BIRD STRIKE SUBSTANTIATION OF A ROTOR COMPONENT BY SIMULATION – TEST CORRELATION, RESIDUAL STRENGTH CAPABILITY

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Abstract

Bird strike strength capability is required by the regulation for large rotorcrafts [1].

For rotor components, substantiations were up to now only performed on components exposed to bird strikes (by the trajectory of the bird through the aircraft), and whose strength could lead to a catastrophic situation ("candidates" were only non massive components). In practical terms, the components generally substantiated were only the main and tail pitch control rods under direct strike.

The compliance was classically shown by analytical calculations based on bird strike test of similar design and test conditions. Thanks to the improvements of simulation capabilities in bird trajectories and FE analysis, it is now possible to have a more accurate evaluation of the components to be impacted, as well as improved FE softwares and solvers, for test correlations / simulations and residual strength capabilities evaluation.

This paper describes the process developed for substantiating by FE analysis a main rotor pitch control rod subjected to a bird strike, up to the safe landing of the aircraft. Then, the substantiation methodology is applied to a new design of pitch rod. It provides details on the flight conditions to be considered at the time of the impact, elasto-plastic behaviour law of the pitch rod material, simulation conditions, hypothesis and results of the bird strike itself by comparison to a test performed on the same component in the same conditions (see Figure 2).

Once the bird strike test is correlated by FE simulation of the pitch rod tested, this process is applied on the other design of pitch rod. Then, a FEM analysis is realized in order to determine the residual static and fatigue strength of the component (the strength or stability could be affected by a permanent deformation).

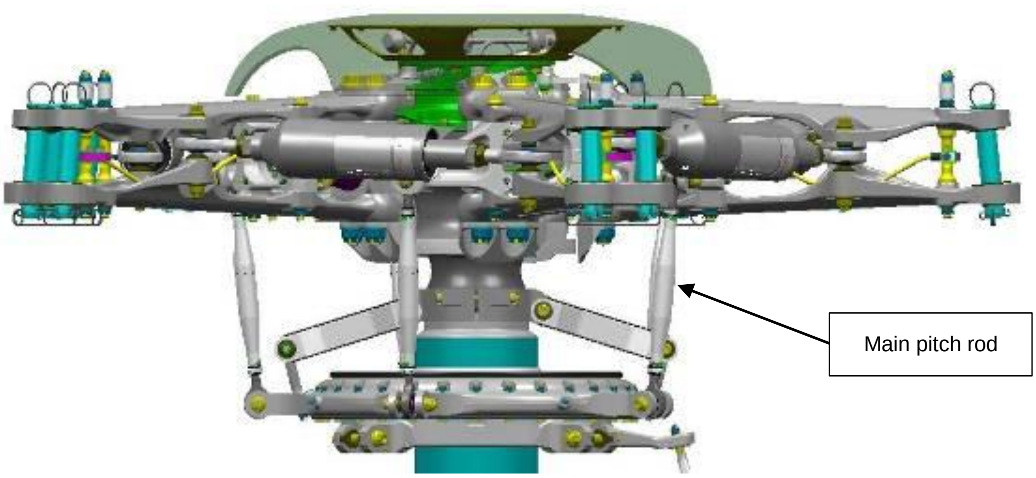

Figure 1: Overview of the main rotor head

1. GENERAL PRINCIPLES

1.1. Regulation

The bird strike strength capability is required by the regulation for large rotorcrafts [1]: "*The rotorcraft must be designed to assure capability of continued safe flight and landing (for Category A) or safe landing (for Category B) after impact with a 1 kg bird, when the velocity of the rotorcraft (relative to the bird along the flight path of the rotorcraft) is equal to VNE or VH (whichever is the lesser) at altitudes up to 2438 m (8 000 ft). Compliance must be shown by tests, or by analysis based on tests carried out on sufficiently representative structures of similar design*."

This requirement results in the direct evaluation of the bird strike strength capability, but also in the consequences of the event in terms of residual fatigue and static strength up to the complete landing of the rotorcraft in safe conditions.

In addition, the compliances are proposed either by direct and complete (full-scale) test or by simulation as soon as the full simulation loop is correlated by test.

1.2. Objectives

The full calculation loop consisting in substantiating the bird strike and the residual strength capability by FE analysis instead of very expensive and time consuming tests, can lead to a significant benefit in the development costs and schedule.

This is only possible if the applicant is able to demonstrate that the modelization process and results are correlated with tests previously performed. In this logic, the first target is to validate the modelization process in comparing FE analysis to test results of the same sub-system or component, in terms of strains, stresses, displacements and / or residual permanent deformations.

In a second step, once this correlation is considered sufficient, the process can be computed on another sub-system or component whose design is considered "similar". In the case of the pitch control rod, the similarity is supposed by the very close design between the tested one and the design of the serial rotorcraft.

By extension, this process can be also a way to enlarge our capability to:

- Perform more reliable sensitivity studies, in order to define the most appropriate analysis substantiation conditions, or the worst or conservative test conditions in prevision of a bird strike test,
- Perform a pure and complete simulation loop of bird strike and its consequences, from the impact to the residual strength substantiation following the impact.

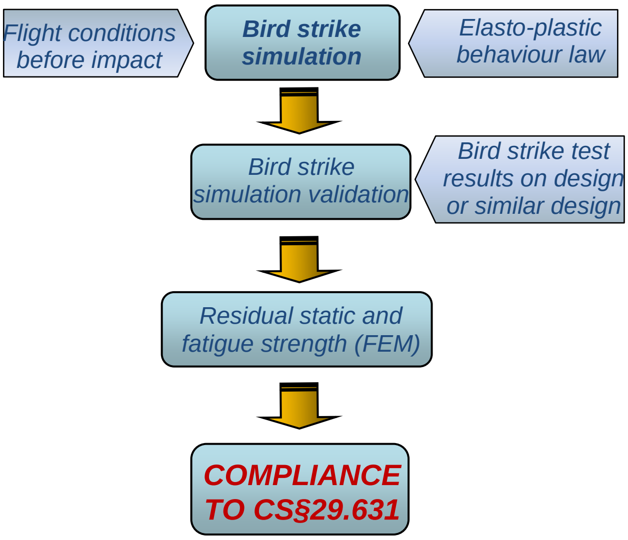

Figure 2: Complete process of computation and validation

1.3. Means of compliance – substantiation logic

The following conditions for computation shall be defined and committed with the Authority:

- Identification of the components exposed to bird strike, for which substantiation is provided,
- Selection of the flight loads before the impact (in fact at the time of the impact),
- Impact speed for each component,
- Bird strike detection criteria leading to :
  - ✓ the remaining flight time up to the landing.
  - ✓ the selection of the flight states to be considered for the end of flight.

1.3.1. Selection of the flight loads before impact

By evidence, the flight loads will affect the behaviour (stress levels, stability) of the pitch control rod at the time of the impact during bird strike test or in FE analysis.

The loads to be considered are the loads applied on the component during flight states corresponding to the most severe conditions specified by the regulation, which are VNE or VH flight states (whichever is the lesser), at altitude up to 2438m (8000ft).

In addition, it is assumed that the most critical case in terms of stability is the case where the pitch control rod supports the highest compressive load recorded during the above flight states.

1.3.2. Components exposed to bird strike

The "candidate" components for bird strike substantiation are the components meeting the following criterion:

- Component whose frontal surface can be subjected to bird strike by the trajectory of the rotorcraft, taking into account the rotation speeds of rotors,
- Components whose strength and/or geometry is known to be potentially significantly affected by a bird strike,
- Components whose malfunction / deformation / failure / … could lead to a catastrophic situation for the rotorcraft.

1.3.3. Impact speed for each component

The impact speed S is obviously the relative speed between the bird and the component, which is the sum of the aircraft forward speed V to be considered for bird strike (175kts) and the rotor rotation speed Ω translated in linear speed at the radius R of the component, according to Figure 3:

(1) $$S = V + \Omega . R$$

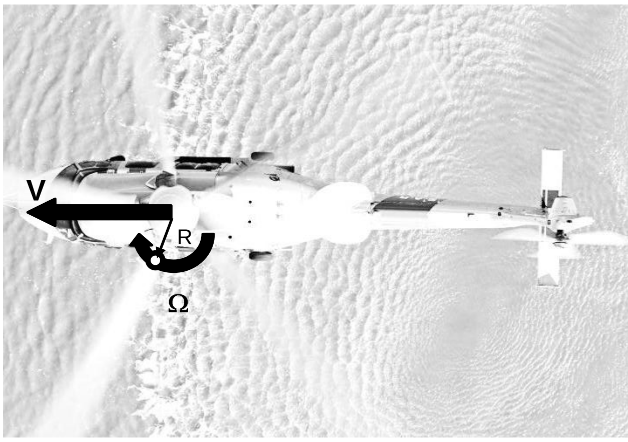

Figure 3: Combination of rotation and forward speeds

1.3.4. Bird strike detection criteria

The detection of the impact (or suspicion of) on a rotor component during flight can be identified through one or more of the following events:

- Visual observation of the bird being in the helicopter path.
- Vibrations linked to damages having occurred on the component due (for example) to its plastic deformation.

Nevertheless, the visual observation is an indication that a bird could have struck a component, without evidence that the strike really occurred if no other external indicator appears.

In addition, vibrations that could appear after the potential strike could not be sufficient to indicate to the crew that a severe technical problem has occurred. Depending on the mission of the helicopter, the mission abortion could not be possible and the vibration level could not be a sufficient reason to abort it.

As a consequence, the damage is considered undetectable or not sufficiently detectable to abort the mission.

After landing, experience shows that the "after last flight" inspection (or equivalent) shall lead to the detection of the impact by the strong probable presence of blood evidences, feathers, bird fragments, …

As a conclusion, it is considered that the strength demonstration shall be performed during the maximum flight time, without flight domain reduction (full spectrum).

2. BIRD STRIKE TEST

2.1. Test conditions

The test apparatus consisted in a gas gun allowing throwing the bird at the requested speed and a velocity measurement system made of a laser barrier to measure the bird impact speed. The prototype pitch rod was fixed to a steel test rig by means of the adequate ball bearings (see Figure 4 and Figure 5). The corresponding tightening torque was applied, as well as a compressive initial load. The impact point was marked with a red target glued on the middle of the test item.

Figure 4: Laser barrier and test bench

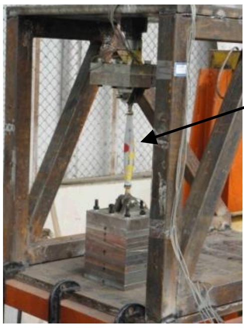

Figure 5: Tested pitch rod installed on test bench

The tested pitch rod was equipped with strain gages to check the applied compressive load prior to bird strike, and high speed cameras were used to record the impact scenario.

The bird mass was adjusted to the certification weight and has been placed into a cloth bag, then inserted into the polystyrene gas gun sabot (see Figure 6).

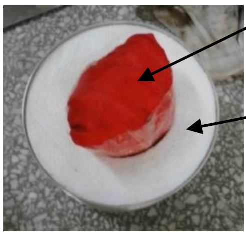

Figure 6: Bird packaged into the cloth bag and the gas gun sabot

The impact conditions were:

- Bird mass: 1000g.
- Bird impact velocity: ≈ 350 km/h.

The pictures below extracted from high speed cameras show the impact scenario: the bird is split in two parts by the tested pitch rod due to its thin shape (see Figure 7). Small parts of bird flesh and feathers as well as the majority of the cloth bag were retained by the pitch rod (see Figure 8).

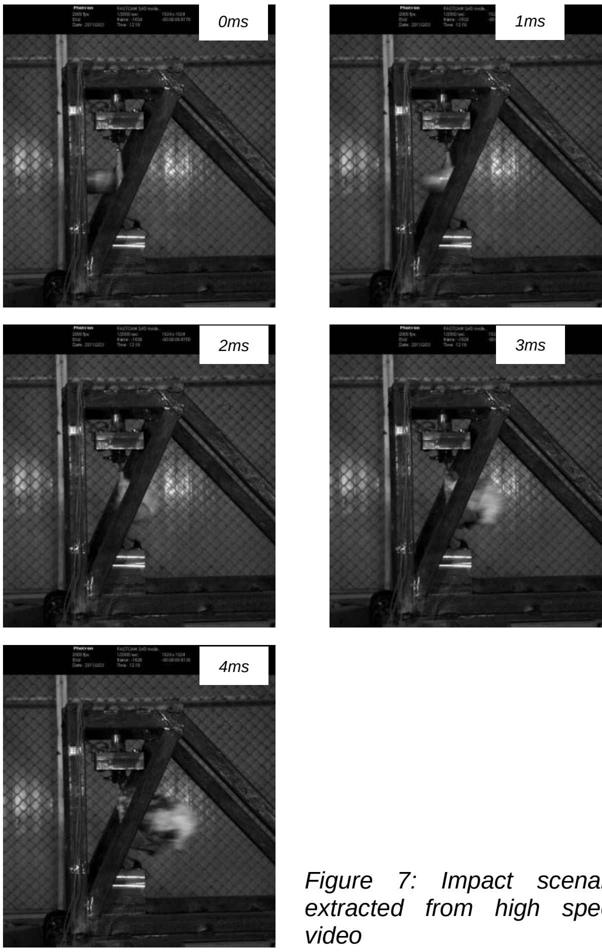

Figure 7: Impact scenario extracted from high speed video

No failure of the pitch rod and its fixations was observed, and the initial tightening torque at ball bearing ends was not lost. On top of that, a significant plastic deformation was noticed. Once the tested part removed from test rig, a spatial digitalization of the tested pitch rod was performed in order to measure its permanent deformation.

Figure 8: Permanent deformation of the tested pitch rod

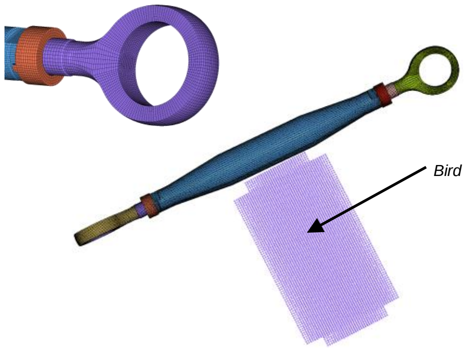

Figure 9: Pitch rod and bird RADIOSS models

2.2. Test simulation

Based on the above description, a RADIOSS model of the prototype pitch rod and test bench was developed.

The main pitch rod was modelled with brick elements and an average mesh size of 0.5mm to 1mm. 3 brick elements are defined through the pitch rod body thickness to get the adequate bending behaviour (see Figure 9).

The bird is modelled with around 67 000 SPH particles with a smoothing length of 3mm compatible with the pitch rod mesh, and allowing affordable computation times. SPH, which stands for Smooth Particles Hydrodynamics, is a relatively new numerical technique for the approximate integration of partial differential equations. Originally developed as a probabilistic mesh free particle method for simulating astrophysical problems in the late 70’s, it uses a pseudo particle interpolation method to compute smooth field variables. Each pseudo particle has a mass, Lagrangian position, Lagrangian velocity, and internal energy; other quantities are derived by interpolation or from constitutive relations. The advantage of this meshless approach is its ability to solve problems that cannot be effectively solved using other numerical techniques. It does not suffer from the mesh distortion problems that limit Lagrangian approaches based on structured mesh when simulating large deformations.

The bird shape is a cylinder with “rounded” ends; its dimensions and its mass are in agreement with the real bird ones measured before bird strike test. The bird material law, close to water, describes an elasto-plastic hydrodynamic behavior with von Mises isotropic hardening and a linear polynomial equation of state for pressure calculation. The bird model was previously validated by comparison with bird strike test results on typical helicopter windshield.

The test rig was modelled by shell elements with an average mesh size of 10mm. Linear material for steel is applied, and thicknesses are set up according to test bench drawings (see Figure 10).

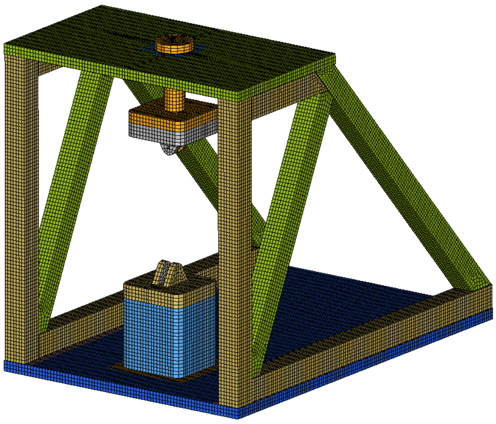

Figure 10: Test rig RADIOSS model

Tensile tests were performed on pitch rod material to get the mechanical plastic characteristics. Based on that, a tabulated law was defined with RADIOSS software and Figure 11 clearly shows the good adequacy between test measurements and simulation results when tensile tests are modelled.

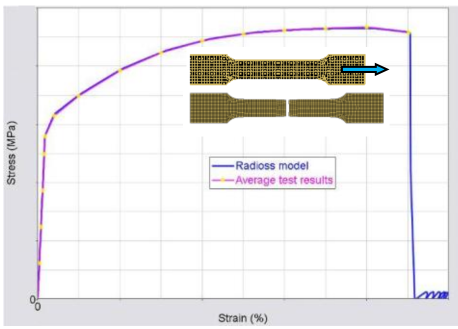

Figure 11: Comparison between tabulated material law for RADIOSS and test results

The link between the pitch rod ends and the test rig fittings is modelled by means of rigid bodies and springs whose stiffness's on all axes are set in accordance with design drawings. An initial velocity is implemented on the bird part, equal to the one measured by the laser barrier.

Several Type 7 contact interfaces are implemented in the pitch rod model. Interface type 7 is a general purpose interface which allows simulating all types of impact between a set of nodes and a master surface. This interface can also simulate auto-impact, especially buckling during a high speed crash. The first one is dedicated to the contact between the bird and the main pitch rod, while others are used to model contact with the test rig parts, and between the pitch rod ends and the rig fittings. In that last case, Type 7 interfaces are completed with Type 11 interfaces to take into account of edge-to-edge contact.

Finally, the initial compressive load is defined by means of two concentrated loads applied to the master node of both ball bearing rigid bodies, through a time dependent function allowing to compute the calculation in different steps:

- Run #1: progressive application of the compression load up to the maximum value.
- Run #2: bird strike simulation.
- Run #3: suppression of the bird and first dynamic relaxation to release dynamic stresses.
- Run #4: progressive release of compression load.
- Run #5: second dynamic relaxation to reach a static equilibrium post bird strike of the main pitch rod and get the final static deformed shape.

2.3. Model correlation

The model correlation is assessed in three steps:

- Firstly, the initial compression state of the tested pitch rod model is checked at the end of Step #1, by comparing the average compression stress given on one hand by the model and on the other hand by analytical method.
- Secondly, Figure 12 shows the good correlation between the test and the simulation, with similar behaviour of the bird which is split in two separate bodies by the main pitch rod (cutter effect).

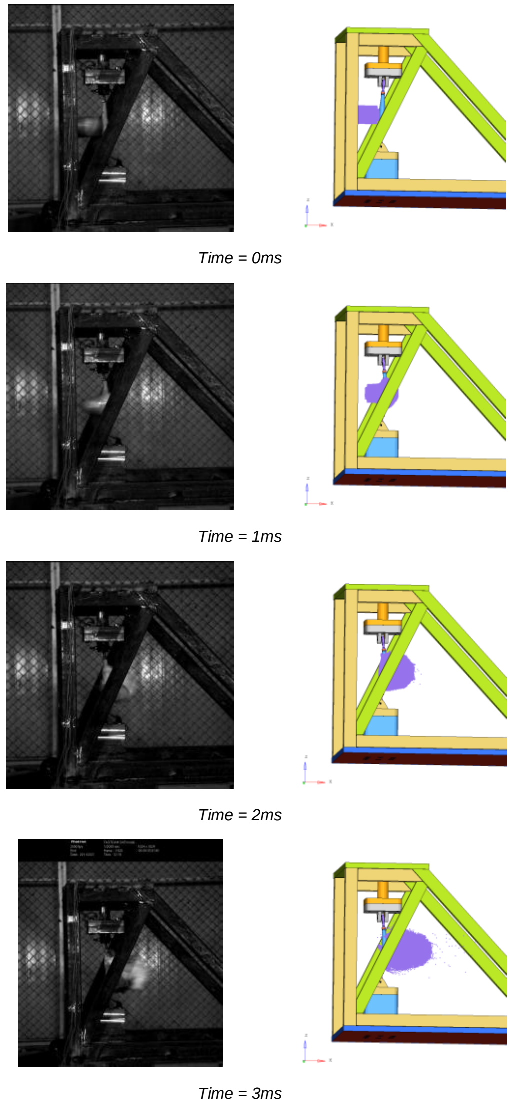

Figure 12: Comparison of impact history between test (left) and simulation (right)

- Thirdly, the final deformed shape of the pitch rod model provided by RADIOSS at the end of Step #5 is compared to the one got from spatial digitalization of the tested item. Indeed, the criterion of success for main pitch rod consists in a residual strength post bird strike sufficient to demonstrate a safe flight and landing. As a consequence, the main information to correlate is the permanent deflection of the pitch rod after bird strike and after complete release from compression load. The pitch rod deformation obtained from the RADIOSS model is thus superimposed on the permanent deformed measured after test. When looking at the difference between the residual displacements of the pitch rod center from simulation and from test, a conservative error of +7% is evaluated.

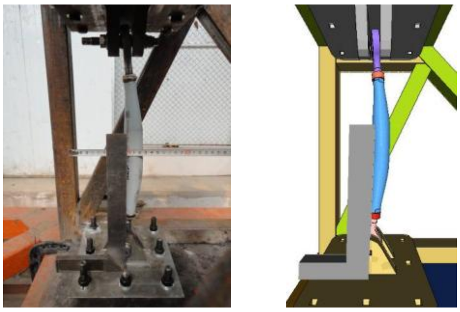

Figure 13: Comparison of final pitch rod shapes between test (left) and simulation Run#5 (right)

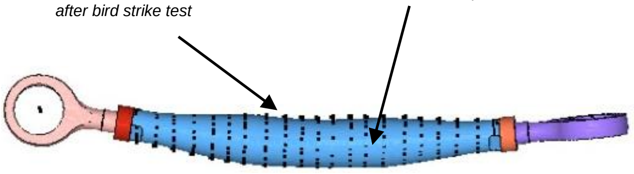

Figure 14: Spatial comparison between simulated and tested pitch rod

The methodology used to model the main pitch rod is now validated. As agreed with EASA, it could be used to substantiate similar design in similar impact conditions.

2.4. Application of the validated method to the serial design and results

Before applying the validated modelling method to the serial pitch rod, the similarity between the tested and the serial designs must be demonstrated as requested by CS§29.631 (see Figure 15). For that purpose, the comparison is done on the material, the dimensions, boundary and impact conditions:

- Tested and serial main pitch rods are both manufactured in metallic materials, and have similar designs that will induce the same bird strike interaction (cutter effect).
- Impact angle and bird mass are identical, impact speeds are in the same order of magnitude so impact conditions are similar.
- Boundary conditions are identical since it is the same ball bearings at pitch rod ends.
- Compression load is applied in the same manner although the value is slightly different.

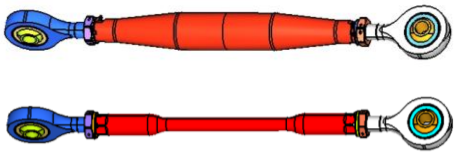

Figure 15: Tested (top) and serial (bottom) main pitch rods designs

Based on the above remarks, similarity of the tested and serial parts is demonstrated, and by application of CS§29.631, the serial design will be justified by RADIOSS simulations by application of the modelling methodology described in this paper (see mesh in Figure 16).

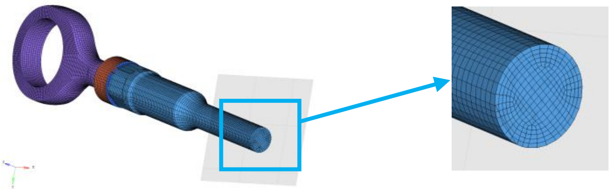

Figure 16: Mesh of serial Inconel main pitch rod (one half with parallel section)

The deformed shape after Run #5 illustrated in Figure 17 was then used to justify its residual static and fatigue strength.

Figure 17: Residual deformation of the serial main pitch rod obtained with RADIOSS superimposed with the initial shape (shadow)

3. RESIDUAL STRENGTH POST BIRD STRIKE

After the bird strike, it must be shown that the main rotor pitch rod is still able to achieve the end of mission and the landing of the aircraft in safe condition.

As a consequence, the strength demonstration is based on flight duration of an entire mission without flight domain limitation.

The strength demonstration consists in a:

- Static substantiation
- Fatigue substantiation

3.1. Static substantiation

The bird strike simulation led to a residual plastic strain with residual deflection of the pitch rod body (see §2.4). As a consequence, in addition to the "classical" static strength demonstration, the buckling strength shall be evaluated. The post bird strike static substantiation is consequently based on the two following criteria:

- No failure under tensile and compressive limit loads defined by the regulation (CS§29.301, CS§29.547).
- No buckling under the compressive limit load defined by the regulation (CS§29.301, CS§29.547).

These requirements lead to the following criteria:

- Positive static safety margin under the tensile and compressive limit loads compared to the material ultimate strength R_m (see §3.1.1),

(2) $$\text{Static margin} = 100 \; \frac{\sigma_{\text{LIMIT}}}{R_M} - 1$$

- Positive static safety margin under the compressive limit load compared to the buckling load F_B. (see §3.1.2).

(3) $$\text{Buckling margin} = 100 \; \frac{F_B}{F_{\text{LIMIT}}} - 1$$

3.1.1. Static substantiation under tensile and compressive limit loads

The static substantiation is performed by comparing the maximal stress in the main rotor pitch rod (under the limit loads) with the material ultimate strength R_M.

The maximal stress in the pitch rod body is obtained thanks to FE model of the pitch rod deformed, whose CAD design has been extracted from the RADIOSS bird strike simulation. This FE model provides the relationship between the compressive / tensile load applied and the stress in the main rotor pitch rod.

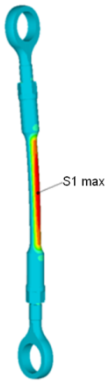

Figure 18: Stress vs load relationship in the main rotor pitch rod

The maximal stresses in the other areas and/or components (pitch rod ends, screws,…) are determined through classical means of compliance : FE analysis, strength literature,…

3.1.2. Buckling substantiation

The buckling substantiation is performed by comparing the limit compressive load with the allowable buckling load obtained by test.

Two buckling tests have been done:

- One test whose initial deflection was greater than the deflection given by the bird strike test (+ 8.5 %).
- One test whose initial deflection was lower than the deflection given by the bird strike test (– 6.8 %).

Figure 19: Main rotor pitch rod (before buckling test) with initial deflection

Figure 20: Main rotor pitch rod on the buckling bench test (at the beginning and at the end of the test)

The buckling law for the two tested main rotor pitch rods is shown below:

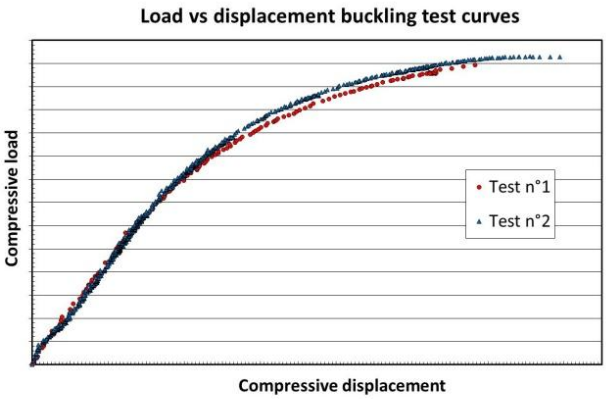

Figure 21: Buckling law for main rotor pitch rod after bird strike

The buckling test provides the buckling load F_B.

As a consequence, the limit compressive load F_{LIMIT} is compared to the buckling load F_B.

3.2. Fatigue substantiation

The post bird strike fatigue substantiation is based on the following criterion:

- No failure during the complete flight time.
- No flight domain limitation compared to domain certified.

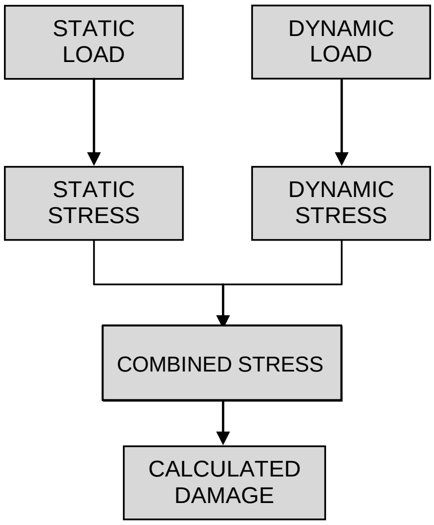

Figure 22: Diagram used for damage calculation and fatigue substantiation

The total damage can be easily calculated knowing the material fatigue properties (fatigue limit and fatigue curve law):

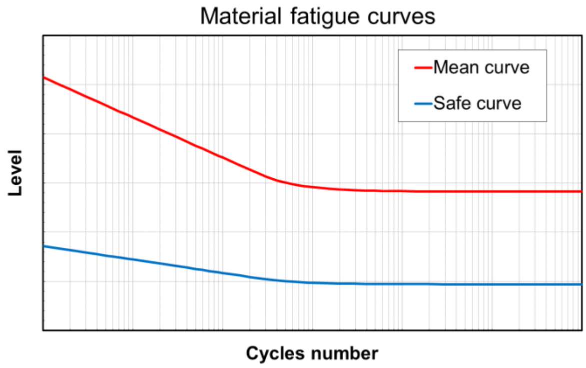

Figure 23: Material fatigue curve

The following hypothesis are considered for this substantiation:

- The impacted main rotor pitch rod has a permanent deflection (plastic strain) with no residual stress,

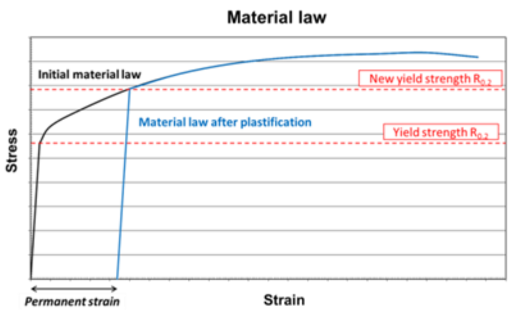

Figure 24: Material elasto-plastic law

- The permanent deflection (plastic strain) has no impact on the main rotor pitch rod global fatigue properties.

The remaining flight time can be calculated with:

- The previous calculated total damage d_{TOT}.
- The associated flight duration t_{FLIGHT}.

$$\text{Remaining flight time} = \frac{100\ t_{FLIGHT}}{d_{TOT}} \quad (4)$$

(where d_{TOT} is expressed in %).

4. CONCLUSION

This new process of full compliance by analysis led to a more accurate substantiation approved by EASA thanks to this detailed test / FEM correlation.
It opens lots of perspectives in terms of prediction of rotor components subjected to bird strike at design phase, in having the possibility to evaluate the strength effect of several influence parameters.
It also allows to optimize designs in order them to be less sensitive to bird strike by their shapes, materials, …
Especially for pitch rods, this process would avoid costly and time consuming tests, allowing to reduce development time and non-recurring costs, as soon as their design is sufficiently close to the tested one.
Then for other components for which simulation could not be fully acceptable yet, the test conditions could be accurately defined by evaluating the most critical load cases for the bird strike test.

5. ACKNOWLEDGEMENTS

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