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DAMAGE TOLERANCE CONCEPTS FOR MODERN HELICOPTERS

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ABSTRACT

Damage tolerant methods have found much interest in the helicopter community in the past years. With the application of damage tolerance it is aimed that structures may withstand reasonable static and dynamic loads despite the occurrence of defects as consequence of fatigue, wear, impact etc. Damage tolerance may be achieved by slow defect growth or fail safe capability of the structure. In the first case, it is assured, that defects propagate slowly and that early detection is warranted. In the second case, defects are absorbed by redundant load paths or defect arresting structures.

Tolerating defects is necessarily connected with the availability of adequate inspection methods and maintenance intervals which have to be approved during the certification procedure. Although designed to the hitherto accepted safe-life philosophy, many helicopters already incorporate a bundle of damage tolerant features. This is for MBB helicopters e.g. the application of composite material, or the redundant load path design in many cases.

The sole qualification of entire helicopters according to the damage tolerant approach seems premature, rather a combined safe-life/damage-tolerance philosophy is adequate at the present time.

1. INTRODUCTION

The helicopter customers generally require a profitable payload, sufficient flight range, and a good manoeuvrability for their aircraft. Therefore, helicopters are designed to be as light as possible, yet strong enough to satisfy these requirements during their operational lifetime.

However, helicopter structures, and especially the components of the rotor system, the drivetrain and the controls are subject to a variety of threats which may seriously affect the aircraft's safety. The most serious threats are:

- ° fatigue, induced by repeated loads
- ° material degradation through environmental effects, e.g. corrosion
- ° ballistic and foreign object damage (FOD)
- ° manufacture and handling induced damage
- ° elevated loads in service compared to design loads
- ° malfunctions of systems like engines, hydraulic units etc.

According to the airworthiness regulations, helicopter dynamic systems are generally certified and operated with the safe life philosophy. This approach is based on coupon and component fatigue tests, and assigns to the component a certain safe lifetime, after which the part has to be replaced, irrespective its actual condition.

Fuselages and landing gear, on the other hand, are designed to withstand static flight and emergency landing conditions, which are specified by the airworthiness requirements.

During the past years, a number of drawbacks of the safe life approach were featured.

When calculating lifetime, usually little information is available about all parameters which actually influence a part's fatigue behaviour. Even less information is available about the mission spectrum and the loads the parts will encounter during their service lives, as the operational requirements of the customers vary within a broad field of missions. All these uncertainties are accounted for by conservative assumptions and adequate reduction factors, Ref.1., which also vary between different manufacturers.

This conservatism and some other shortcomings of the safe life approach have enforced tendencies towards another method, the so-called damage tolerance method. This means that an aircraft containing defect parts should operate safely until the damage is discovered and removed. In January 1983 the Federal Aviation Administration (FAA) published an Advance Notice, Ref.2., proposing to yield damage tolerance requirements for the fatigue evaluation of rotorcraft structures, except if it can be established that the application of damage tolerance features for a particular structure is impractical. The proposals resulted from the FAA's assessment that there is a potential for preventing crashes and saving lives by damage tolerance.

Also the European Airworthiness Authorities Steering Committee AASC identified several aspects of the safe life requirements not well covered, and supports in principal "the shift of emphasis to damage tolerance for the substantiation of fatigue critical structures", Ref.3.

Finally, from the customers' side, the damage tolerance approach is expected to reduce maintenance and increase reliability and safety, Ref.4. For the military customers especially ballistic damage tolerance, as part of the general damage tolerance, is a stringent requirement for the helicopter's survivability.

Although no new regulations for damage tolerance application have yet been set forth by the authorities, it is likely that damage tolerance will be a specific design and probably also certification feature in the future. Therefore, helicopter manufacturers are busy collecting arguments for and against the new philosophy.

It is found that many damage tolerance features are realised in present helicopters, Ref.5., and for almost all new helicopters being in the design stage considerations are taken to add damage tolerance capacity.

The scope of this paper is to highlight design features for helicopter damage tolerance achievement and the procedures to assess this method. A number of examples for damage tolerant design, verified in MBB helicopters, are presented. Finally, the limitations for the application of damage tolerance are shown.

2. DAMAGE TOLERANCE CONCEPTS

General

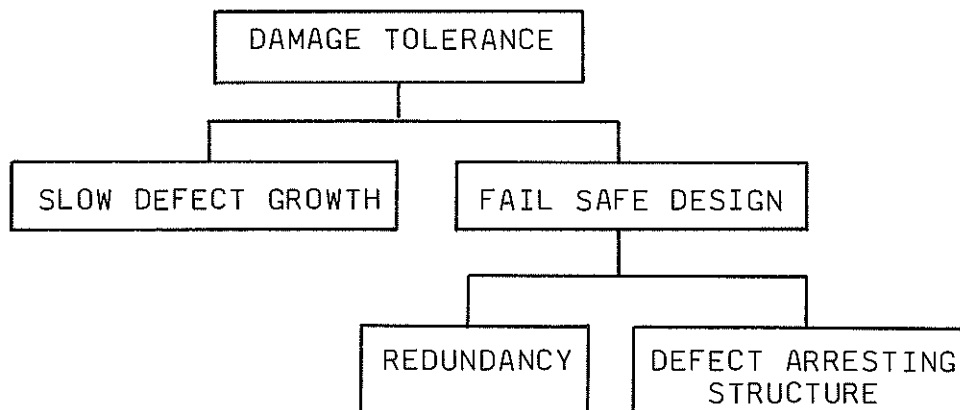
To bring damage tolerance design into a helicopter must start in the early design phase. It must be decided upon basic design concepts which contribute to security and damage tolerance, as

- redundancy of systems (e.g. engines, hydraulic units etc.)
- avoidance of critical design features (e.g. high friction in the thrust faces of roller bearings)
- favourable arrangement of systems (e.g. to protect sensitive components) .

Also, the detail structural design should be damage tolerant, where possible. The scope of this paper is limited to this second category of damage tolerance. The general guidelines for the attainment of structural damage tolerance are features as

- good detail design with low stresses in critical portions
- redundancy in load paths,
- selection of materials with favourable fatigue and fracture properties.

These and other guidelines can be summarized in the following scheme:



This scheme is a generalisation of the scheme as established in the very beginnings of damage tolerance. This was for military fixed wing aircraft in 1974 by the specification MIL- A- 83444, Ref.6., and for civil transport aircraft by advisory circular AC 25.571-1, Ref.7. By these regulations compliance was permitted through the slow crack growth or the fail safe approach. The fail safe approach covered "multiple load paths" and "crack arrest structure".

The fail safe approach

Fail safe through multiple load paths (redundancy)

Multiple load paths or redundancy can, as other damage tolerance features be found in many present day helicopters.

This approach comprises that loads are transmitted by two or more load paths, the redundant paths being either load-carrying (active) or unloaded (passive). In case of failure of the primary load path, the loads are redistributed on the redundant load paths. Multiple load path design is achieved, e.g. by

- ° redundant components
- ° double lug joints
- ° separation of different load types, e.g. tension and shear on separate load paths
- ° multiple bolt connections
- ° skin, frame and stringer design
- ° application of material with inherent multiple load path features, like fiber composite material.

For the assessment of damage tolerance through multiple load paths, the probable locations of failures and the bearing capability of the redundant load path(s) must be shown under the redistributed loads. Minimum static as well as repetitive loads have to be sustained until the detection of the original failure.

A prime task is the set-up of appropriate inspection intervals combined with appropriate inspection methods. For this the now achieved safety standard can serve as a goal. Tolerating defects should enhance the economy of operating helicopters, but it should not reduce safety. Short inspection intervals will enhance safety, but they might be unacceptable to the customer, because of long downtime and high inspection costs.

A possible approach for the establishment of inspection intervals is to combine the probabilities of occurrence of a defect of the primary load path between two inspections with the probability of the failure of a redundant load path .

The resulting failure probability should not be greater than the failure probability with the conventional safe life method.

The length of an inspection interval is influenced by the degree of redundancy and the probability to detect a failure.

Detection of defects can be achieved by

- ° change of the aircraft's vibration level
- ° visual inspection
- ° special indicators.

Defect arresting structures

Using this method is to design components such that

- ° stress levels will be sufficiently low, so that cracks incurred in service or manufacture would not propagate
- ° crack stoppers and structure containments limit the extension of defects.

Defect limiting, or crack arresting structures in helicopters

are found in fuselages, which are semimonocoque constructions of skins, with stringers, frames and cut-outs acting as crack stoppers.

For the investigation of the damage arresting capacity of fuselages full-scale fatigue tests are performed thus revealing locations of possible failures, crack propagation velocities and crack arrest potential.

Also, detectability and repairability are investigated during these tests. The tested load levels represent high but realistic combined loads.

The results of these tests serve as guidelines for the inspection intervals and inspection procedures being proposed to the customers in the manuals.

Distinct containment provisions are relatively few in helicopter structures.

They can be found in systems where high rotor rpm threatens an individual system of the aircraft, e.g. the engines or cooling fans.

It must be shown that a disassembly of those components can be limited by the containment provisions to an extent uncritical for flight safety.

The Slow Defect Growth Approach

Initially called the slow crack growth approach, being applied to single load path structures this method is generalized here for any kind of propagating defect, in order to also cover e.g. delaminations or loss of stiffness in composites.

Despite precautions taken, it is possible that flaws, cracked fibers, delaminations etc. are present at the beginning of a part's service life. Despite rigorous NDI quality control processes it is likely that small cracks are hidden under doublers or in grooves, or in holes of riveted joints. In composite parts, flaws or delaminations can be encountered after the curing process.

During the service, on the other hand, threats like wear, debris kicked up by the rotor downwash, dropped tools or ballistic impact can cause defects.

The slow defect growth method yields that until the onset of an unstable defect propagation, the structure has to maintain satisfactory strength, deformation, and stiffness. A defect propagation has to be slow enough to assure detection before a catastrophic failure.

The assessment of slow defect capability is provided by fatigue testing combined with an analytical crack growth calculation. Other than in the fixed wing aircraft industry, where essentially all damage tolerance assessments performed in the past ten years (U.S.military aircraft, AIRBUS A-310, BOEING 757 and 767, and others) have used the slow crack growth approach, the value of this method for the assessment of damage tolerance of helicopters and especially for high loaded mechanical components has still to be proven.

The slow crack growth method starts with the evaluation of critical areas of the structure, which are areas whose failure can affect flight safety. The identification of critical areas may

be done by

- actual cracking experience through service operations
- fatigue testing
- analysis.

Prime candidates for critical areas are highly stressed areas. Also poorly inspectable portions may be taken into account.

The analytical tool for the calculation of crack propagation velocities, critical crack lengths, as well as the judgement whether a crack propagates slow (stable) or fast (unstable), is fracture mechanics.

The main parameter for fracture mechanics is the stress intensity factor K for static and ΔK for cyclic loading,

$$K(a) = S \sqrt{\pi \cdot a} Y(a)$$

$$\Delta K(a) = \Delta S \sqrt{\pi \cdot a} Y(a),$$

with the static stress S , the cyclic stress range $\Delta S = S_{\max} - S_{\min}$, the crack length a , and the correcting function $Y(a)$. For standard geometries, $Y(a)$ can be found in text books, for complex parts it must be found from tests.

For a given stress S , the crack length becomes critical when K equals K_c , which is a material-dependent value and which is called the fracture toughness. The higher K_c , the better is the damage tolerant behaviour.

During cyclic loading, the crack length increases with the number of load cycles, N . The crack growth rate da/dN is a function of ΔK and the stress ratio $R = S_{\min} / S_{\max}$. The integration of this function results in the crack length $a(N)$. Fracture occurs when

$$\Delta K = K_c(1-R).$$

Damage tolerant features through slow defect growth are realised in many existing helicopters. The avoidance of stress concentrations and the choice of materials with high fracture toughnesses, such as high-purity electro-slag remelt steels, titanium alloys, and some aluminium alloys, Ref.8, contribute to the slow defect growth capacity. Also fiber composites contribute to the slow defect potential. It has been shown that especially delaminations are retarded by the choice of resins with a high fracture toughness, and by fibers with a small fiber diameter and a high ultimate strain, Ref.9.

3. DAMAGE TOLERANT DESIGN IN MBB HELICOPTERS

Although designed and certified according to the safe life philosophy, the currently certified MBB-helicopters B0105 and BK117 show a number of examples for the foregoing defect tolerance concepts. For helicopters presently in the design stage, increased damage tolerance capacity is introduced.

Lifting system

Fig.1 shows the B0105/BK117 main rotor hub. Damage tolerant from redundancy is the flange connection between hub and M/R shaft.

Twelve studs form active load paths for the thrust force and the mast bending moment, corresponding bushes provide for a separate transmission of the shear forces induced by the rotor torque. All used materials have a slow crack propagation.

The main rotor blade c.f. retention bolts within the hub, Fig.2, show fail safe character because they can transmit full centrifugal force even when completely cracked through. In this mode the bolts are working as cantilevered beams. Additionally, these bolts have shown to be damage tolerant by slow crack growth. A conservative crack growth analysis for a circumferential .1mm deep crack resulted in a 1200 flight hrs time until total crack through of the bolt. It is assured that such a crack can be found by routine inspections before total crack through.

On the occasion of a crack in a web of the M/R shaft, Fig.3, a slow crack growth verification was performed. The crack geometry properties of the shaft were extracted from former fatigue tests. Fig. 4 shows the fractography of one of the tested shafts showing the crack origin and the crack frontiers after equal numbers of the multistage fatigue cycles. Crack propagation properties da/dN were taken from the AISI 4340 steel, which is equivalent to the shaft's BOEHLER STERN NMH steel.

Assuming an initially 2 mm deep elliptically shaped crack within the shaft's tubular cross section, the crack length was calculated as a function of flight hours for the BK117 load spectrum. It showed that the entire wall thickness, 20 mm, will be cracked through in approximately 3250 flight hours, Fig.5. The stress intensity corresponding to this crack length, turned out to be far from critical ($K = 1420$ vs. $K_c = 4500 \text{ Nmm}^{-3/2}$), indicating a stable crack growth.

Provided an adequate design, components from composite material represent inherent fail safe characteristics due to a high number of single fibres and thus multiple load paths. Additionally, from the individual layers of the laminate crack arresting and slow defect propagation features result.

The B0105 glass fiber composite M/R blade, Fig.6, has not only proven its durability towards fatigue and environmental ageing, Ref.10., distinct blades surpassed the 10000 flight hours limit, but also its damage tolerance towards FOD and ballistic impact, Ref.11. For the BK117 M/R blade with a similar design but a carbon fiber blade tip, damage tolerance towards lightning strikes had to be proven. Fig.7 shows the impacted skin area with the lightning damage increased by artificial cutout and additional sawcuts. Under elevated torsional fatigue and constant centrifugal loads fibers failed very slowly from the ends of the sawcuts. This test proved that the rotorblade will safely continue its function for at least several hours after the occurrence of a defect of similar extent.

Fig.8 shows the FEL rotor system which is in the design stage and which is also the subject of other papers of this meeting. The damage tolerant potential of the FEL-rotor is due to its clear design, its excellent inspectability and the choice of materials with good damage tolerant behaviour. The central piece, the blade fitting and the blade retention

bolts are made from titanium, which has proven a small crack propagation rate.

The upper and the lower hub plates are made from quasiisotropic carbon fiber composite, whereas the main rotor blades are from carbon and glass fiber composite material.

Blade pitch motions are allowed by two elastomeric bearings, the inboard bearing being a radial and the outboard bearing a conical elastomeric bearing.

Fatigue tests in the design stage have been performed with the hub plates, blade attachment pieces, with the elastomeric bearings and a complete hub assembly with dummy bearings.

All tests have been carried out with overloads. Loss of stiffness as well as crack propagation were monitored. All parts showed a good natured behaviour with respect to repeated loads.

As an example, Fig.9 shows the slow degradation of the radial stiffness of the conical bearing, measured under various centrifugal loads. Fig.10 shows the first failure mode, i.e. shim cracking, and Fig. 11 the second failure mode, which is a slow crumbling of elastomer between the shims. This failure mode is easily detectable by visual inspection.

Fatigue tests on the FEL- main rotor blade attachment region also showed a slow stiffness degradation and crack propagation. Cracks within the blade will be announced by a change of the vibration level far before the blade's strength is jeopardized.

Tail Rotor System

Examples for damage tolerant features of the B0105/BK117 tail rotor are the composite tail rotor blade and the blade mounting fork.

Due to the glass fiber composite, the tail rotor blades have often proven their damage tolerance

- ° in tests, with respect to fatigue and FOD
- ° in service with respect to FOD and ballistic impact.

Fatigue failure can easily be detected through surface cracks and the probable locations of fatigue failure are well known from bench tests.

Extensive tests have proven the excellent FOD behaviour of the blade, Ref.11. Figs.12 and 13 show ballistically impacted tail rotor blades with roving damages, local delaminations, and splintered foam core. In both cases flights were continued without further incident back to the bases for about twenty minutes.

The tail rotor blade mounting fork, Fig.14, has proven its fail safe capacity in fatigue tests. Although one lug was cracked through, all dynamic loads were sustained without new cracks.

For future tail rotor systems, designs are in work with enhanced damage tolerance capacity. As in the FEL main rotor system composite and elastomeric materials will be used, which add slow defect propagation and fail safe characteristics to the design, which additionally simplify the design, reduce the number of parts and improve inspectability.

Controls

Although substantiated according to the safe life philosophy, the components of the B0105 and BK117 control systems reveal damage tolerance features from the use of materials with slow defect propagation behaviour. Used materials are e.g. aluminum 3.1354 T351, and steels 1.4044.5 and 1.7220.5. Also stress levels have been sought to be so low as to not allow a crack propagation.

Probable locations of failure from fatigue or wear have been found by bench tests. Fig.15 shows a crack in a clevis lug of a swashplate, revealing the additional fail safe behaviour of this design.

Drive Train

A damage tolerant feature in the drive train are the Thomas-type couplings, Fig.16, representing active multiple load paths. Tests proved full load capacity even after the break-through of a complete link of the twelve steel laminae between two bolts. For a damage tolerant assessment, adequate inspection intervals would have to be established on the basis of the former fatigue tests. Account would have to be taken of the poor inspectability of the assembled pile.

Gear boxes have already to incorporate a damage tolerance behaviour under the present regulations. FAR 29.927 (c), e.g., yields a 15-min. dry-running capacity under autorotative conditions, i. e. power off, for helicopters of the transport category. As a consequence of an oil-pressure defect overheating of gears and bearings can occur, leading to wear and finally to failure of the gear box.

During the militarization of the B0105 a dry-run power-on test with the main transmission, Fig.17, was performed. Rotor rpm, input torque and T/R output torque could be held constant for more than twenty minutes after a total loss of oil. The test was terminated after slight rpm variations and increased temperature in a ball bearing of an input shaft, to prevent damage of the testrig.

In-service proof of the dry running capacity of the tail gearboxes was shown during an at least 30-minutes flight after the loss of oil following a ballistic impact. No spallings or wear was found on the gears.

Presently the inspection intervals are due to service experience. Inspections are: pre-flight check of oil level indicators, 10 hrs check of chip detectors, and TBOs of 1200 hrs and 2400 hrs for BK117 M/R gearbox and T/R gearboxes, respectively. Intervals are being increased as soon as the experience from fleet leader helicopter provides sufficient information. An even improved damage tolerant assessment would assign special on-line indicators which would have to be redundant, Ref.12.

An example for a defect arrest structure in the drive train is the housing of the cooling fan, Fig.18. For FAA certification compliance has to be shown with §29.908, which yields that fan blades would be contained in the case of a failure.

This has been shown for the certification of the B0105 LS where the behaviour of a disassembling cooling fan was investigated. Fig.18 shows that no parts penetrated the housing of the cooling fan.

Fuselage

Due to their large geometrical extensions, fuselages often represent structures with multiple load paths. Additionally stiffeners, stringers, frames, and holes act as crack stoppers. Examples for these damage tolerant features in fuselages of MBB helicopters are shown in Figs. 19 and 20.

Fuselage structures of the BO105 and the BK117 have been tested in full scale fatigue tests with reasonable, but high flight loads. Crack origins and crack propagation were monitored.

4. LIMITATIONS

Despite many damage tolerant features already realized in helicopters there are reasons why the application of damage tolerant methods has been limited in the past. Different from fixed-wing aircraft, where the damage tolerant approach has become the primary substantiation method, in helicopter industry the safe-life approach is still the only qualification procedure.

This is due to important differences between fixed-wing aircraft and helicopters. The main differences with respect to the applicability of damage tolerance are

- ° the significantly higher frequencies₅ of fatigue load cycles in helicopters (e.g. about 10^5 cycles/hour for main rotor components)
- ° large variability in helicopter flight spectrum
- ° the design of critical assemblies of helicopters, which generally use components of small and complex shape with often only one load path.

Complex components, as e.g. rotors, transmissions and controls make fail-safe inspections cumbersome and necessitate costly and sophisticated inspection systems for early detection. Often the use of redundant load paths or crack stoppers is not applicable for mechanical parts because of space and weight restrictions.

The design for a slow defect-growth is much more difficult for helicopters than for fixed-wing aircraft, due to complex parts geometries and greater scatter of crack propagation rates at high numbers of loading cycles.

Questionable is, e.g., the application of damage tolerance as sole substantiation philosophy for rotating control rods. On the one side it would require too much confidence in the behaviour of cracks in the high-cycle mode of loading, on the other side it would mean an unjustified penalty from the weight of additional load paths and failure indication systems, Ref.13.

On the other hand, the shortcomings of the safe-life method which have led to the application of damage tolerance in fixed-wing aircraft have been compensated for much more successful in the helicopter industry.

Information about the fatigue behaviour of critical components of helicopters is gained not only from one but many component fatigue tests, thus providing for a sound understanding of the part's critical areas and a statistical basis of its fatigue strength. Additionally, environmental effects are accounted for in more and more fatigue tests. Also the large variability in flight spectrum of helicopters is presently discussed by authorities, operators and manufacturers. Spectrum variability could e.g. be accounted for by the monitoring of effective operating spectra or by appropriate damage recordings.

Summing up, it may be said that the safe life method is in a slow, but permanent change, accounting for the experiences from manufacturers, customers and authorities.

5. CONCLUSIONS

Although helicopter substantiations are presently performed according to the safe life method, there are good arguments and possibilities to incorporate damage tolerant features. Not the unconditional, but appropriate adaption of damage tolerant features will increase safety and decrease maintenance costs on the long term.

Yet it seems premature to qualify helicopters by damage tolerant methods alone, due to poor inspectability in many cases, lacking confidence in crack propagation methods at high numbers of loading cycles, unsuitable redundant structures, etc. Yet extensive in-service experience has to be required in order to correlate tests and analytical methods.

It seems desirable, at the present, to incorporate damage tolerant features wherever possible, especially by the use of

- ° materials with slow crack propagation rates,
- ° improved design concepts with good inspectability.

The substantiation may be carried out according to the damage tolerant approach for a few critical components, given a high safe life margin, as it is the case e.g. for composite rotor blades.

For the major part of critical components, threatened by fatigue, wear, impact etc. a modified safe-life approach taking into account damage tolerant features by the incorporation of improved reduction factors seems appropriate at the present.

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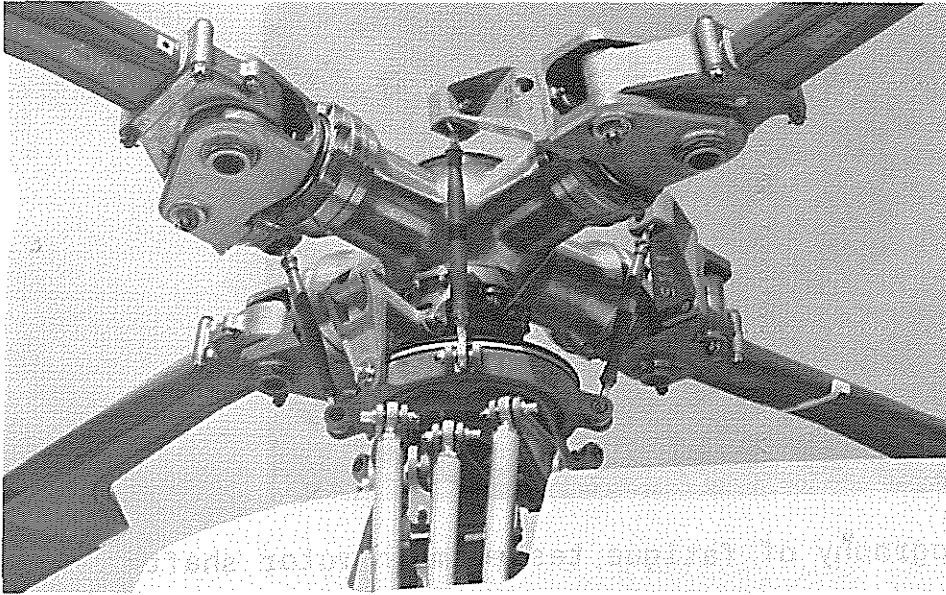


Fig.1
B0 105 M/R head



Fig.2
Centrifugal force
retention system in
B0 105 M/R head

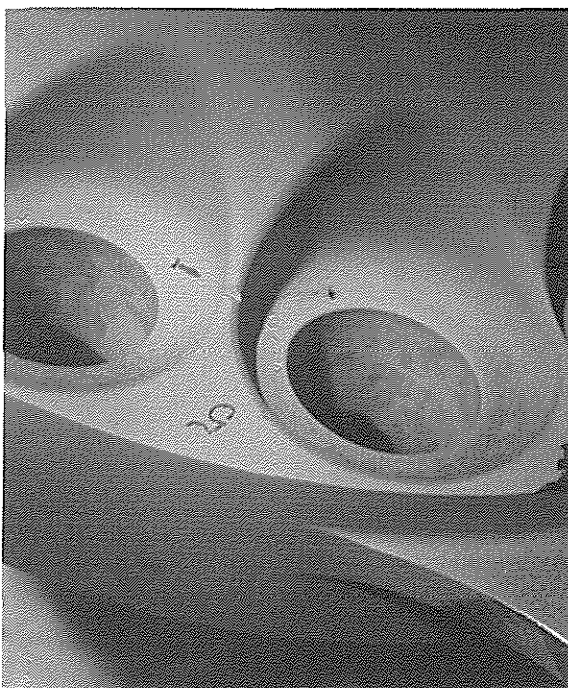


Fig.3
Notch and cracks in a web of
the B0 105 main rotor shaft

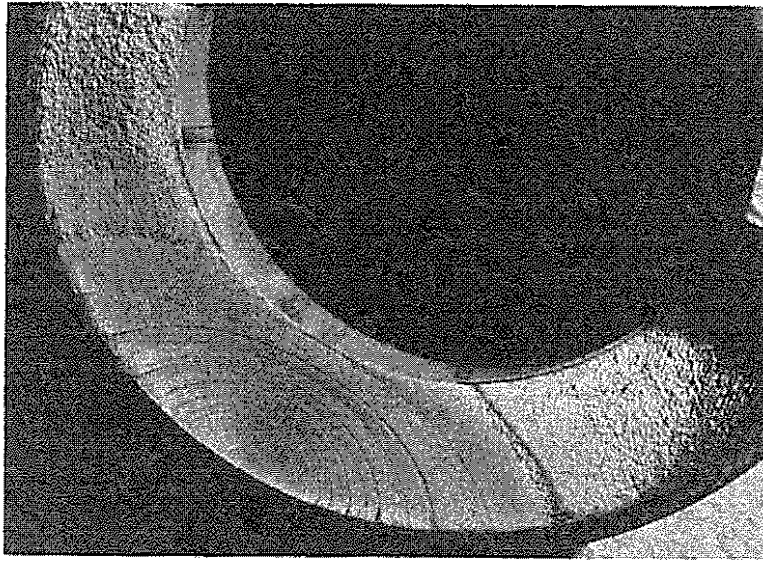


Fig. 4 Fractography of fatigue tested main rotor shaft

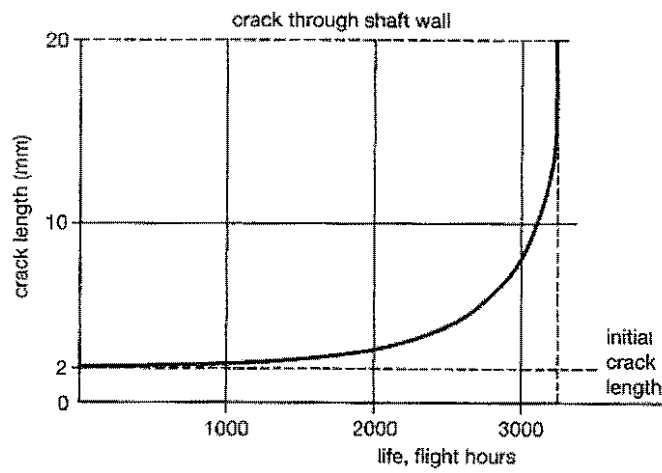


Fig. 5 Crack propagation in BK 117 main rotor shaft

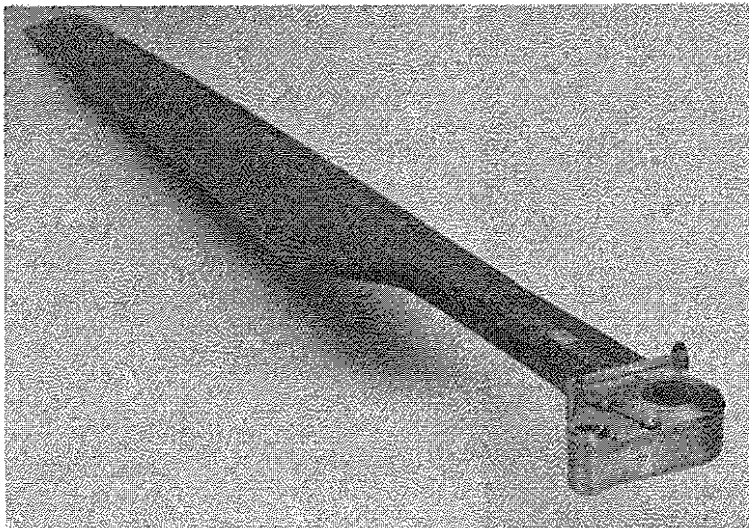


Fig. 6 B0 105 main rotor blade

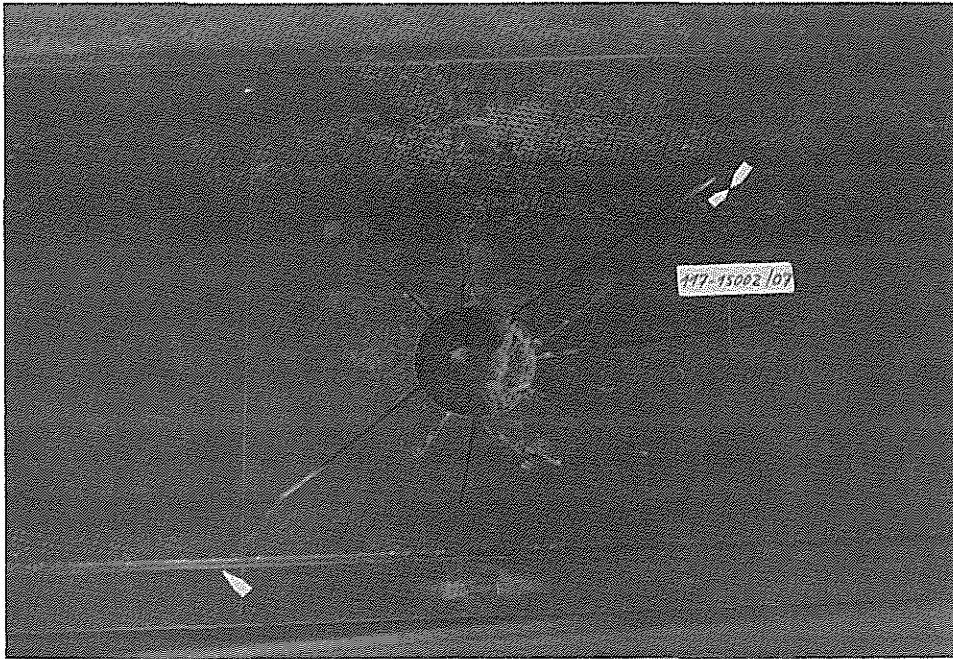


Fig. 7 BK 117 blade skin with lightning strike damage. Arrows indicate crack tips after fatigue test.

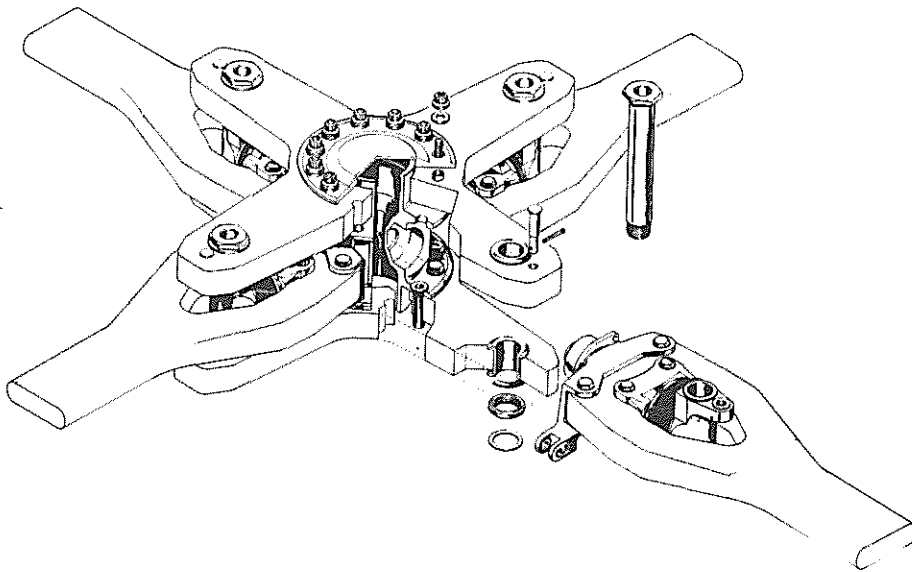


Fig. 8 FEL rotor system

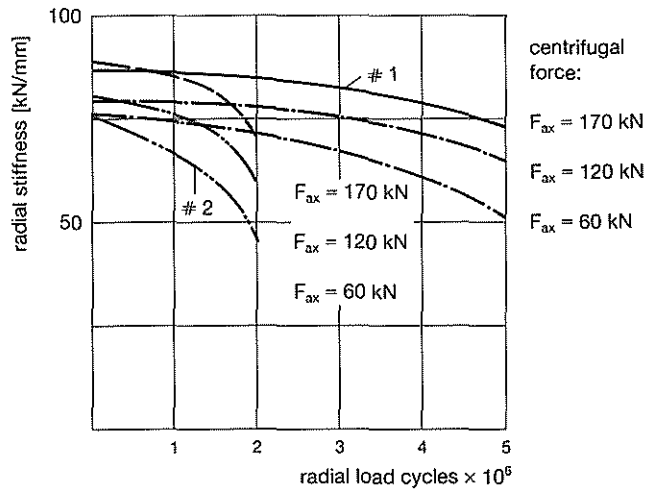


Fig. 9 Stiffness degradation of two conical elastomeric bearings

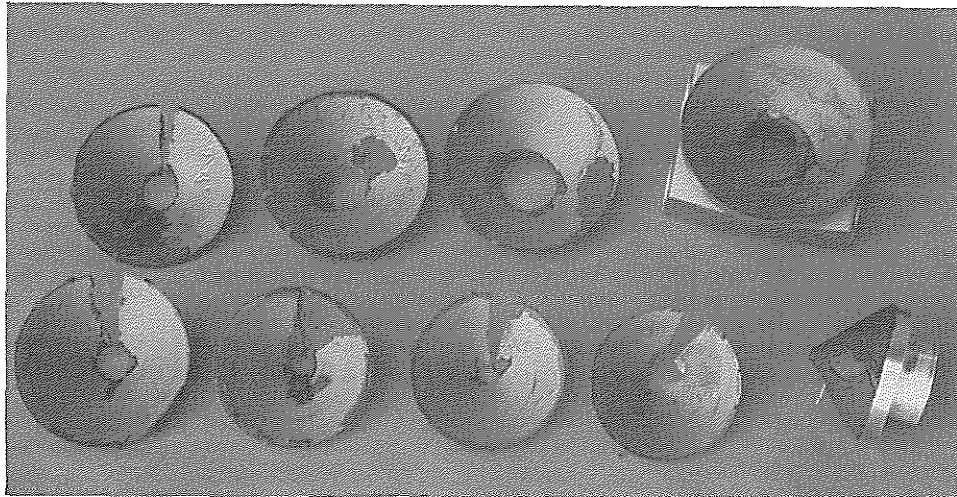


Fig. 10 Cracked shims in conical bearing

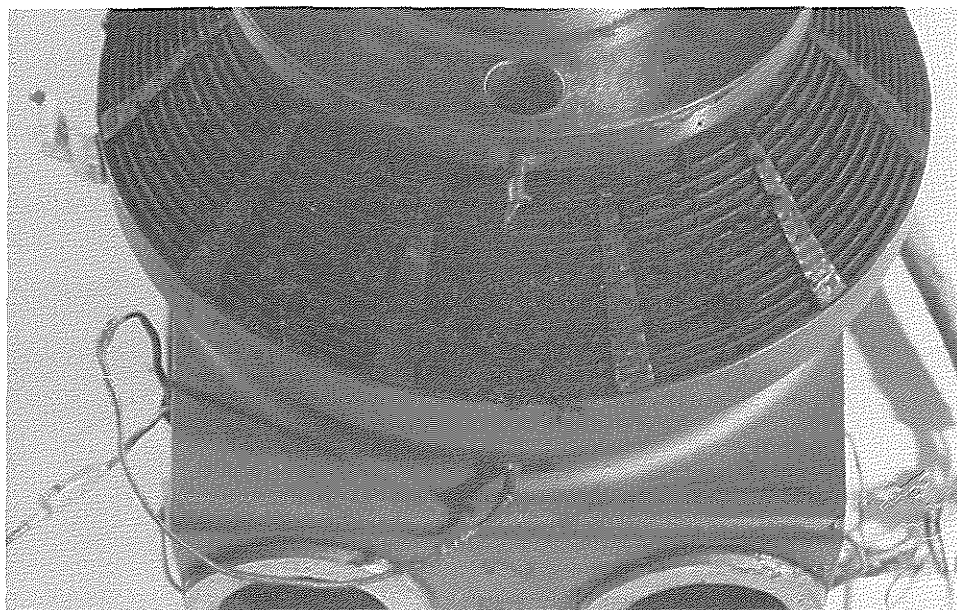


Fig. 11 Conical bearing after fatigue test with cyclic radial and torsional loads, and constant axial load

Fig.12 B0 105 Tail rotor blade with ballistic impact in aerofoil section

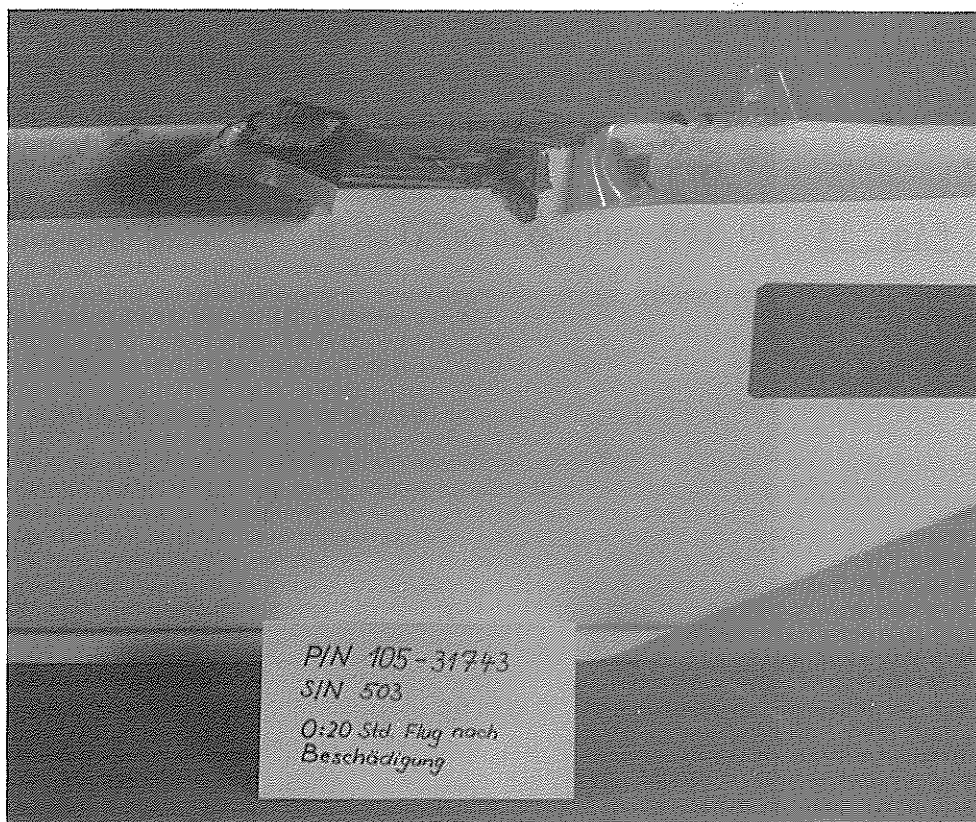
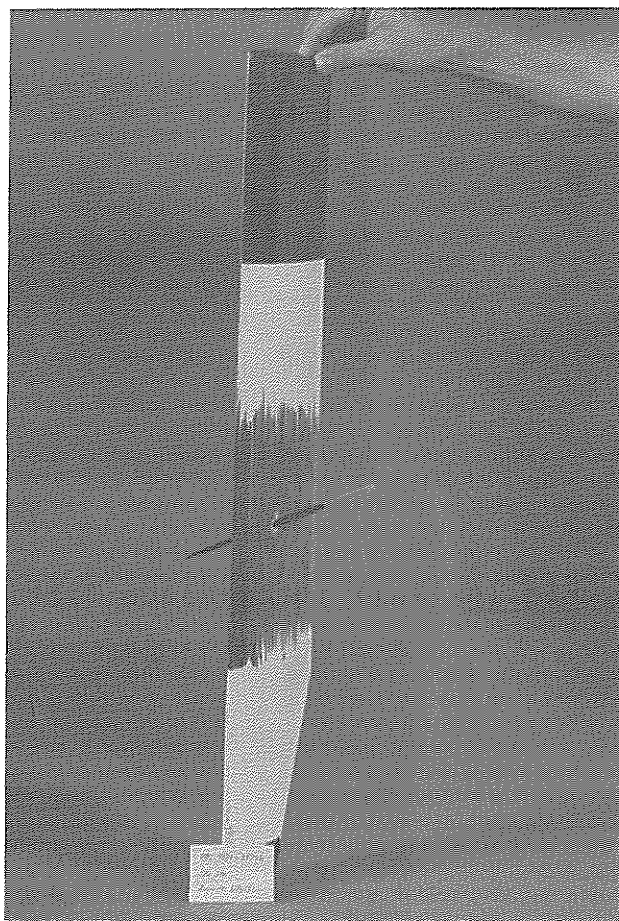


Fig. 13 Tail rotor blade with ballistic impact in leading edge

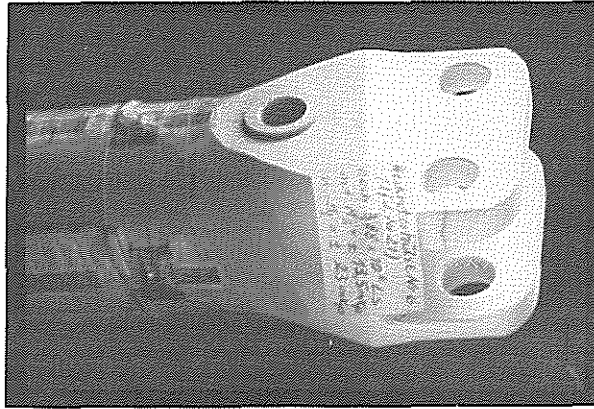


Fig.14 Tail rotor blade fitting with cracked lug (bench test)

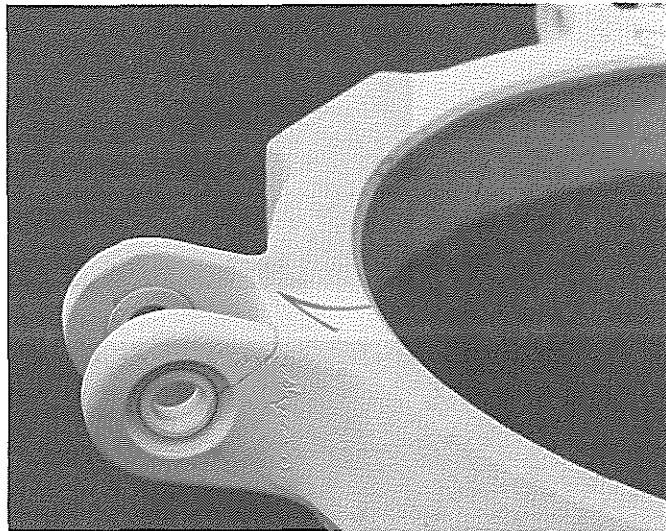


Fig. 15 BO 105 swashplate with bench test induced crack

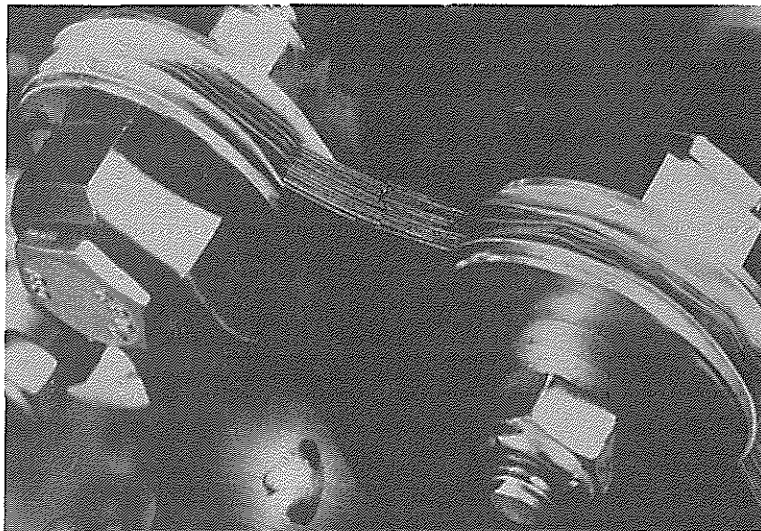


Fig. 16 Thomas-type coupling cracked in static bench test

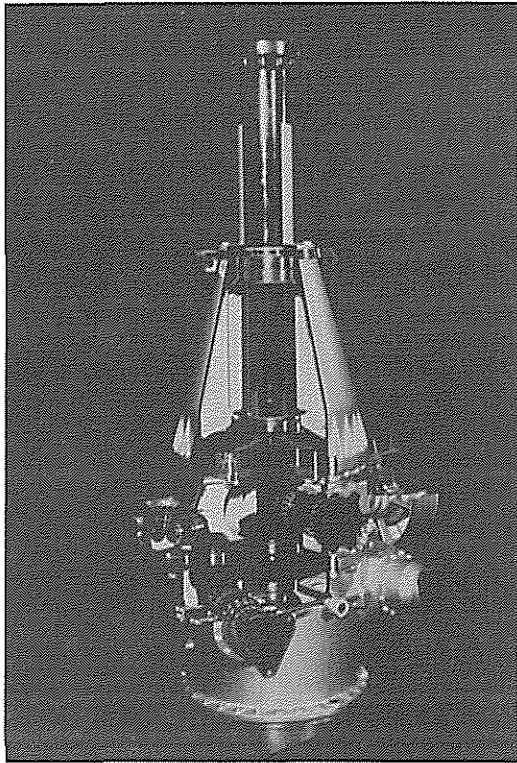


Fig. 17 BO 105 main transmission

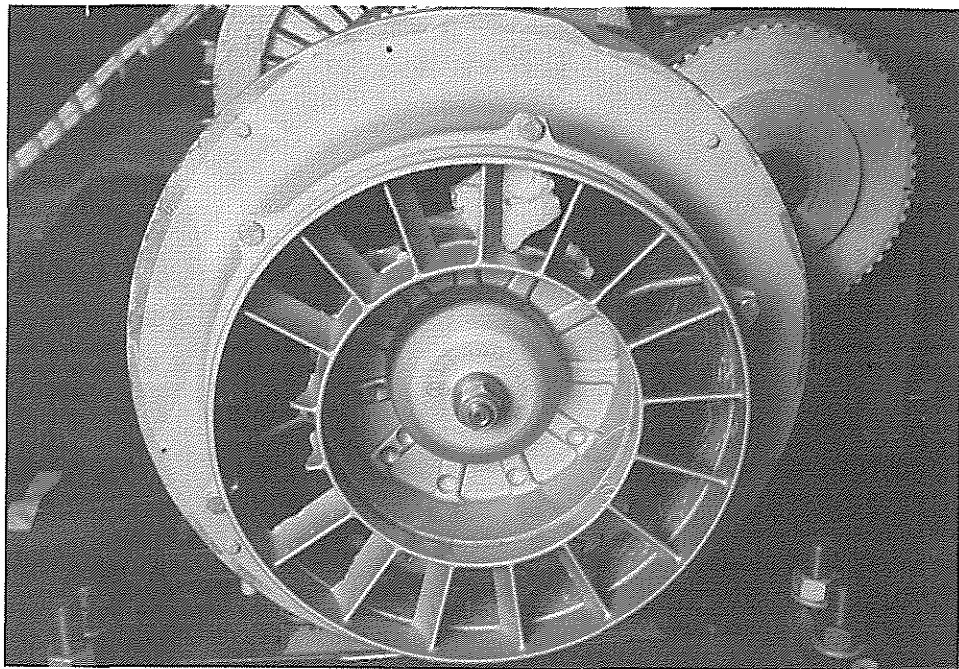


Fig. 18 Cooling fan after whirl test with artificially weakened fan blade

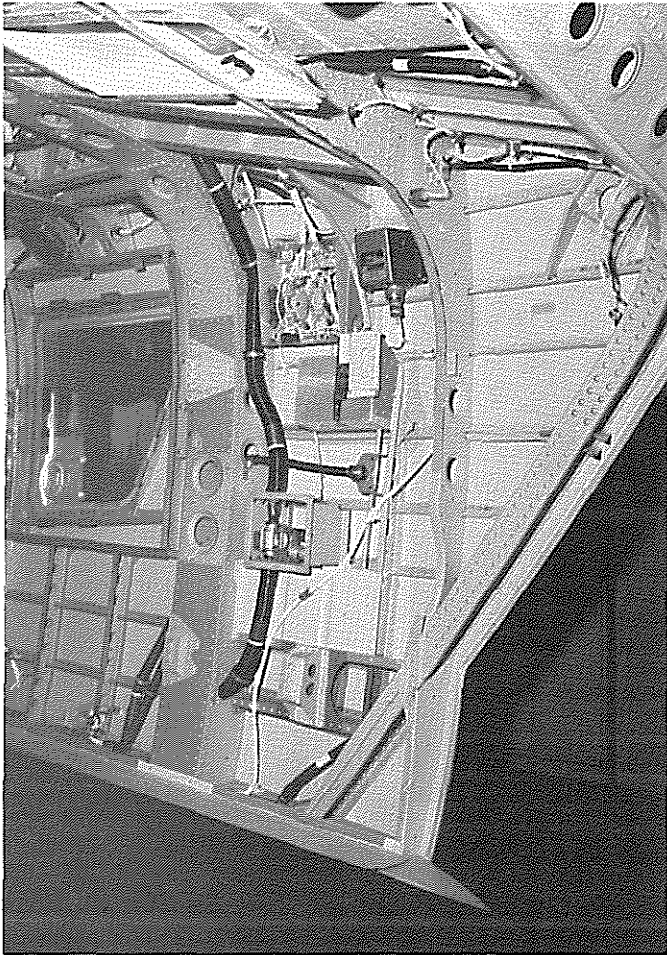


Fig. 19 Section of BK117 fuselage

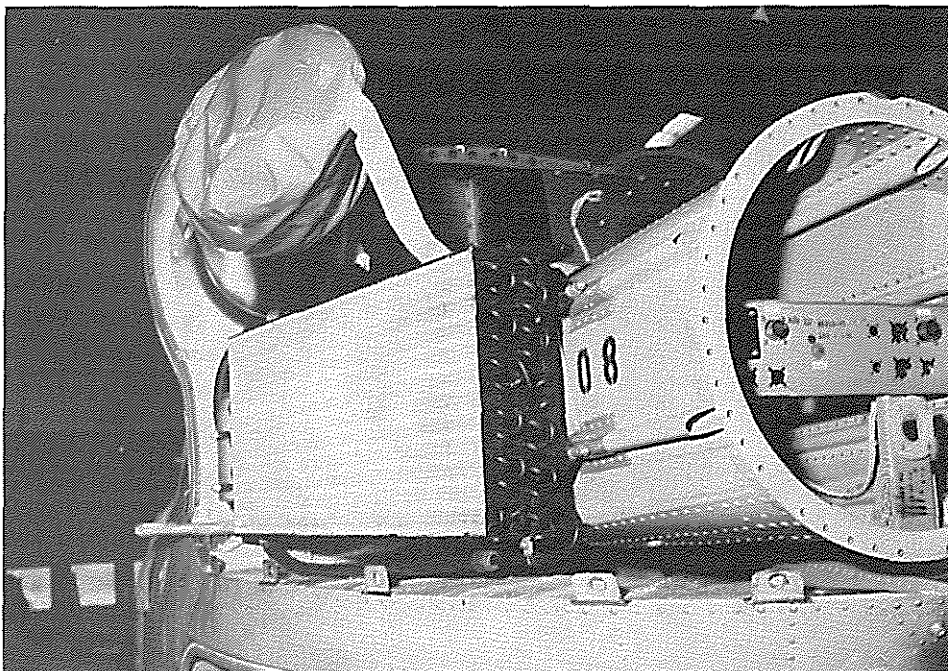


Fig.20 Multi-bolt attachment of BK 117 tail boom