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AGEING OF COMPOSITE ROTOR BLADES

F.Och

Messerschmitt-Bölkow-Blohm GmbH

Postfach 801140

8000 München 80, Germany

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Garmisch-Partenkirchen

Federal Republic of Germany

Deutsche Gesellschaft für Luft- und Raumfahrt e.V.
Goethestr. 10, D-5000 Köln 51, F.R.G.

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F.Och

Messerschmitt-Bölkow-Blohm GmbH

Postfach 801140

8000 München 80, Germany

Abstract:

To provide an adequate design data base for MBB's glass fibre rotor blades, now in service for more than 10 years; environmental effects on the design properties of the material had been established by coupon testing including temperature and artificial weathering of about 5000 hours of exposure, both unloaded and loaded.

To evaluate the long term effects of the environment on composite rotor blades, MBB is conducting a surveillance programme, where high time service main rotor blades, used in different climatic zones, are considered. Up to now blades with 2600, 3700 and 6100 hours, flown over the Gulf of Mexico and the North Sea region respectively, have been tested.

Coupon data shows a reduction in interlaminar shear strength due to accelerated ageing, whereas no weathering influence could be found on bending strength.

Composite main rotor blades following more than 6000 hours of flight time show no degradation in their properties.

1. Introduction

Composite rotor blades, as it is well known in the rotorcraft community, have matured to a powerful and economic dynamic aircraft structure, due to the performances inherent in composite materials.

The high specific static and fatigue strength in combination with the ability of composite materials to "tailor" the mechanical properties are immediately evident. These advantages as well as the flexibility to achieve the desired geometry, e.g. tapering of planform or twist distribution when desired for aerodynamic efficiency, or tapering the section thickness to thin tip aerofoils to overcome problems of high tip speed on the advancing side, or use of special shaped aerofoils such as the "droop snoots", and the ease of fabrication of smooth faired shapes, using moulds in the production process, led to very successful developments.

Design flexibility to achieve proper balance and optimum structural material placement allows for a natural frequency distribution relative to the harmonic forcing frequencies which leads to minimum vibratory loads generated by the blades, as it is with close weight and balance reproducibility. When close tuning to some frequency occurs, the higher internal damping of composites is highly effective in limiting blade response.

From working with composites, it has been learned that there is resistance to corrosion as well as to handling and impact damage, so that the servicing costs of rotor blades are low, and when failures are finally induced, they behave in a damage tolerant fashion.

- AERODYNAMIC REQUIREMENTS
 - SMOOTH FAIRED SHAPES
 - TAPERING OF PLANFORM AND/OR SECTION THICKNESS
 - TWIST DISTRIBUTION
 - SPECIAL SHAPED AEROFOILS
- DYNAMIC REQUIREMENTS
 - DESIGN FLEXIBILITY FOR TUNING
 - HIGH INTERNAL DAMPING
 - CLOSE WEIGHT AND BALANCE REPRODUCIBILITY
- STRENGTH REQUIREMENTS
 - HIGH SPECIFIC STATIC AND FATIGUE STRENGTH
 - FLEXIBILITY IN STRUCTURAL MATERIAL PLACEMENT
 - RESISTANCE TO HANDLING AND IMPACT DAMAGE
 - DAMAGE TOLERANCE
 - RESISTANCE TO CORROSION
- ECONOMIC REQUIREMENTS
 - EASE OF FABRICATION
 - HIGH DEGREE OF INTERCHANGEABILITY
 - LOW SERVICING COSTS

Fig. 1 Advantages of Composites for Rotor Blades

It must be remembered however that not all the benefits, listed in Fig. 1, can be obtained together, but they can be proven during development and structural testing. Yet the questions of ageing of composite rotor blades and of the long term effects of service environment remains open until long term experience is obtained, if no results can be drawn from artificial weathering.

2. Operational Scenario

For light multi-purpose helicopters like BO 105 or BK 117, which are or will be engaged in civilian as well as in military operations, the following types of mission must be expected [1]:

- CIVILIAN OPERATION
 - UTILITY
 - EXECUTIVE
 - RESCUE
 - POLICE
 - OFFSHORE
 - LIGHTHOUSE SUPPLY

- MILITARY OPERATION
 - LOH
 - SCOUT
 - ANTITANK

Fig. 2 Mission Types of Light Helicopters

2.1 Loading Situation of a Hingeless Rotor

For hingeless rotors, i.e. without flapping hinges it is possible to transfer high moments from the blades to the hub and the fuselage, producing high moment loading at the blade root area. This moment loading can be reduced by coning the hub arms and thus producing an unloading moment from the centrifugal forces. Normally the precone angle will be chosen for zero moment at design rotor thrust. Other thrust conditions will result in corresponding moments and it should be pointed out that these moments, primarily resulting from cyclic control inputs, are the basis of improvements in handling qualities of hingeless rotor systems [2]. Trim conditions, which need a rotor produced moment to overcome, for instance, c.g.-travel or slope landing conditions, require an alternating first harmonic moment in the rotating system for the hingeless rotor.

Higher harmonic blade loads and moments at the blade root result from unsteady aerodynamic flow conditions in forward flight. For a dynamically well-tuned hingeless rotor these higher harmonic moments are relatively low compared with the first harmonic moments needed for trim or flight manoeuvres. The main section of a hingelessly attached blade outside the attachment area normally creates no problems. The loads are lower, and there will be enough structural material, as a high moment of inertia around the rotor axis is desirable for flight dynamical autorotational behaviour reasons.

The highest loaded section of the blades of a hingeless rotor is therefore the blade root attachment area, where the following loads have to be reacted:

- centrifugal force
- flapwise bending moment
- chordwise bending moment
- torsional moment.

2.2 Environmental Conditions of Light Helicopters

Light multi-purpose helicopters have been and continue to be flown over a temperature range from less than -40°C up to more than $+45^{\circ}\text{C}$ with a relative humidity up to 100% even at the highest temperature.

It is not normally possible to average out the effects of different climates for helicopters, as they may spend their entire operational life in one locale [3].

MECHANICAL	<ul style="list-style-type: none"> o RAIN o SAND o HAIL o IMPACT 	
THERMAL	<ul style="list-style-type: none"> o LOW TEMPERATURE o HIGH TEMPERATURE o THERMAL CYCLING 	} DIFFERENT HUMIDITY
ELECTRICAL	<ul style="list-style-type: none"> o LIGHTNING STRIKE o P-STATIC 	
CHEMICAL	<ul style="list-style-type: none"> o SULFUR DIOXIDE ATMOSPHERE o CLEANER 	} DIFFERENT TEMPERATURES
PHYSICAL	<ul style="list-style-type: none"> o INFRARED RADIATION o ULTRAVIOLET RADIATION 	
ELECTRO-CHEMICAL	<ul style="list-style-type: none"> o CORROSION 	

Fig. 3 Adverse Environments for Rotor Blades

It is well known that epoxy resins absorb small amounts of moisture, causing a reduction of the temperature at which the polymer changes from a glassy to a rubbery solid (glass transition temperature). The result being a degradation in the elevated temperature matrix controlled mechanical properties of the composite such as transverse tension, compression and shear, which effectively reduces the allowable working temperature of the material.

A conservative yet realistic environment applicable to rotorcraft will be found in the humid subtropical climate of the Gulf of Mexico region. This climate has a strong maritime character and is influenced to a large degree by the amount of water surface provided by lakes, coastal marshes, flooded rice fields and the Gulf [4].

Winds are usually light and rainfall is heavy but brief in this area.

The winter months are normally mild, but usually the temperature drops to freezing or below for some days each year.

The summer months are quite warm, but maximum temperatures rarely exceed 40°C. Summer relative humidity exceeds 80% for about twelve hours per day. High humidity occurs mainly at night with 90% or more. Thunderstorms occur each month and several local storms, including hailstorms and tornadoes occur most frequently during the spring months.

The mean daily solar radiation is 36 watt hours/m².

3. Blade Description

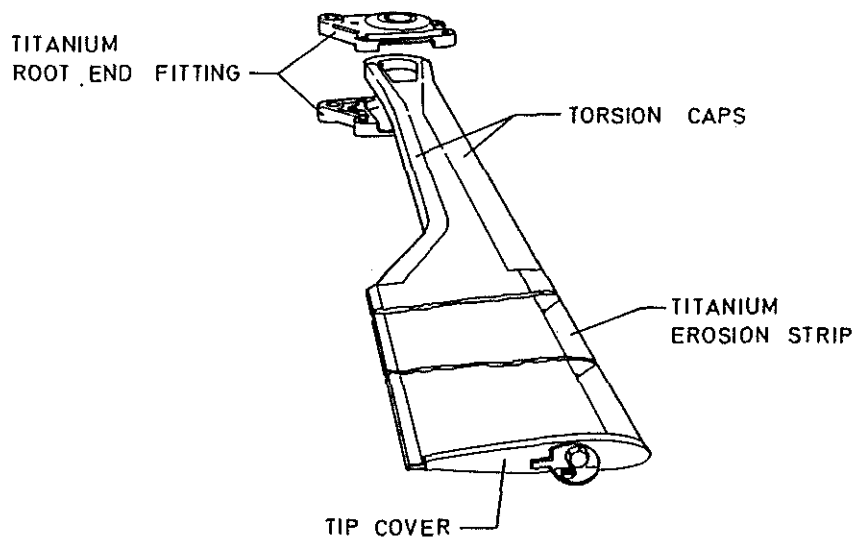


Fig. 4 BO 105 Main Rotor Blade Assembly

As shown in Fig. 4, the root end of the BO 105 main rotor blade is enclosed by a clamshell type titanium fitting and attached to the hub by main and leadlag bolts. Leading edge erosion protection is provided by a segmented titanium nose cap. To match the first inplane natural frequency, the root end area has a reduced chord ("swan neck").

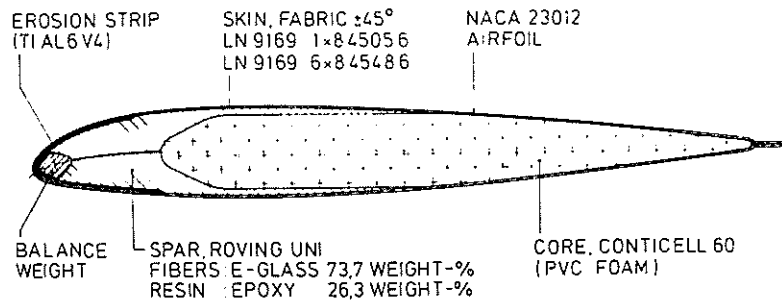
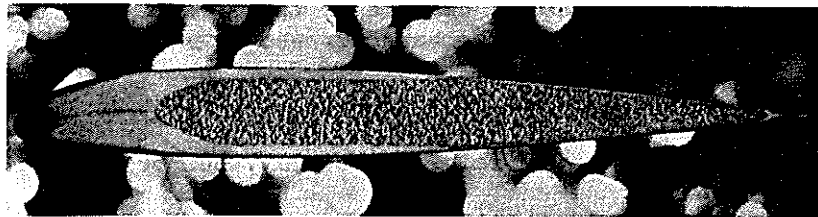


Fig. 5 BO 105 Rotor Blade Section

To fulfill the dynamic and strength requirements, the BO 105 main rotor blade is built up of the following structural parts:

- spar, made of unidirectional E-glass, contributes to flapwise (77%), chordwise (40%), and torsional (32%) stiffness and reacts centrifugal forces as well as bending and twisting moments;
- skin, made of $\pm 45^\circ$ orientated E-glass fabric, contributes to chordwise (52%), torsional (44%) and flapwise (14%) stiffness and reacts twisting and bending moments;
- core, made of modified PVC foam, contributes to torsional stiffness (12%) and prevents skin buckling when bending and twisting moments are applied;
- erosion strip, made of TiAl6V4, contributes to torsional (12%), flapwise (9%) and chordwise (8%) stiffness, joins the upper and lower skins and provides the necessary leading edge protection;
- balance weight, made of lead, to position the centre of gravity near the quarter chord line.

4. Testing of Environmental Effects

As the rotor blade is subject to alternating loads, testing is mainly concentrated on fatigue strength establishment.

4.1 Artificial Weathering

In order to take care of any influence on mechanical properties induced by the manufacturing process, all coupon specimens were cut out of production blade spars from various stations and differed mainly in the length to height ratio, relating to bending and shear failure respectively.

The specimens of unidirectional E-glass were exposed to the following three variations of artificial weathering:

Climatic Condition No. 1:
x hours at 90°C and 70% relative humidity
(x = 10 resp. 100 resp. 1000)

Climatic Condition No. 2:
1 cycle = 168 hours
= 4 · (15 hours at ultraviolet radiation + 9 hours
water submersion) + 72 hours at 70°C

Climatic Condition No. 3:
1 cycle = 168 hours
= 4 · (10 hours at 72°C and 92% relative humidity +
+ 14 hours at -40°C) + 10 hours at 72°C and
92% relative humidity + 62 hours at 23°C
and 50% relative humidity.

To evaluate the influence of loading, climatic condition No. 3 was also conducted with additional applied stresses of 400 N/mm^2 in the bending fatigue specimens and 10 N/mm^2 in the shear fatigue specimens. The size of the coupons and the test fixture configurations are shown in Fig. 6.

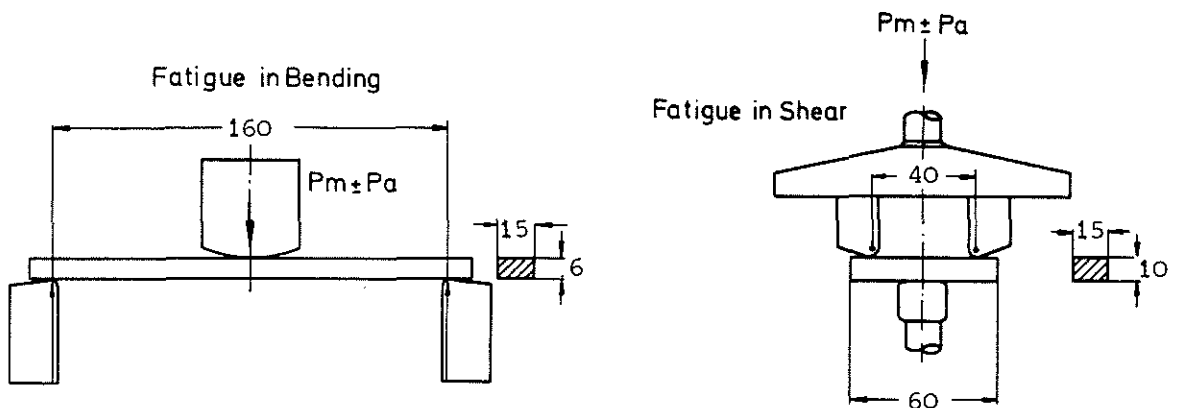


Fig. 6 Bending and Shear Fatigue Testing

From bending fatigue tests no adverse influence of artificial weathering on bending strength could be found. This result was expected as fibre controlled mechanical properties do not show a degradation when the material has absorbed moisture.

Fig. 7 summarizes the endurance limits (values at 10^8 cycles and $R=0.11$) of each preconditioned data set plotted versus number of cycles or hours of climatic exposure of the shear fatigue specimens.

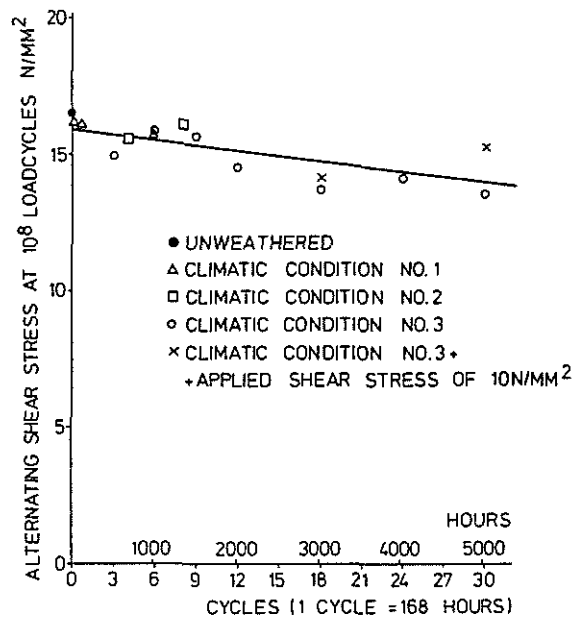


Fig. 7 Artificial Weathering Effects on the Shear Fatigue Strength

The conclusions which can be drawn from the data in Fig. 7 are:

- for the duration of ultraviolet radiation and water submersion included in climatic condition No. 2 testing, no degradation is evident;
- the data from climatic conditions No. 1 and No. 3 falls within the same scatter, and after about 5000 hours exposure, there was an average 12% reduction in endurance limit;
- loading the specimens during environmental preconditioning does not appear to be a significant variable.

Short beam bending tests were also conducted at -40°C , 30°C and 70°C respectively to evaluate the effect of test temperature on static and fatigue shear strength. From the data of Fig. 8 it is observed that test temperature effects both static and fatigue strength by the same amount, i.e. about 25% higher shear strength at -40°C and about 25% lower shear strength at $+70^{\circ}\text{C}$ in comparison with room temperature.

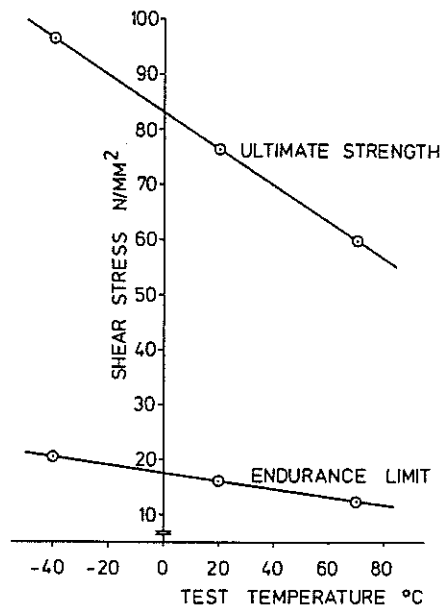


Fig. 8 Test Temperature Effects on Shear Strength

4.2 Service Usage

To evaluate the long term effects of the environment, MBB is conducting a surveillance programme, where high time service main rotor blades, used in different climatic zones, are considered. Up to now blades with 2600 (S/N 684) and 3600 (S/N 263) flight hours flown in the U.S.A. over the southern coastal region of Louisiana and the Gulf of Mexico as well as blades with 3700 (S/N 220) and 6100 (S/N 224 and 231) flight hours flown in the U.K. over the North Scottish coastal region and the North Sea have been or are going to be tested.

4.2.1 Blade Inspection

An inspection, according to BO 105 Maintenance and Overhaul Manual, was performed on the blades in the as-received condition. The inspection, which included visual and coin tap analysis revealed some areas of erosion and local debonding. The majority of the visual inspection findings are representative of normal service wear. All blades showed indications of delaminations in the torsion caps near the root end fitting, but it could be said that they were in a flightworthy status.

4.2.2 Natural Frequencies Determination

To avoid relatively high vibratory loads, the natural frequencies must be well tuned in relation to the harmonic forcing frequencies. This proper tuning is done by choosing materials with the right mechanical properties and by proper placement of these materials.

Any adverse influence of service usage, on the elastic properties of composite rotor blades can be checked by natural frequency measurements. This was done with the blades with 3600 flight hours and 6100 flight hours respectively for the first and second flapwise and the first chordwise frequency. The blades were installed in a clevis arrangement attached to a rigid fixture, which cantilevered the blade by main and lead lag bolts at the root end. The blades were bent according to the mode shapes of the corresponding frequencies. When released they produced an oscillation which then was allowed to diminish in free decay, measured by strain gauges.

The results of the blade frequency tests are presented in Fig. 9. It can be seen that frequency measurements from new and used blades are within the same scatter. These tests also show considerable scatter of the 1. chordwise frequency due to the BO 105 specific attachment design.

BLADE S/N	DATE OF FABRICATION	FLIGHT HOURS	SERVICE AREA	NON-ROTATING FREQUENCIES IN HZ		
				1. FLAPWISE	2. FLAPWISE	1. CHORDWISE
50/55/56/57	1/70 - 2/70	1000	OTTOBRUNN	NOT MEASURED	NOT MEASURED	3.02±0.15
201/209/211/221	11/70 - 12/70	1200	"	"	"	3.07±0.17
238/241/247/250	3/71	1200	"	"	"	3.38±0.27
224	2/71	6100	NORTH SEA	1.02	6.17	3.60
231	2/71	6100	"	1.02	6.17	3.50
263	4/71	3600	GULF OF MEXICO	1.03	6.20	3.10
3273	7/79	0	—	1.06	6.19	3.20
3517	11/79	0	—	1.05	6.25	3.05
3923	7/80	0	—	1.04	6.17	3.20

Fig. 9 BO 105 Main Rotor Blade Natural Frequencies

4.2.3 Full Scale Fatigue Testing

Full scale fatigue tests are conducted with the root end and the aerofoil section of the blade [5].

The root end section specimen consists of blade section inboard of aerofoil section, titanium attachment fitting, main and lead lag bolts as well as titanium inner sleeve. The outboard end of the specimen is built up with loading doublers and load application attachments, where flapwise, chordwise and torsional loadings are applied by eccentrics. An axial steady load which simulates centrifugal force is also applied to the specimen. Specimen and test bench are shown in Fig. 10 and Fig. 11.

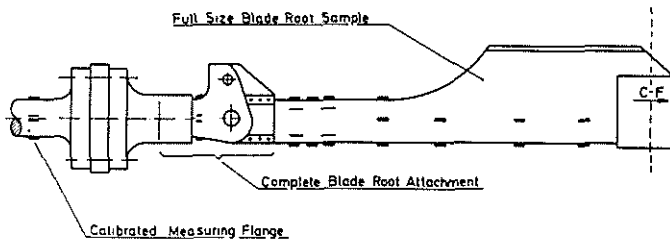


Fig. 10 Blade Root Specimen

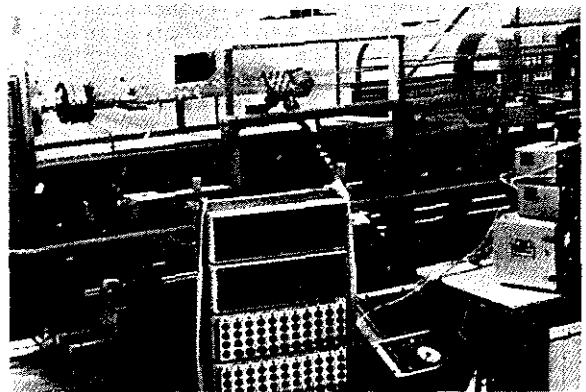


Fig. 11 Test Bench for Blade Root Testing

To demonstrate the damage tolerance characteristics of used blades, testing on the blades S/N 684 and S/N 220 was carried out with flight loads.

After 400 000 cycles of the 2600 hours blade the delaminated torsion caps showed indications of cracks and therefore were removed for inspection of the spar, but no damage could be found and the test was stopped.

After about 1 million cycles the 3700 hours blade also showed cracks in the torsion caps, but testing was continued with very low crack propagation in the caps up to more than 15 million cycles without any decrease in stiffness. Thereafter the load was increased by nearly 50% and the crack propagation accelerated. The test was stopped after 2.5 million cycles of elevated loading with a crack length in the caps of more than 200 mm and a stiffness reduction of more than 10%.

The two other blades were tested with relatively high loads up to 1.35 (S/N 263) resp. 0.5 (S/N 224) million cycles with cracks in the torsion caps. With this load new blades failed between 10^5 and 10^7 cycles. The

test with the used blades is interrupted to make inspections with Computer-Tomography and will be continued thereafter.

The blade's aerofoil section, where centrifugal forces are low and flapwise bending predominates, is tested on the blade resonance test bench in flapwise bending. In this machine the first free-free mode is excited by an eccentric at a point near a node, whereas the blade is supported at another node of its flapwise bending mode. The amplitude is controlled by the stroke and the speed of the eccentric. Specimen and test bench are shown in Fig.12 and Fig.13.

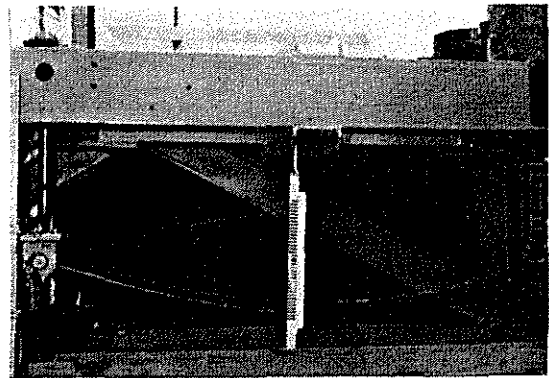
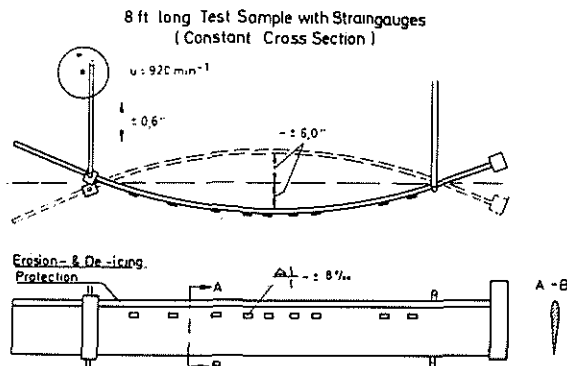


Fig. 12 Aerofoil Section Bending Specimen

Fig. 13 Resonance Test Bench

After more than 14 million cycles at 0.6% alternating strain which is equivalent to a bending stress of 250 N/mm^2 in the blade spar or 60 N/mm^2 in the blade skin, the aerofoil section of the blade S/N 684 shows no failure.

The aerofoil sections of blades S/N 224 and S/N 263 have not yet been tested.

The results from full scale fatigue testing indicate that there is no adverse influence of service usage on composite rotor blades.

4.2.4 Coupon Testing

Fibre composites may fail either by a fibre failure or by a failure of the matrix or the interface of fibre and matrix. Two different types of coupon specimens are therefore tested, which were cut out of the spar of service used blades.

Three point bending of relatively slender specimens (Fig. 6) leads to high stresses in the glass fibres on the upper and lower surface, thus

producing fibre failure. The data points and the regression curve for a stress ratio of $R = 0.2$ are presented in Fig. 14. Results of specimens (marked with triangles) which were cut out of the blade S/N 684 are well within the scatter of specimens cut out of new blades.

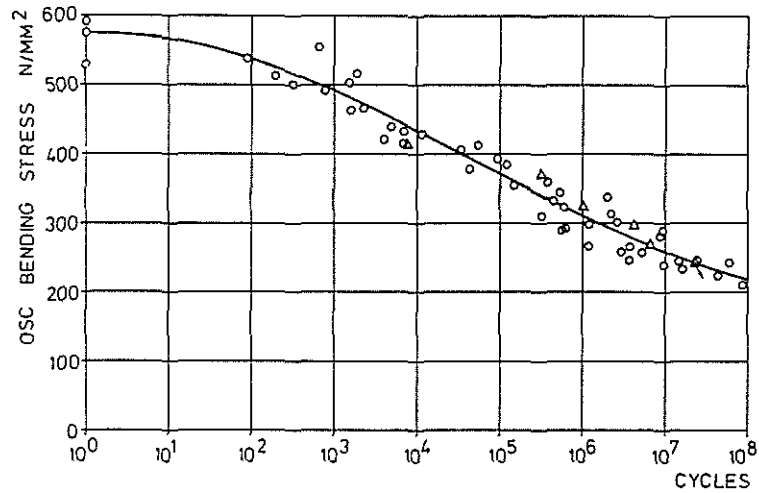


Fig. 14 Bending Fatigue S-N Curve

Three point bending of shorter specimens (Fig. 6) leads to high inter-laminar shear stresses in the neutral plane of the specimen which produces matrix or interface failure. The data points and the regression curve for a stress ratio of $R = 0.11$ are presented in Fig. 15. Results of specimens (marked with triangles) which were cut out of the blade S/N 684 are well within scatter of specimens cut out of new blades.

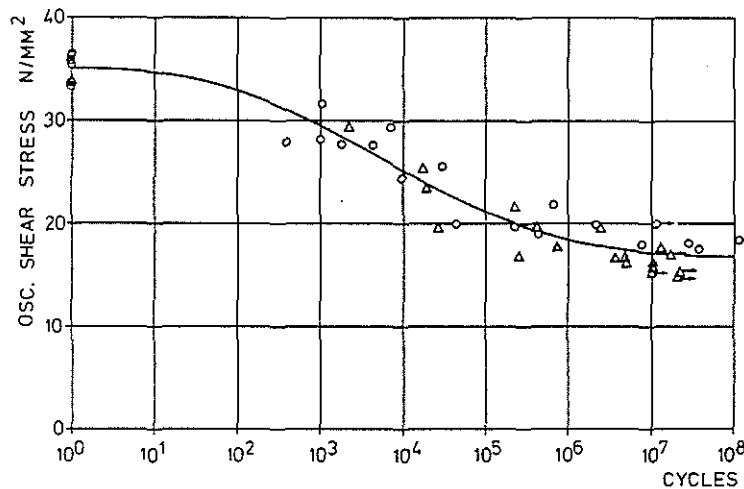


Fig. 15 Shear Fatigue S-N Curve

5. Concluding Remarks

From 20 years experience at MBB, with composite rotor blades being in service for 10 years, with the "fleet-leader" blades having more than 6000 flight hours, and from testing of numerous coupons cut out of rotor blades, the following conclusions can be made:

- generally the advantages expected from composite material are fulfilled, making it, when properly designed and produced, the best structural material for rotary wing applications [6];
- successful development of the hingeless rotor, used for the BO 105 and BK 117, has mainly evolved from utilising mechanical properties for the rotor blades inherent only in composite materials;
- composite materials are susceptible to both rain and sand erosion and rotor blades must therefore be protected at the leading edge and blade tip areas;
- impact strength of composite rotor blades is reasonably good, which can be deduced from service experience, where main rotor blades cut off branches in excess of 50 mm without any damage to the blades;
- artificial weathering of coupon specimens shows a significant reduction in endurance limit of matrix controlled properties after sufficient time of exposure;
- up to more than 6000 flight hours in different climatic zones no adverse effects of the environment on composite rotor blades could be found, neither with full scale components nor with coupon specimens cut out of used blades;
- as all high time blades showed varying quantities of delaminations in the torsion caps near the root end fitting, MBB decided to add wrapping layers in this area, after fatigue tests had shown that they could prevent the delaminations propagating even with high loads applied.

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