ANALYSIS OF RESIDUAL STRENGTH OF A HELICOPTER TAIL BOOM

Piotr Reymer, Andrzej Leski

Air Force Institute of Technology
Księcia Bolesława Street 6, 01-494 Warszaw
tel./fax: 022 685 10 13
e-mail: piotr.reymer@itwl.pl, andrzej.leski@itwl.pl

Abstract

The aim of this work is to determine the residual strength of a Mi-24 helicopter's tail boom with a structural damage. The idea of this work has come from the fact that these helicopters are operated on a battlefield and often suffer such damages. It may be crucial to make a quick estimation whether any particular damage can cause a critical failure to the whole structure. The scope of this work covers static loading of the structure during landing.

The analysis has been based on a numerical model that makes use of the Finite Element Method. The model has been developed using reverse engineering techniques. Structural discontinuities have been modelled in characteristic sections where stress concentrations occur. Boundary conditions and loads applied have been chosen to simulate normal and hard landings. Two failure criteria have been chosen: one based on the Crack Tip Opening Angle (CTOA) method that enables very efficient verification, and the second concerning the tail boom tip dislocation, taken from the helicopter's alignment manual. The specific load history has been designed to enable detection of tail boom tip dislocation due to plastic strain in the vicinity of damage tips after the hard landing.

Keywords: *residual strength, tail boom, crack tip opening angle*

1. Introduction

Military helicopters operated on any battlefield are highly susceptible to various combat damages caused by, e.g. projectiles or shrapnels. Damages can affect any structural part and significantly diminish its mechanical strength. Survivability and vulnerability of aircraft and helicopters have been vital topics of scientific projects for many years [1, 2]. The helicopters being continuously present in contemporary armed conflicts make the topic even more important.

Despite various protective shields and armours introduced to helicopter's structure, complete protection of the whole helicopter's body cannot be achieved. Moreover, there are helicopters operating in areas of armed conflicts without any armors. Therefore, such damages can be anticipated to occur quite frequently in next years, hence the need for suitable tools to assess health/maintenance status of the damaged structure and to support a decision-making process regarding the future of the damaged helicopters.

The aim of this work is to develop a method for calculating the residual strength of the Mi-24's tail boom with a structural damage. The structures of tail booms of present-day helicopters are very similar so the developed method is expected to be easily applied to other helicopter types as well.

2. Numerical calculations

2.1. Numerical model

Subjected to this analysis is the Mi-24's tail boom. Like most of aircraft structures, it has been made of an aluminum alloy and is a thin-wall construction. The structure can be divided into groups: frames and ribs that form the circumferential skeleton, stringers and a vertical stabilizer beam forming the longitudinal skeleton, and the skin to cover the skeleton [3]. A helicopter tail boom is affected by complex loads during operational use of the helicopter. Among the loads one can distinguish aerodynamic loads such as the tail-rotor produced thrust and thereby effected bending moment along the tail boom (left-right) and the twisting moment. The inertial load caused by the helicopter manoeuvres can result in bending moments (left-right and up-down).

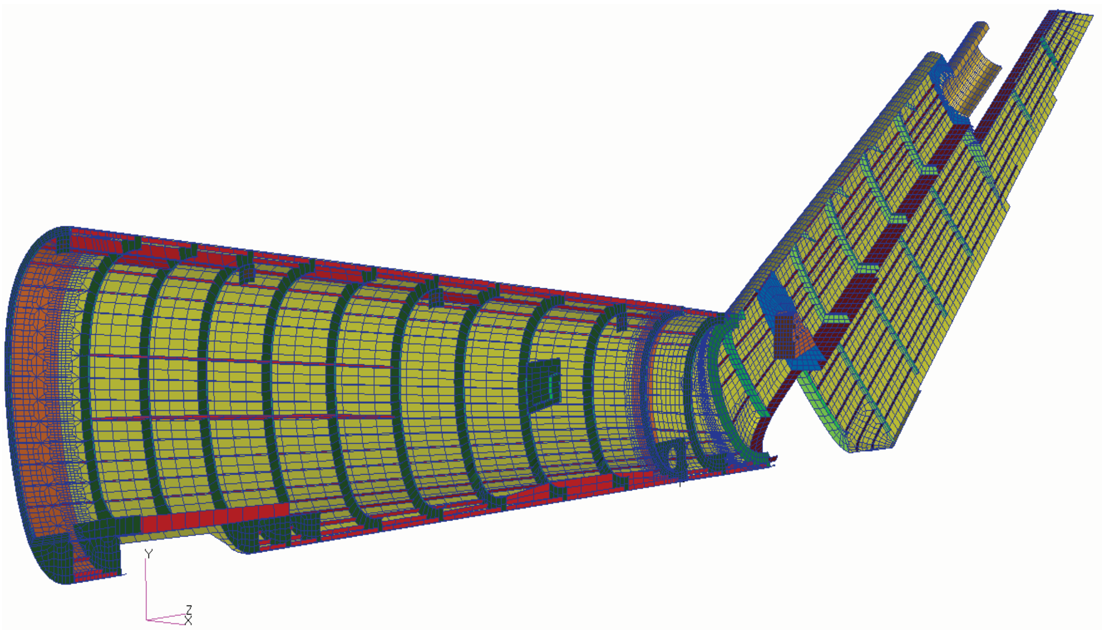

Fig. 1. Global FEM model of the tail boom with vertical stabilizer of the Mi-24 helicopter (right side)

The finite element (FE) model has been developed for the residual strength assessment. It has been based on measurements taken for a real Mi-24's tail boom. The photogrammetric technique has been applied to take measurements. Available technical documentation [3] has also been used, as well as results of detailed visual inspection. The FE model consists of 30 000 finite elements. A general model has been outlined in Fig. 1. Four-node shell elements have mainly been used. Brick elements have been chosen for the modelling of selected frame sections. In addition, structural parts such as the horizontal stabilizer and the tail bumper have been modelled using beam elements [4].

The FE model has been developed with the grouping technique applied. This has made the model well-prepared for fast and easy modifications during the analysis. The structural components not involved in the load transfer, however important while considering the inertial loads, have been represented in this model in a reduced, generalised form. Suitable adjustments of density of the applied materials have provided capability to maintain the correct total weight of these components.

Material properties of the D-16 aluminum alloy have been taken from the materials-testing results. The strain-stress relationship is shown in Fig. 2. Because of high stress concentrations in crack tips, the nonlinear strain-stress relationship has to be used in calculations. Plastic deformation is crucial for the determination of value of one of the selected criteria (see below).

This work has been a part of some more extensive research project. The project consists in, among other activities, taking strain measurements for some real structure during a flight. Using strain gauge data, the FE model has been validated. The comparison between the strain gauge results taken from the structure under well-known loading conditions and those taken from the FE model shows both to be in good agreement [4].

The model has been developed using commercial software: GOM, Unigraphics and MSC.Patran. The FE calculations have been made using the MSC.Marc software.

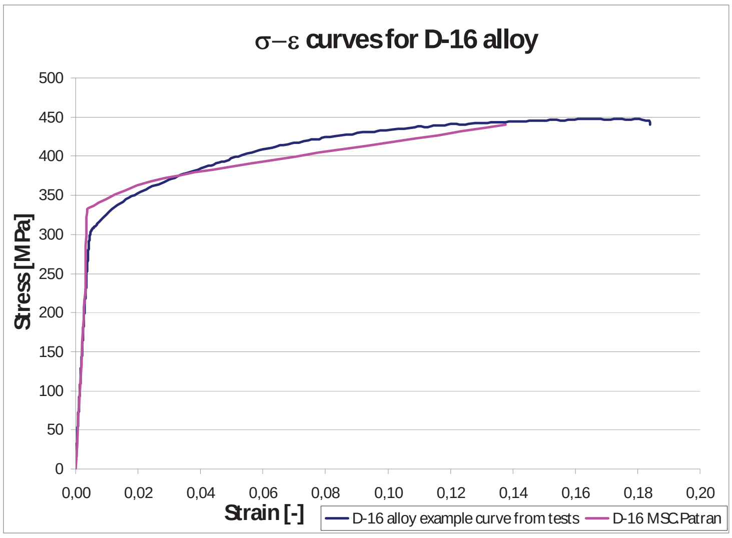

Fig. 2. Duralumin D-16 properties from laboratory test

2.2. A ballistic damage to the tail boom

After a tail boom gets a hit it may happen that the structure cannot withstand loads affecting it, and it then becomes destroyed. There are at least a couple of probable failure modes that may damage the helicopter's tail boom, e.g.:

- rapid crack propagation while loads increase,
- plastic deformation that makes a helicopter grounded,
- crack propagation due to fatigue, and
- buckling.

The first two failure modes, i.e. the rapid crack propagation and the plastic deformation have been taken into consideration in this paper. The two other failure modes require different numerical calculations.

The way how to perform the analysis has been shown for damages in two characteristic cross-sections. These cross-sections have been chosen on the grounds of obtained stress-analysis results. In both cross-sections the stress (the maximum principal tensile stress) levels are higher than it is in the surrounding area. The first cross-section (A) is situated in front of the boom, close to the access hole in the bottom of the boom. The second cross-section (B) is situated in the vertical stabilizer area where the horizontal part meets the vertical one. The damage under consideration is a hole shot through the skin and stringers connected with it. The damaged stringers have been modelled by 'removal' thereof, i.e. by lack of corresponding finite elements in the FE model. The damage to the skin is a sharp crack.

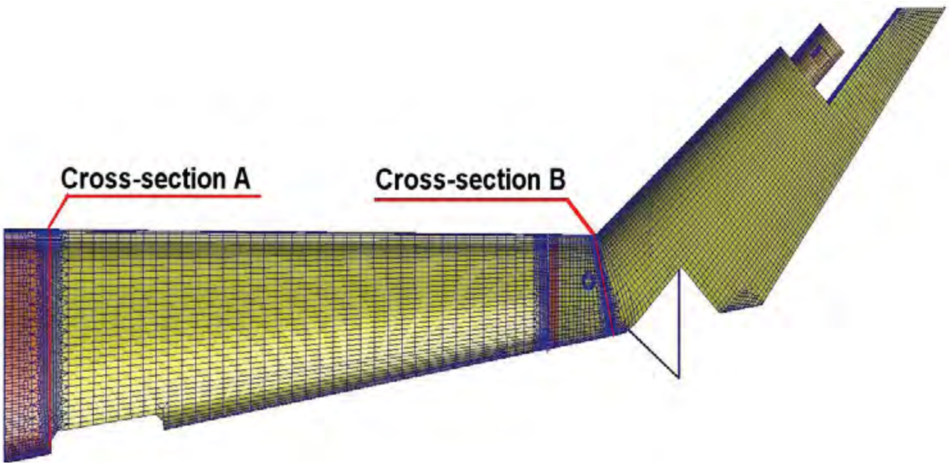

Fig. 3. Damages in cross-sections under considerations

As a result of numerical simulations, a damage of particular size can be classified as safe, according to the assumed criteria (see below). Additionally, the maximum size of a safe damage can be assessed. These calculations have been carried out sequentially, by means of iteration. The first step is to check the criteria for small-size damage. If the criteria have been met, the size of the damage is increased and the analysis is performed once again. In this way the maximum size of the safe damage can be obtained. The initial size of the damage in question in cross-section (A) is presented in Fig. 4.

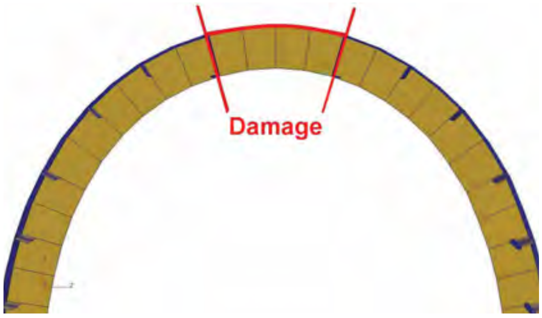

Fig. 4. The initial size of the damage in cross-section (A)

The FE model has to be adjusted for a particular size of the damage prior to the analysis. The mesh has been refined in the area of the cross section under analysis. Special attention has been paid to the crack-tip surrounding area.

2.3. Criteria for a catastrophic damage

In this analysis two criteria for a catastrophic damage has been applied. The first one is a crack tip opening angle. This criterion can be used for cracks in aluminum sheets [5-10] getting torn. It can be easily and in a simple way implemented in the FE calculations [11]. The angle under consideration is calculated using displacements and positions of three selected nodes at the crack tip. The way of selecting the nodes for calculations is shown in Fig. 5. The critical value of the angle has been set at 5°. This criterion is responsible for preventing the crack from rapid growth and propagation under the load affecting the structure.

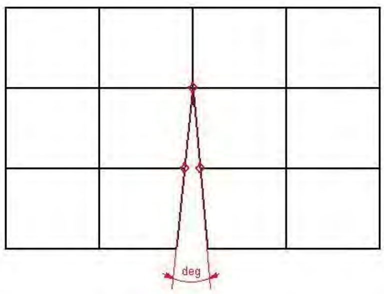

Fig. 5. The Crack Tip Opening Angle definition in a FEM model

The second criterion is plastic deformation of the end of the tail boom. Correct operation of the tail rotor and the driveshaft requires the tail boom to be properly set towards the fuselage. According to the alignment manual developed by the Original Equipment Manufacturer, the permanent deformation of the end of the tail boom in vertical direction must not exceed +5/-30 mm. This deformation has been calculated in the FE model using the change in position of a chosen node (node 112 shown in Fig. 6) under the simulated hard-landing conditions.

Our own procedure has been developed using the Patran Command Language. It has been intended for fast calculation of plastic deformation for some selected load step during the analysis in the MSC.Patran environment [9-10].

The code generates a report file and writes in the data. Based on the analysis of the data, the maximum size of the damage as well as the maximum load capacity of the damaged structure can be assessed.

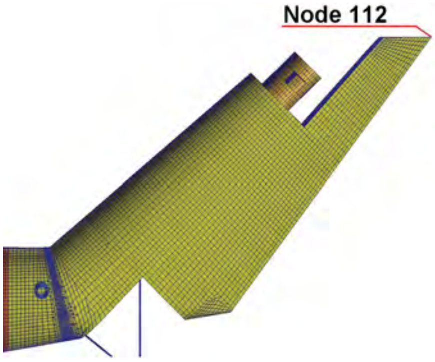

Fig. 6. Node 112 corresponding with the alignment point on the top of the vertical stabilizer

2.4. Loads

Critical loads affect the helicopter's tail boom during the correct or hard landing. The difference between loads during the correct and hard landing lies in the value of vertical acceleration. The chosen value of vertical acceleration implicates a change in analysis results. The load severity level can be set for each damaged helicopter on the basis of predicted usage of the helicopter. In this analysis the load consists of vertical acceleration and the nominal tail-rotor thrust needed to compensate for the main rotor torque. In Fig. 7 the change in loads throughout the analysis is presented. The nonlinear quasi-static calculations consist of three phases. In the first phase both loads have increased from the zero to 19.62 m/s^2 (vertical acceleration) and to 7500 N (tail-rotor thrust). During the second phase the vertical acceleration has increased to a value equivalent to the 3.5 g overload, with the tail-rotor thrust remaining constant. During the last phase both the loads have been diminished down to 9.81 m/s^2 (vertical acceleration) and to 0 N (tail-rotor thrust). In this way the plastic deformation of the tail boom can be obtained.

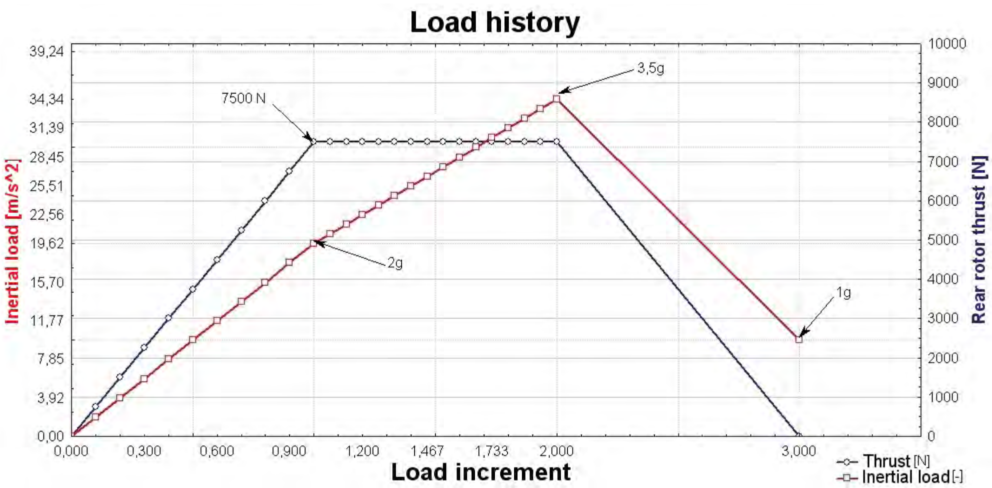

Fig. 7. Load history

6. Results

This analysis consists of several simulations performed for several characteristic damages. For each case different sizes of damages have been given consideration until any of the two criteria has been satisfied. In this way the effect of the damage propagation on the monitored parameters can be followed and the critical size of the damage - captured.

Some exemplary results have been shown below for the cross-section (A). Fig. 7 shows the increase in the crack tip opening angle as the crack advances. For this location of the damage the critical size is five-bay-large damage.

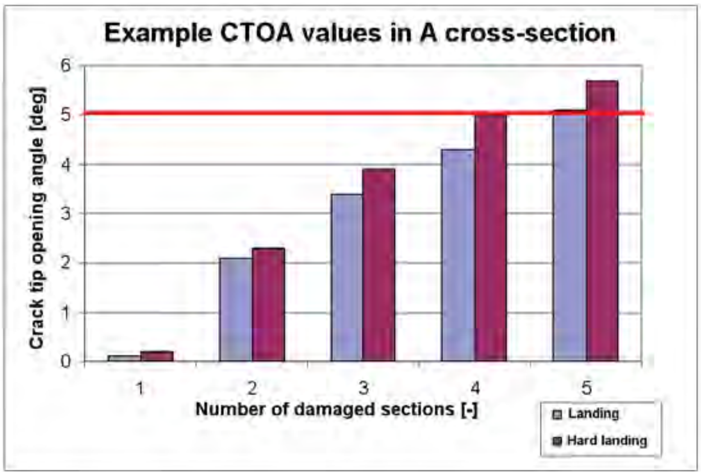

Fig. 7. Increase of the Crack Tip Opening Angle

In Table 1, values of the crack tip opening angle have been shown for both sides of the crack (left and right). Some difference between the left and the right sides can be noticed. It results from the direction of the tail-rotor thrust. This force has the most significant effect on the residual strength, far larger than the inertial load during the correct landing or the hard landing.

Tab. 1. Tabularized opening angles for the damaged upper, front part

	Damaged upper, front part			
	Landing [2g]		Rapid hard landing [3.5 g]	
	Right [°]	Left [°]	Right [°]	Left [°]
A_1	0.2	0.2	0.2	0.2
A_2	2.1	2.2	2.1	2.3
A_3	2.8	3.4	2.9	3.9
A_4	2.8	4.5	2.2	5.0
A_5	2.1	**5.1**	1.6	**5.7**

The plastic deformation criterion based on the permanent deformation of the tail boom has not been as severe as the crack tip opening angle criterion. The plastic deformations of node 112 are shown in Fig. 8. Some increase in the plastic deformation as the damage size increases can be noticed.

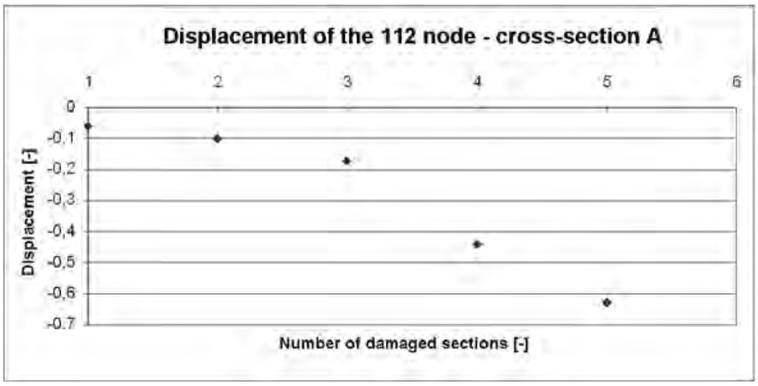

Fig. 8. Increase in the plastic deformation of node 112 as the damage size increases

7. Conclusions

The presented analysis has proved that there is some reserve in residual strength of a damaged tail boom or a vertical stabilizer. The assessment of residual strength for particular damage needs calculations carried out in the in this paper presented way. It should be kept in mind, however, that any real structure is affected by changing loads throughout its operational use, which can make the damage increases due to fatigue. Good results of residual strength analysis should be supplemented with the *da/dN* crack growth rate analysis and the analysis of buckling.

The above-described method can be successfully used to pre-assess the influence of damage on the helicopter's tail-boom structure. This method together with two easy-to-apply criteria enables quick assessment of whether the helicopter with damage is able to fly. Between two used criterions the more severed one was a CTOA criterion.

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