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APPLICATION OF DAMAGE TOLERANCE TO INCREASE SAFETY OF HELICOPTERS IN SERVICE

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INTRODUCTION

In the past, all helicopters have been designed to safe-life requirements. Introduced in October 1989, FAR 29.571 at Amendment 28 requires damage tolerance substantiation for transport category helicopters. Therefore, the majority of helicopters currently in service were designed to safe-life requirements. In general, the safe-life approach has proven to be adequate. However, there have been a number of field problems with cracking components, which lend themselves to the application of a damage tolerance approach. Damage tolerance analysis allows addressing the safety of the cracking components by

- Evaluation of the field cracking, supported by the laboratory evaluation of the field-returned cracks.
- Establishment of the inspection interval in conjunction, if necessary, with operation limitations.
- Specification of fixes to be applied to the structure to either increase the inspection limit and/or lift the operation limitations.

To accomplish the above listed tasks, crack growth analysis is performed using the appropriate usage spectrum and the flight load survey data. If necessary, usage spectrum reviews and additional flight load surveys could be required. The crack growth analysis results are verified by the laboratory evaluation of the cracked components, and if necessary by the additional crack growth testing of the field-returned components with cracks or the pre-cracked components.

GENERAL CONSIDERATIONS

Safe Life

The safe life of a helicopter component is the service time in flight hours that will precluded the initiation of fatigue cracks. The safe life is calculated using the usage spectrum, flight-measured loads, and the fatigue strength determined from full-scale fatigue testing of as-manufactured components. To ensure high reliability of the calculated life, the fatigue strength of the component is reduced by three standard deviations, which would correspond to approximately one component out of a thousand with a fatigue crack. The reliability of safe-life helicopter components is, in

general, higher than 0.999, determined by the fatigue strength reduction, as other elements of analysis, usage spectrum, and measured flight loads are conservative, i.e., are above their average values.

The reliability of the safe life is not known, as its determination would require consideration of other sources of randomness besides fatigue strength—such as usage spectrum, flight loads, and damage accumulation (Miner's Rule). The safe life does not account directly for such events as the presence of cracks due to manufacturing, maintenance, environment, or discrete damage.

Therefore, the reliability of the safe life could be lower than calculated if the above mentioned events are relevant, i.e., if their combined probability is of the same order as the probability of having a fatigue crack. The reliability of safe-life components can be increased by lowering their replacement times or decreasing their usage.

Damage Tolerance

Damage tolerance of a helicopter component is ensured by inspection or part removal before a crack grows critical. The inspection interval or removal time is calculated for the assumed crack using the usage spectrum, flight-measured loads, and the material crack growth data. The damage tolerance starts where the safe life ends, i.e., when there is a crack; it also accounts for events not covered by the safe life, such as cracks caused by manufacturing, maintenance, environment, or discrete damage.

In general, the reliability of components designed to damage tolerance requirements is higher than that of components designed to safe-life requirements. The reliability of damage tolerance is not known, as its determination would require consideration of the following variables: crack growth data, flight loads, usage spectrum, initial crack sizes, and inspectable crack sizes (Ref. 1). The reliability of damage tolerance components can be increased by more frequent inspection, a more thorough inspection method, or both.

Scope of Damage Tolerance Application to Safe-Life Components

Overall, the safe-life approach yields components with an adequate reliability level. However, there are situations where the reliability level of safe-life components needs to be increased, for example,

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- a. Components having field problems.
- b. Components that are susceptible to damage due to manufacturing, maintenance, environment, etc.
- c. Components whose reliability has been adequate to the design requirements such as usage, quality, maintenance, environment—but which needs to be increased due to increased requirements.

The components in group (a) are of the primary importance, as they are proven threats to the safety of the fielded fleet, whereas components in groups (b) and (c) are only potential field problems.

The only way to increase reliability of safe-life components is to decrease the retirement life or their usage. For components of group (a) this could mean grounding of the fleet; for components of groups (b) and (c), this would mean severe economic and logistic impact. Another option is to re-evaluate these components using a damage-tolerance approach, which allows realistic evaluation of actual and potential field cracking problems, and determination of measures that would allow an increase in the components' reliability to an acceptable level. Usually, the acceptable level of reliability is defined by the damage tolerance requirements (Refs. 2, 3, and 4). The following measures alone or in combination could increase reliability of any safe-life component:

- Inspection program
- Limitation of the operation envelope
- Modification of maintenance program
- Modification of manufacturing processes
- Structural modification
- Redesign

PARTICULAR APPLICATIONS TO FIELD PROBLEMS

Fatigue cracking of any safe-life component during its service can mean that this component's fatigue life does not meet the safe-life requirements. That requires immediate action to determine the cause of cracking and to ensure the safety of remaining in-service components. To accomplish that, a thorough post-failure investigation needs to be performed, including the following data about the component in question:

- Failure data
 - Total time
 - Type of usage
 - Maintenance records, etc.

- Fleet survey data
 - Service history
 - Maintenance history
- Field investigation of the failed part
 - Failure origin and its extent
 - Metallurgical evaluation
 - Conformity check
 - Striation count

Once the post-failure examination excludes any straightforward reason, the safe-life evaluation of the fatigue life should be examined. Fig. 1 presents a flow chart of safe-life methodology. The shorter-than-calculated fatigue life could be due to

- a. More severe usage, e.g., logging, higher GAG rate, high altitude operations.
- b. Higher loads, e.g., rotor out-of-balance loads, residual loads due to assembly.
- c. Lower fatigue strength due to corrosion, fretting, manufacturing defects, casting anomalies, etc.
- d. Miner's Rule.

The first three elements of the safe-life methodology are easy to evaluate. The effect of Miner's Rule, which combines the load spectrum with the fatigue strength, cannot be directly assessed since partial damage used to accumulate the fatigue damage cannot be measured. Miner's Rule assumes that damage accumulation is independent of the damage size, and does not account for the load sequence. There are a number of publications that showed large variability induced by the application of Miner's Rule (Refs. 5, 6, 7). In general, this could lead to either shorter or longer calculated fatigue life. It could be a suspect of premature failures in cases involving both high and low cycle loads, as Miner's Rule cannot account for the load sequence.

Damage tolerance analysis (Fig. 2) offers capabilities not available in safe-life analysis, as it considers that the growth of a crack depends on its size, and accounts for the presence of damage (the initial crack) and the load sequence.

The post-failure evaluation and examination of the fatigue life analysis, allowed to define and verify data for the crack growth analysis in terms of selection of the critical location, assumed initial damage, appropriate usage spectrum, and appropriate flight load survey data and crack growth predictions. If necessary, usage spectrum reviews and additional load surveys could be required, as well as an additional crack growth testing of (1) the field-returned components with cracks or (2) the pre-cracked components. The results of the crack growth analysis can be used to determine an appropriate

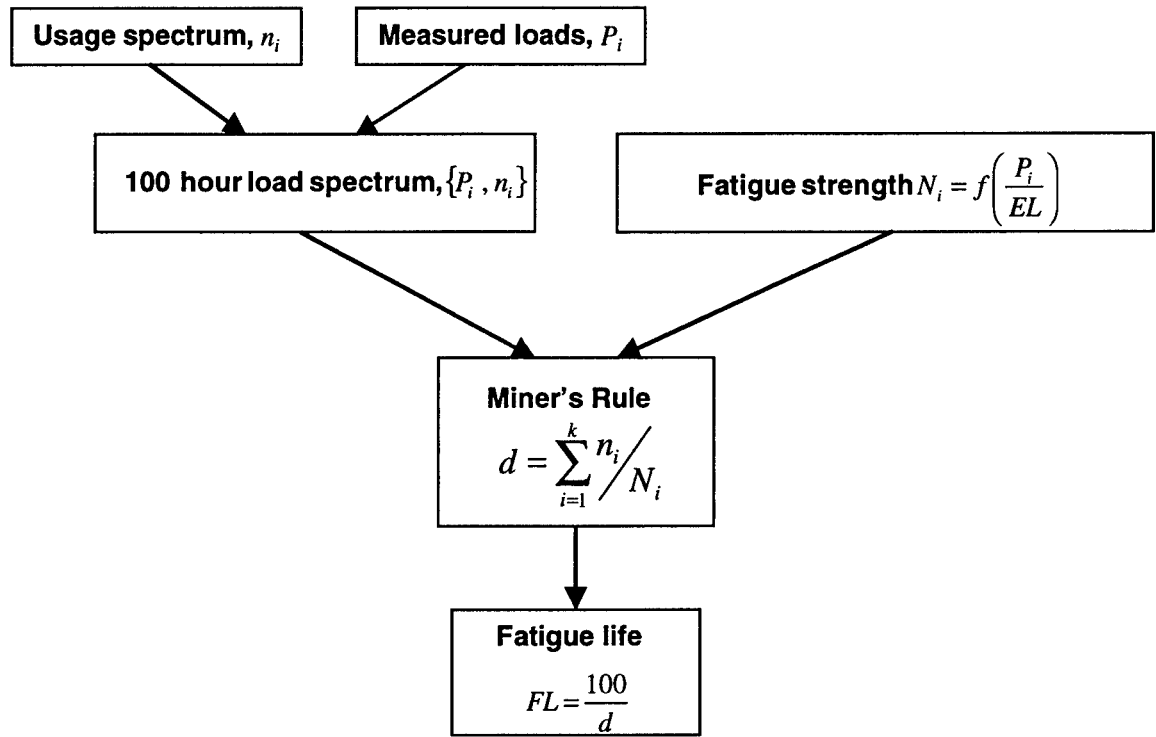


Fig. 1. Safe-life methodology.

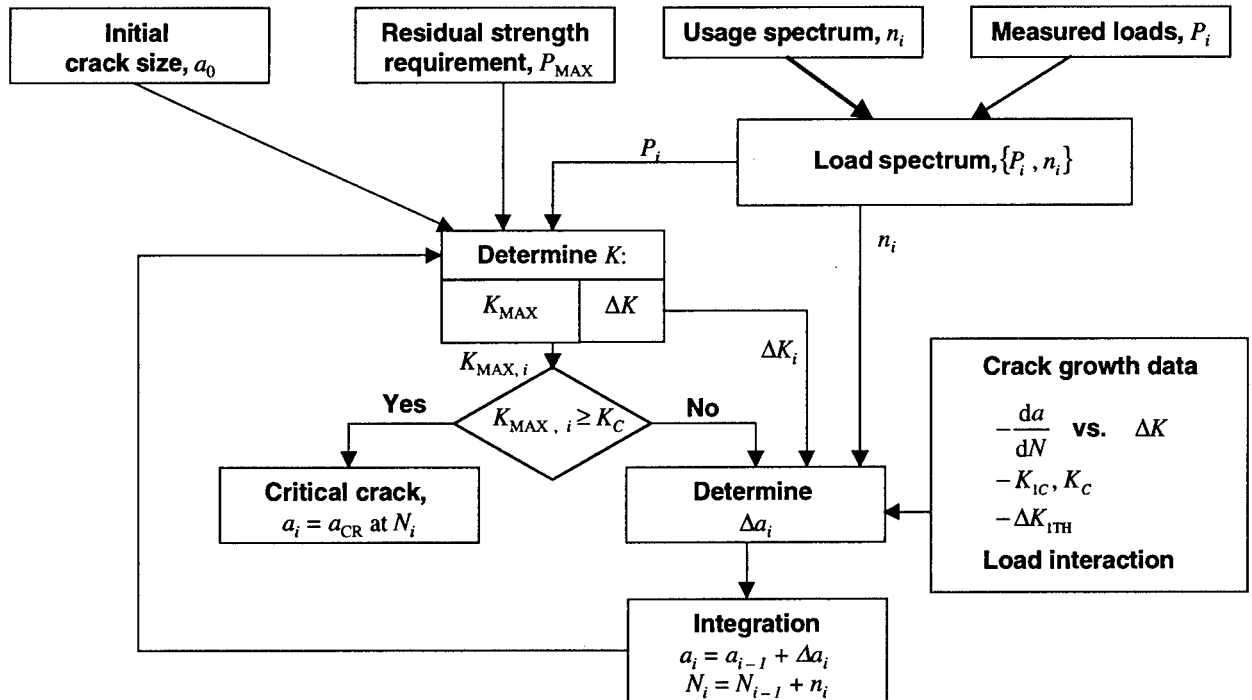
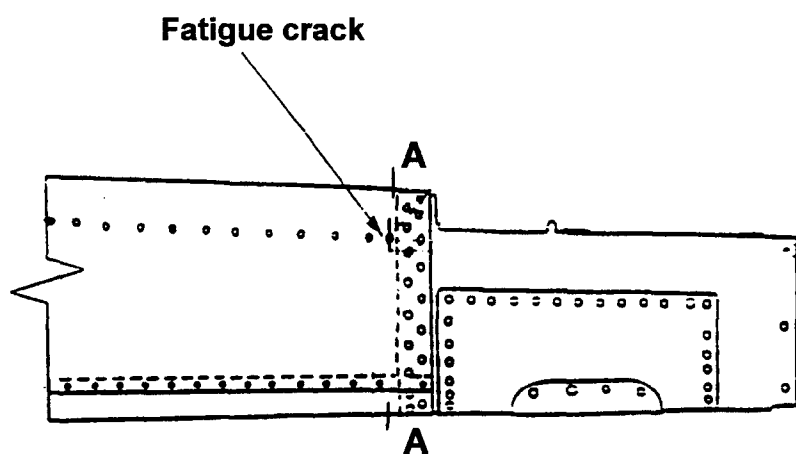


Figure 2. Damage tolerance methodology.

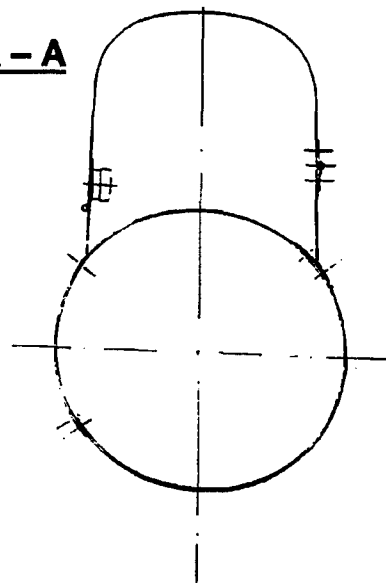
inspection interval to restore safety to the acceptable level defined by the damage tolerance requirements. Crack growth analysis can be performed for various scenarios of initial cracks, load spectrum, and part geometry to address options available to tackle the problem, which would include

- Inspection using various inspection methods.
- Limitation of the operation envelope.
- Structural modifications.

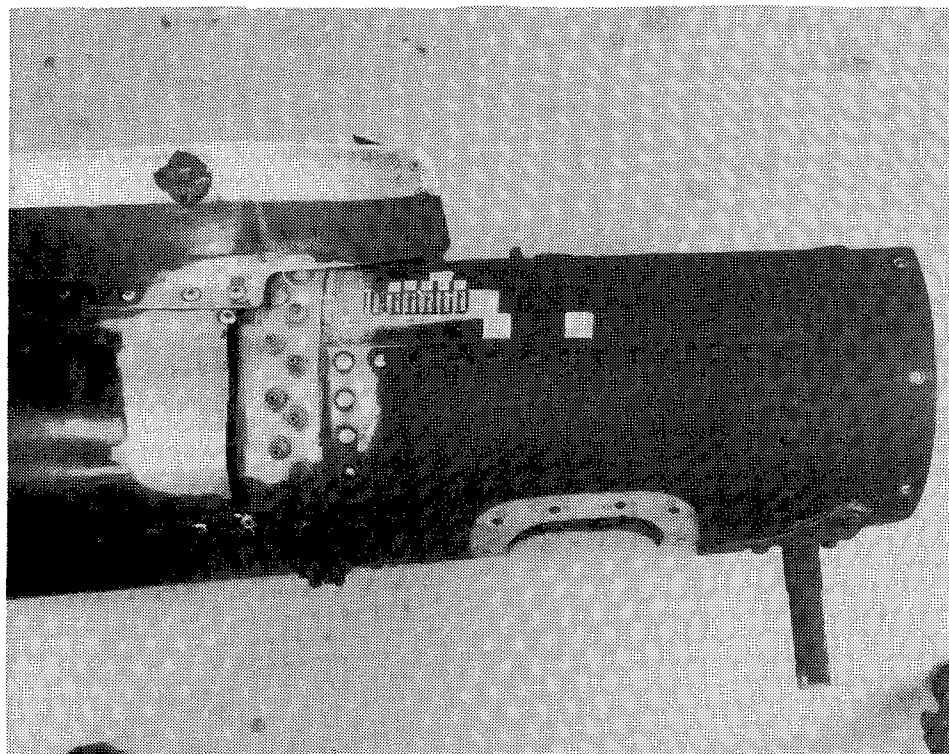
(a)



(b)

A - A

(c)



In case the first option (a) yields an unacceptable inspection interval, the remaining options (b) and (c) can be exercised in order to increase an inspection interval to the acceptable level.

EXAMPLES

Severe Load Spectrum: Monocoque Tailboom

Fatigue cracking of the skin was detected at the out-board section of the tailboom (Fig. 3). The cracking

Figure 3. Tailboom: geometry, critical section, and crack-growth test result.

originated at the hole of the last rivet attaching the drive shaft cover support to the skin. The cracking was caused by high vibratory loads at this section, being the result of the combined action of the main rotor and tail rotor excitations. The flight load survey with the strain gauges at the critical areas of the tailboom was flown for the baseline tailboom and a modified tailboom. The modified tailboom incorporated "dynamic fixes" which changed the dynamic response of the tailboom and lowered both magnitude and frequency of the vibratory loads at the critical area of the tailboom. Also, to extend the inspection interval, the skin thickness of the critical area has been increased. Based on the strain data from the flight survey, an inspection interval was determined using the crack growth analysis for the crack in the cylindrical shell, without considering the beneficial effect of the drive shaft cover supports on crack growth.

To verify crack growth analysis and to extend the inspection interval, field-returned tailbooms with fatigue cracks were tested under the flight load spectrum. The crack growth test results confirmed the conservatism of early crack growth results and showed the beneficial effect of the drive shaft cover supports as an additional load path (Fig. 3c). The test results allowed extension of the inspection interval and addressing of the load variability at the tailboom critical section.

Discrepant Components Due to Manufacturing: Tail Rotor Blade

A number of tail rotor blades (Fig. 4) were produced with excessive sanding of the skin around the doubler tip, which caused fatigue cracking of the skin. The flight load survey data were available for the beamwise and chordwise bending moments at the station near the area affected by sanding. The stress spectra at the critical areas were determined, followed by the crack growth analysis of the blade with a cracked skin. The inspection intervals were established for blades with plain spars (Fig. 3b), and spars reinforced with glass fibers, (Fig. 3c). The presence of the reinforcement substantially increased the inspection interval.

The inspection intervals ensured the structural integrity of the blade, allowing for corrective action to fix the problem without affecting the operation of the fleet and its readiness.

Components Made of Material Susceptible to Stress Corrosion: Main Rotor Grip

The main rotor grips on older helicopters was made of 2014-T6 aluminum alloy (Fig. 5). This material shows low resistance to stress corrosion, which could cause problems in highly stressed areas—particularly when accompanied by high residual stresses. The lugs of the main rotor grip with thermally fitted bushings are

highly loaded by centrifugal force and beamwise and chordwise moments. The crack growth analysis of the grip was performed to establish an inspection interval to increase its reliability. Subsequently, the main rotor grip material has been changed to 7075 T73 aluminum alloy, which shows higher resistance to stress corrosion.

Components Redesigned to Meet Increased Structural Integrity Requirements:

Main Rotor Pitch Link

The main rotor pitch link (Fig. 6) was originally designed with an aluminum tube, which failed due to fatigue cracking. The pitch link was redesigned with the aluminum tube replaced by a steel one. Both designs have infinite safe life. To show the higher reliability of the redesigned pitch link, crack growth analysis was performed to show its damage tolerance (Ref. 8). The crack growth analysis was verified by crack growth testing of selected elements of the pitch link, rod end "banjo" (Fig. 6b), and the threaded shank (Fig. 6c). Also, material crack growth data were generated by crack growth testing of center cracked panels made of the pitch link material, 15-5PH stainless steel heat treated to 155–170 ksi minimum ultimate tensile strength.

CONCLUSIONS AND RECOMMENDATIONS

The damage tolerance of safe-life helicopter components can be evaluated using crack growth analysis. To accomplish that, load spectrum, stress distributions, stress intensity factor solutions, and material crack growth data are required.

Crack growth analysis determines inspection intervals that can be used to ensure structural integrity and to increase reliability. Inspections can be used to address field problems resulting from fatigue cracking and to prevent such occurrences. In the latter case, the decision to introduce inspections should be based on the criticality of the components and their sensitivity to inherent or external damages, and to variations in usage and loading.

The ultimate goal of any structural integrity requirements, whether safe-life, or damage tolerance, is to ensure an acceptable level of safety. The level of safety can be measured by reliability, which is the probability of not failing. Therefore, reliability is the common denominator which can be used to verify adherence to structural integrity requirements, to evaluate various approaches, both structural and methodological, and to optimize structures with regard to structural integrity. It is recommended that guidelines be established to evaluate reliability of fatigue critical components for both metal components (Ref. 1) and composite components (Refs. 9, 10).

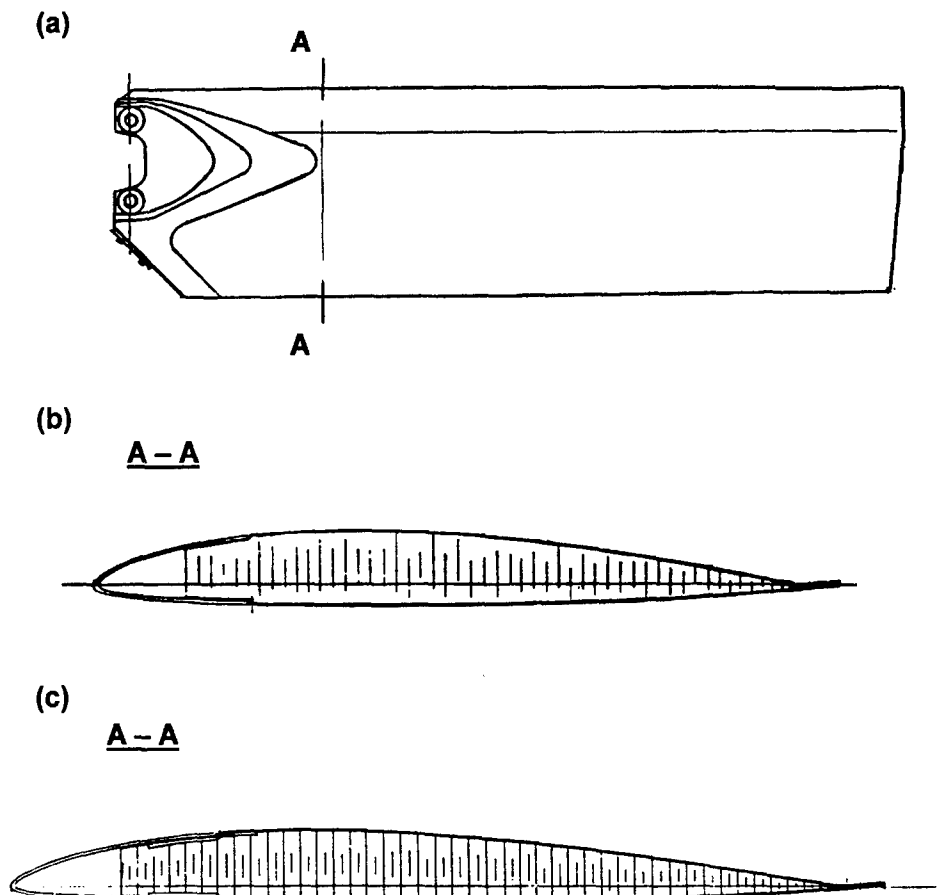


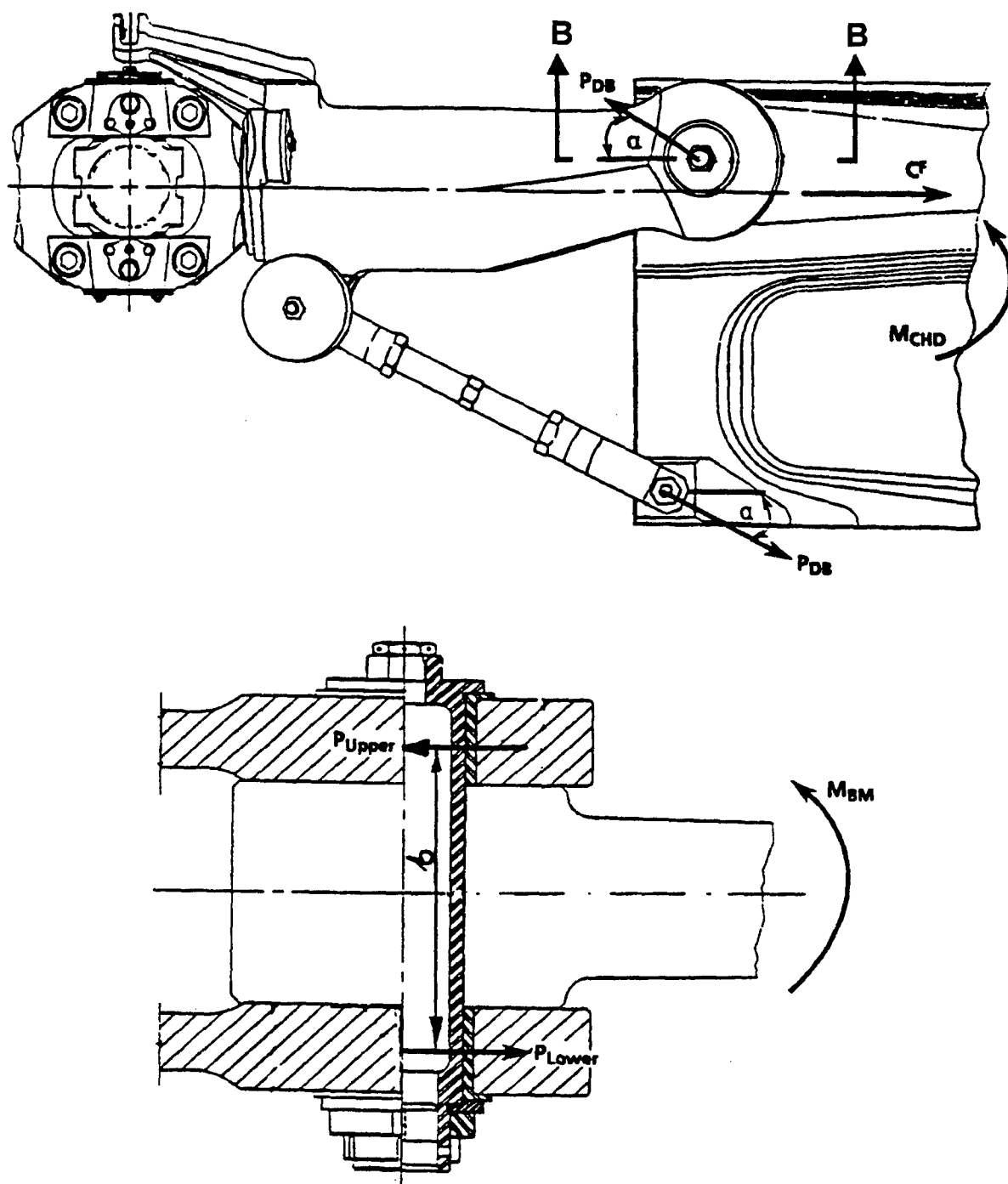
Figure 4. Tail rotor blade: geometry and critical section.

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Section B - B

Figure 5. Main rotor grip: geometry and loading.

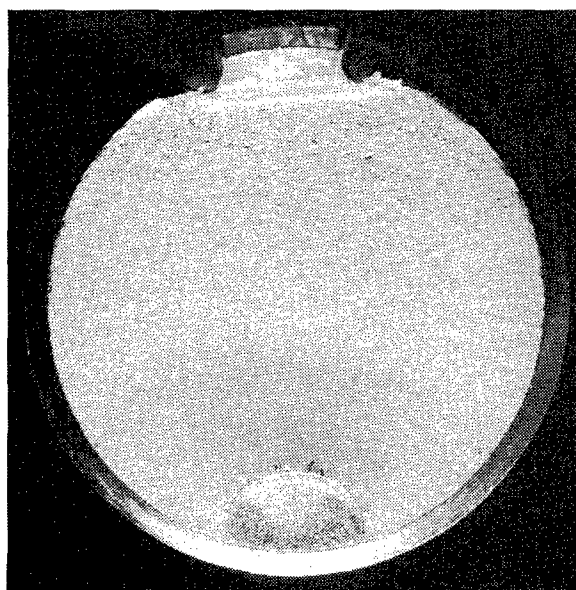
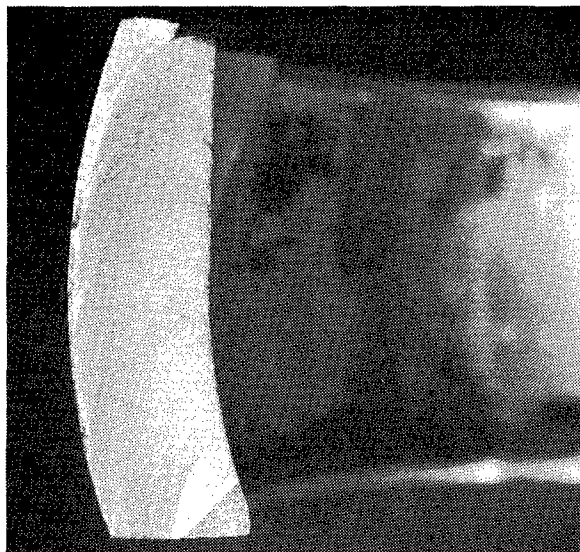
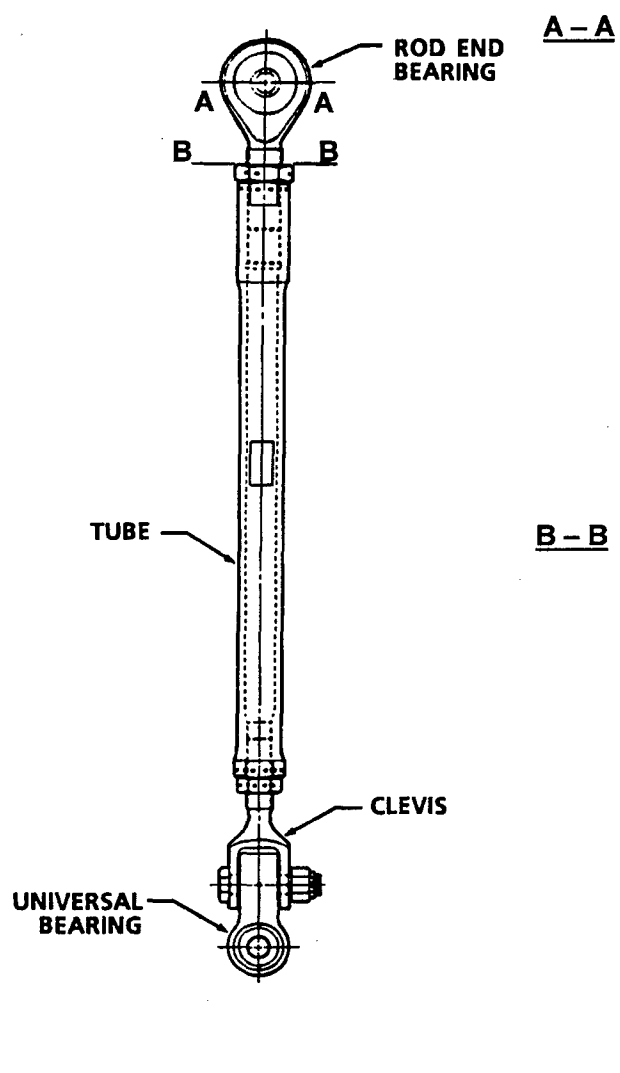


Figure 6. Main rotor pitch link: geometry and crack-growth test results.