS): the FAR regulation indeed points out how the determination of the real operative usage is a fundamental issue, as it should be for the design of every aircraft, but even more critical in the case of helicopters. Just to quote a possible source of variability, in addition to multi-role machines (particularly the military ones, used by different customers in dif-

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