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STRUCTURAL DESIGN AND ANALYSIS ASPECTS OF COMPOSITE HELICOPTER COMPONENTS

Wolfgang Buchs
Horst Bansemir

Messerschmitt-Bölkow-Blohm GmbH
Ottobrunn, West Germany

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THE CITY UNIVERSITY,LONDON,ECIV OHB,ENGLAND

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W. Buchs
H. Bansemir

Abstract

Fibre reinforced composites can be widely used in helicopter structures such as cowlings, empennages, fuselages,main- and tailrotors. Lower weight and costs are the benefits for using these materials. In addition they offer the possibility of the realisation of new hingeless and bearingless rotor concepts. The reason for these developments is their simplicity which improves the reliability and reduces weight and costs.

Different rotor blades have already been developed for helicopters, wind tunnels and wind energy converters. The requirements for the dynamic behaviour of the rotors are reached with the advantage of high fatigue strength.

Several manufactured empennages and fuselage substructures show that extreme light-weight structures with a good resistance against damage and crack propagation can be designed.

The stiffness and stress distributions as well as the strength of the composite structures are calculated with the help of theoretical models. Using unidirectional composite material data the mechanical behaviour is studied and by using special failure criteria the strength of the components is determined. The results of the theoretical analysis are verified by component tests.

1. INTRODUCTION

Reading recent publications one can get easily the impression, that structural technology is entering a new area in these days:

- all sailplanes at the 1985 world championship were made of composites
- competition yachts are made of composites
- automotive industry is applying composites more and more
- modern business, transport and fighter aircraft contain more composites than in the past
- many helicopter manufacturers have development programmes for a wider use of composites in rotor and fuselage structures.

This publication shall shortly introduce structural designs and analysis aspects of various areas of the application of composites in helicopters, as it is presently state of the art.

2. BASIC DESIGN AND ANALYSIS ASPECTS

2.1 Design Aspects

About ten years ago everybody was delighted by the advantages of composites in structures

- high strength and stiffness to density ratios
- high fatigue life
- smooth surfaces
- low crack propagation after impact
- free of corrosion

Concerning material prices, the compared to metal structures high level was expected to decrease considerably with wider application. Consequently many manufacturers introduced composites in rotorblades and secondary structures(substituting metal structures) and gathered service experience.

Today we are facing a slightly changed situation, as the expected decrease of material prices has ended at a level, which is still at a factor above the one of metals.

Therefore, in order to be competitive with metal structures, the composite designer has to arrange a well-balanced compromise of technical advantages and the cost situation. Although it is obvious that some technical advantages like high fatigue life yield low in-service costs, the composite designer must also offer a manufacturing price (material,manhours, share in tooling etc) which is at least not higher than the one of a corresponding metal structure.

As a rule of thumb presently a mass saving of 20% and a cost saving of 10% to 20% as design goal at the beginning of a composite component development can be taken. A possible higher amount of mass saving would spoil the envisaged cost improvement.

Regarding the higher material prices: How can a cost saving be achieved at all?

First of all labour costs for part manufacturing have to be looked at. The composite component should be free of compromises coming from metal semiproducts. A double curved shape e.g. in the most cases impacts only the tooling costs and not the labour costs.

Additionally the costs for posttreatment should be limited. The ideal composite component drops out of the mould,ready for integration. Post-treatment is limited to removing excessive matrix and peel-ply fabric at areas to be bonded.

The *joining* costs are the second area in which composites can save money. Large composite units with integrally cured stiffeners, load introductions etc. obviously comprise lower joining costs as similar metal structures, which are composed of many small parts.

Concerning the tooling costs specially the tooling concepts for prototype manufacturing had ben reconsidered in the last years. "Soft" composite tooling, suitable for manufacturing some 5 to 10 prototype parts were developed. They can be manufactured at low costs and easily modified, if the prototype testing requires a change.

2.2 Analysis Aspects

Development work was performed on many fibre composite helicopter components for a long time. As in different components different fibre and resin materials were used, main emphasis was laid in the beginning on a material data bank for unidirectional fibre composite layers. With the help of these data static and dynamic analysis can be performed using laminate stiffness and strength theories.

As the main- and tailrotor can be considered as the most important components of a helicopter, most of the basic analysis was concentrated on these fibre composite structures.

Finite elements were derived in order to calculate the shear center as well as the shear stresses due to transverse shear and torsion loading. Specially for the design of "flex beams" of rotor systems the correct prediction of shear stresses and shear stiffnesses are mandatory. Beyond, this cross section analysis program allows the determination of all important data for the design of blades /1/.

For the root areas of the blades and rotor hub plates SN-curves were investigated for glass and carbon quasi-isotropic laminates /2/. For thick laminates, Figure 1 shows little influence of studied manufacturing procedures on the dynamic interlaminar shear strength.In Figure 2 four SN-curves are given: two with glass fibre laminates and two with carbon fibre laminates. One of each type is cut out of a sample plate with an optimized curing cycle and the other one is out of a plate built for a rotor hub. The SN-curves for carbon fibre composites show about 30% higher values than the ones made of glass fibres. The difference of the shear strength between sample and component is negligible.

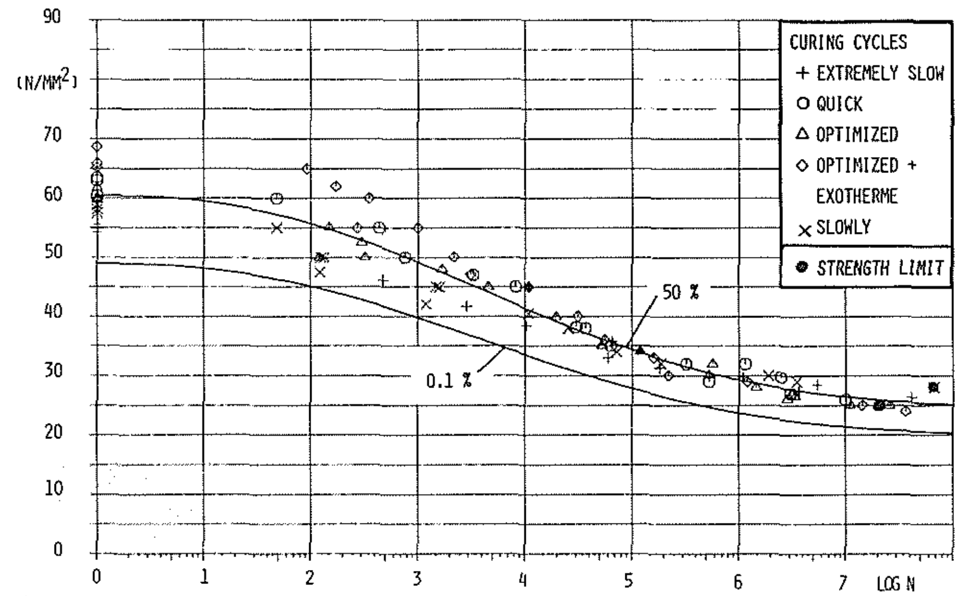


Fig. 1: SN-curve measured with samples with various curing cycles

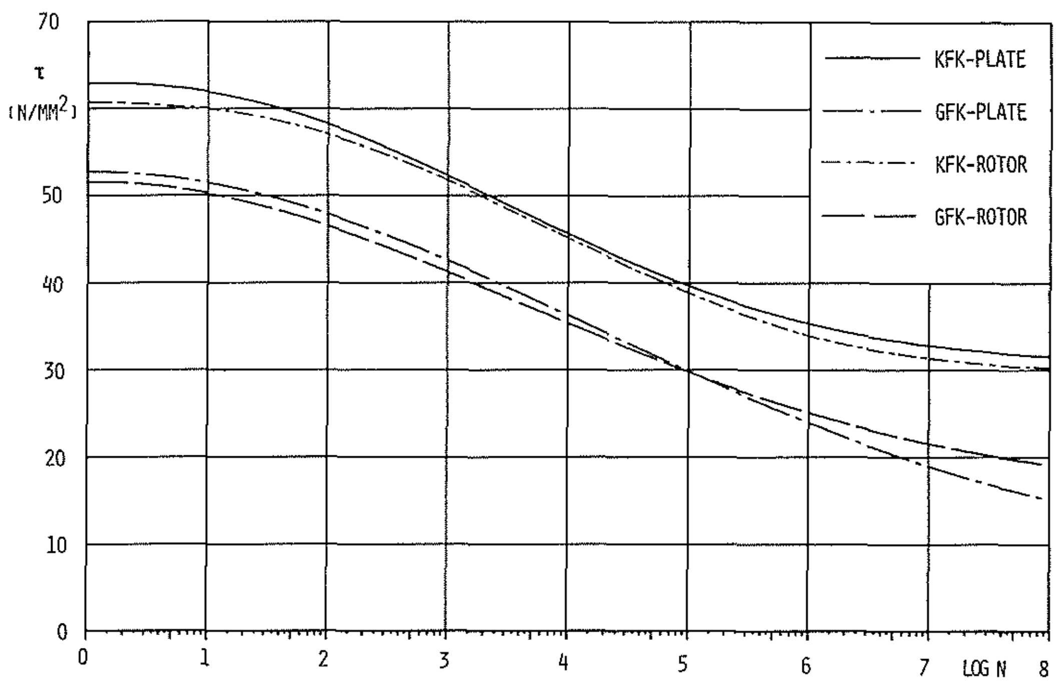


Fig. 2: SN-curves of GFC and CFC samples with the optimized curing and out of rotor hub plates

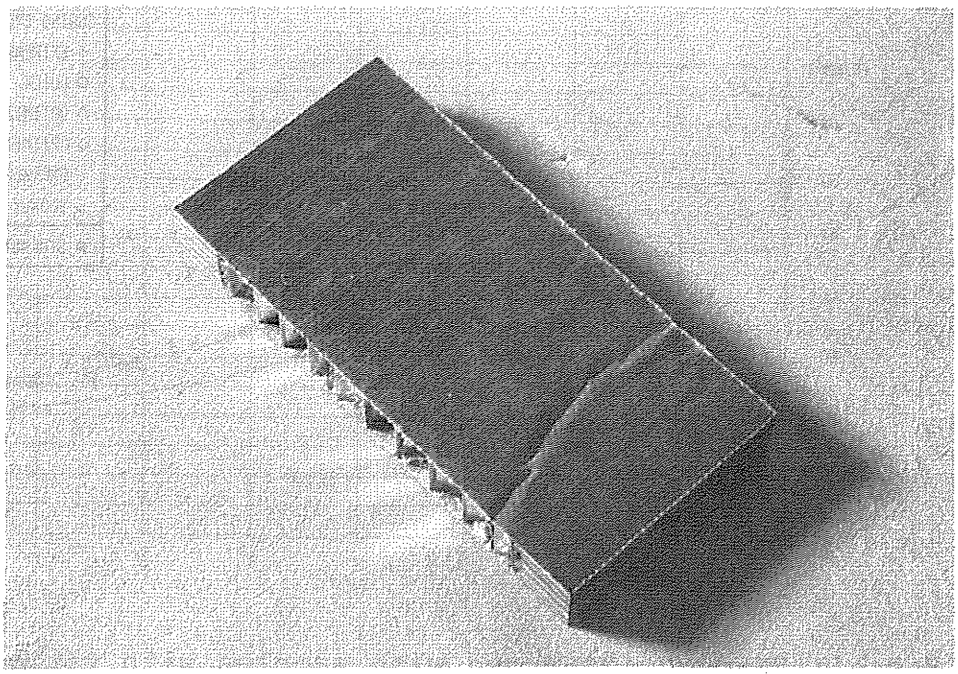


Fig. 3: Wrinkling failure mode of sandwich fibre composite sample due to compression

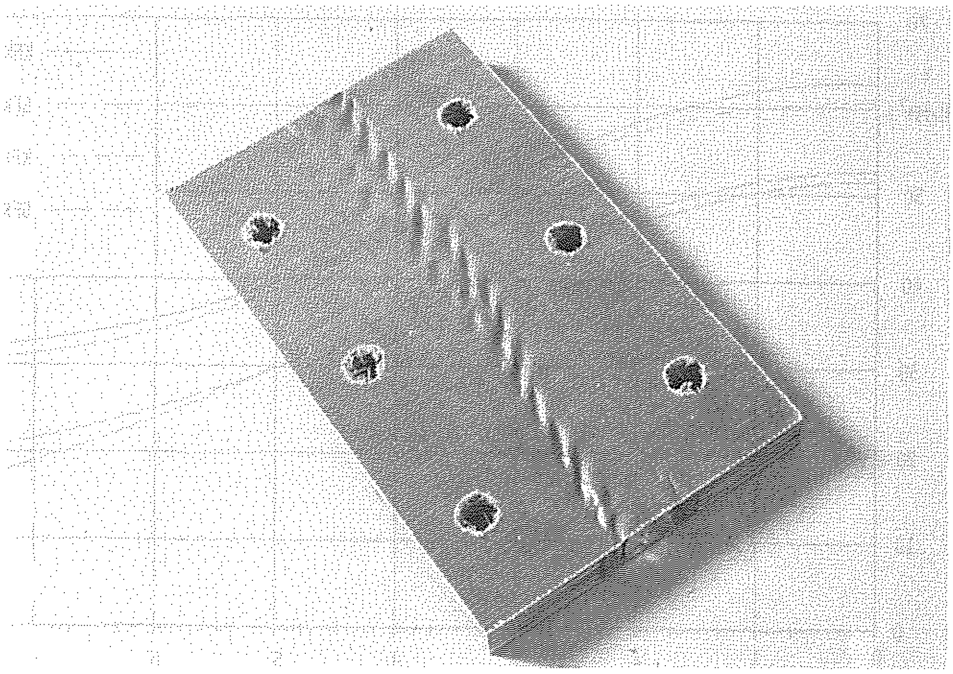


Fig. 4: Wrinkling failure mode of sandwich fibre composite sample to to in-plane shear

For fuselage structures sandwich constructions are used by MBB. The often occuring failure mode of these structures is wrinkling of the face sheets due to compression and shear. Basic theories of the stability failure modes were derived for sandwich structures and correlated to test results /3/. The analysis allows a good prediction of ultimate strengths of such structures.Wrinkling failure modes see Figures 3 and 4.

3. ROTOR SYSTEMS

Composite materials were intensively used for the design of main- and tailrotor systems at MBB /4/. The aim is to eliminate all attachment bearings, especially the lubricated ones, by using the advantages of the elastic and strength properties of composite materials. For a long time the BO 105 helicopter has been using a hingeless rotor system. But a lubricated bearing that allows pitching angles is still used.

In order to eliminate the pitch bearing and to simplify the attachment to the rotor shaft, a composite tail rotor was developed and flown on the helicopter BK 117 (Figure 5) /5/.

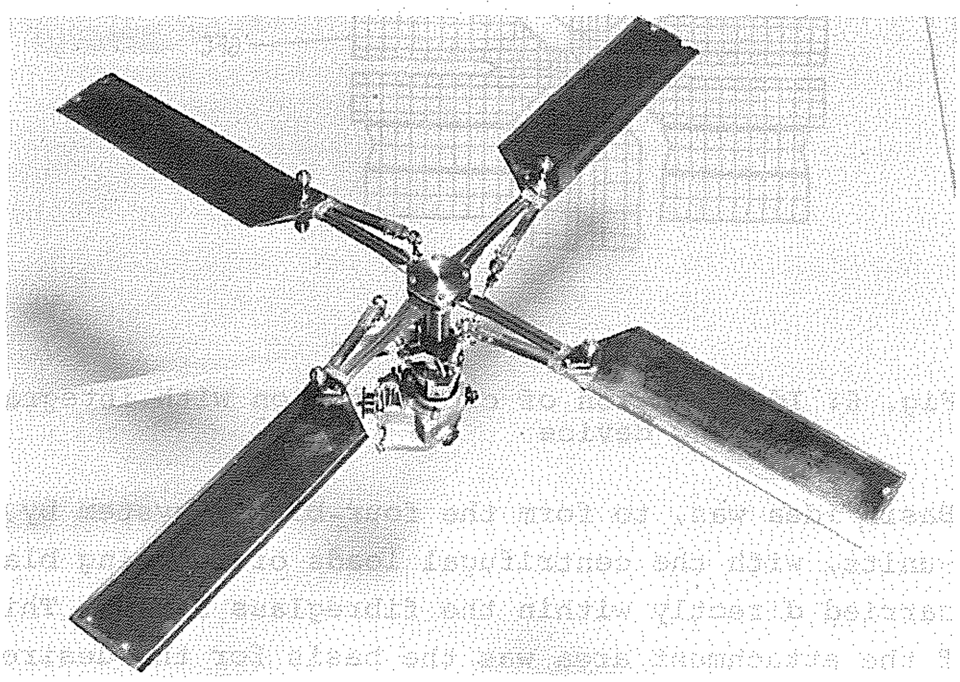


Fig. 5: Bearingless tailrotor

Three specialized elements were used for this design:

1. An element with low torsion stiffness and a high lead-lag and flapping stiffness
2. A flat, rectangular plate, forming the "flap hinge"
3. A central specially shaped plate which transfers the torque to the blades (Figure 6).

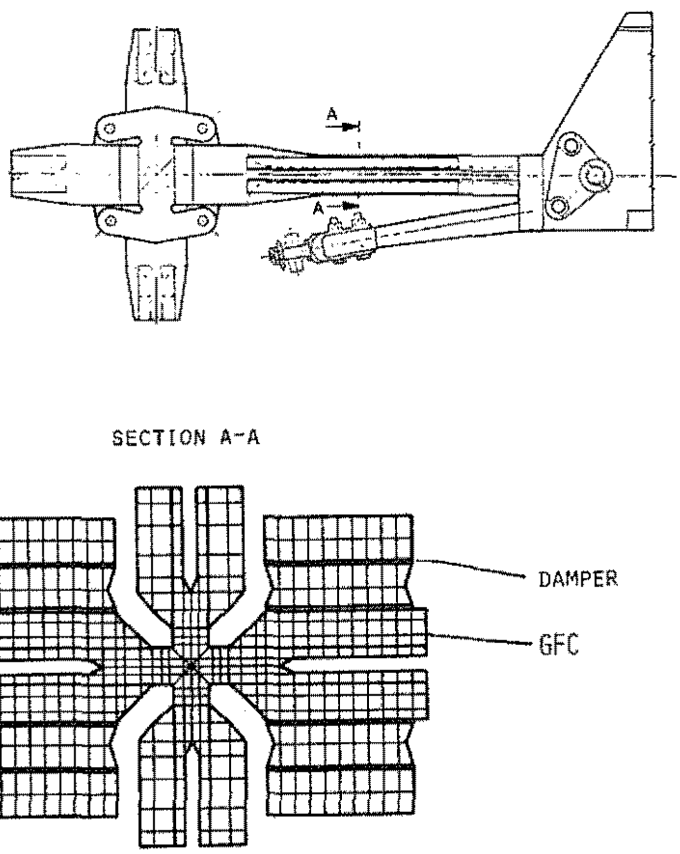


Fig. 6: Idealization of cross section with integrated damping device

Basic idea was, to form the four-bladed system by two double-units, with the centrifugal loads of opposing blades being carried directly within the fibreglass straps. This design of the attachment area was the basis for the desired flow flapping stiffness of this tailrotor. In Figure 6 an idealization of a cross section with an integrated damping element is shown. The design of the damper consists of two carbon fibre plates bonded to the blade with a viscoelastic damping layer in between. The pitch angles are applied with the help of a pitch horn with high bending stiffness and low mass. For the prediction of the stresses a two dimensional finite element analysis was performed. The stresses were lower than the strength of the material.

For this design the torsional stiffness was found to be lower than specified. Analytical work is now concentrated on optimizing the attachment area including the "flap hinge": The strain per degree flapping angle should be as low as possible. Two main possibilities are used by MBB to reach this goal:

1. The design of a carbon glass hybrid element, which includes the "flap hinge". The reduction of strain is gained because most of the centrifugal force is transferred by the carbon fibre area whereas the flapping moments are mainly transferred by the glass fibre area.
2. The attachment element will be optimized with respect to stresses by changing geometric dimensions. Constantly distributed stresses in radial direction due to flapping moments will be the result.

For modern mainrotors MBB has two different concenpts: An all composite rotor without lubricated bearings and a rotor with elastomeric bearings. The first one uses a flex beam, similar to the described four bladed tailrotor /6/. This concept will be used for a 2500 kg helicopter (Figure 7). The present design includes a steel rotor shaft, where the blades are attached (Figure 8). Several carbon fibre composite rotor hubs were investigated in order to replace the steel drive shaft attachment.

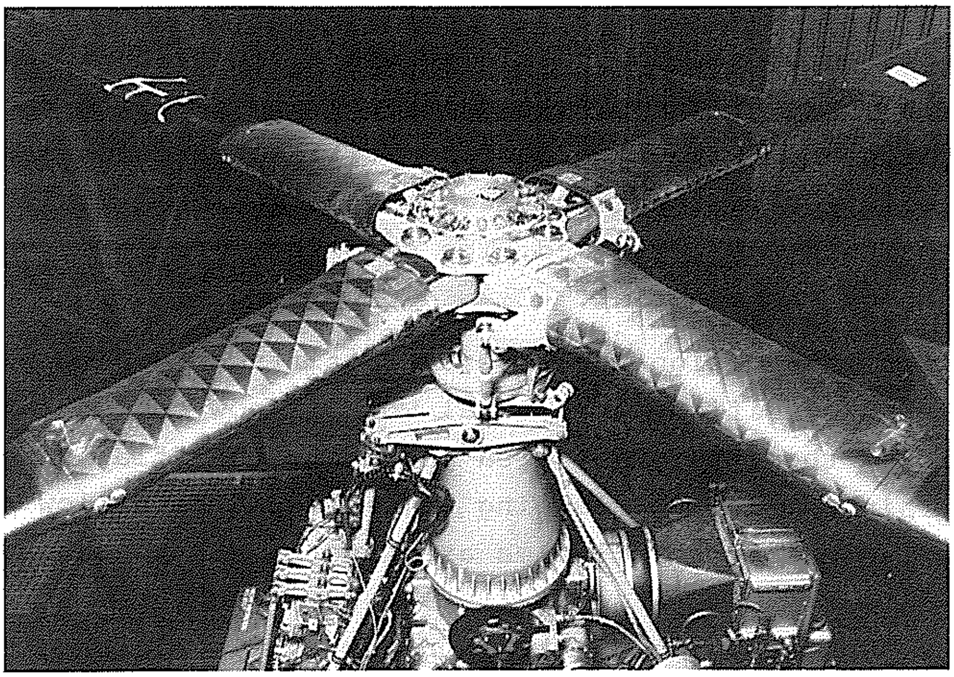


Fig. 7: Bearingless mainrotor for a light helicopter

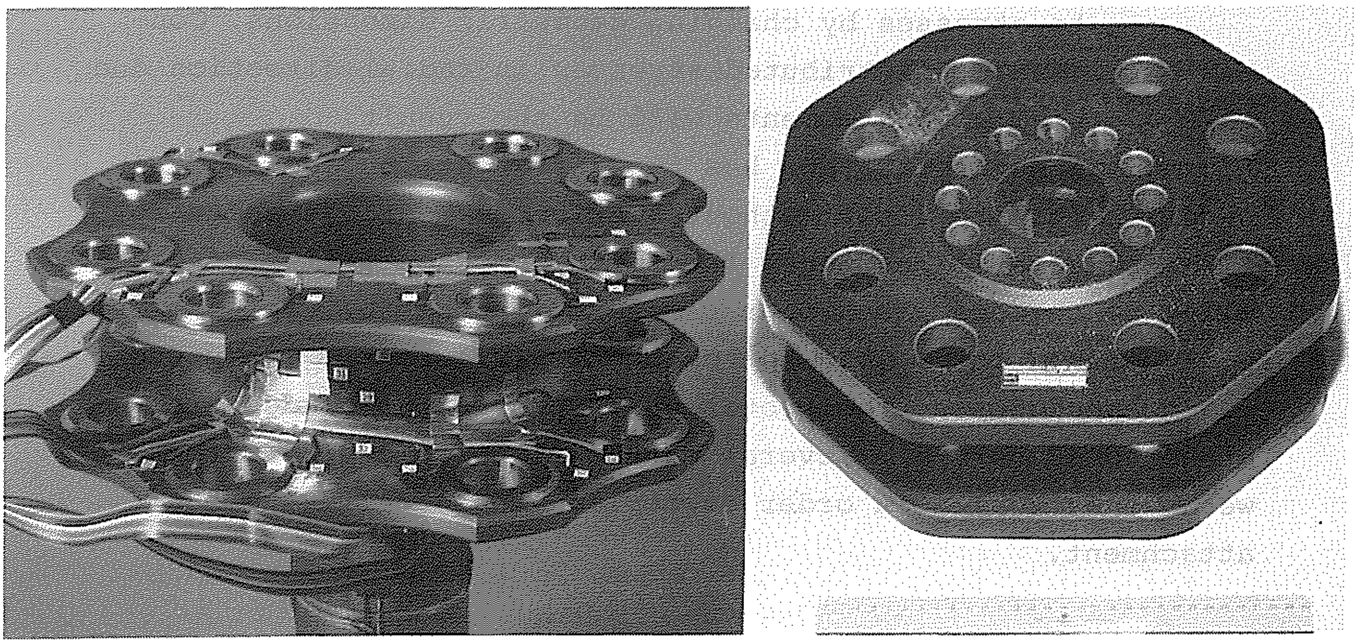


Fig. 8: Rotor shaft with hub

The elements of the blade are: Blade attachment area, "flap hinge" and torsional flex beam. A carbon fibre cuff transmits the pitch to the blade. The cuff is stiff in lead-lag direction and is connected to the blade by a damping device. The rotor was intensively tested on the whirl tower and is now prepared for flight evaluation on a BO 105 helicopter.

Another composite rotor with elastomeric bearings was developed by MBB for a 4000 to 6000 kg helicopter (Figure 9). The hub of this rotor consists of two carbon fibre composite plates which are bolted to a central metal part. The blades are attached to the hub by elastomeric bearings, which allow the pitch of the blades. In Figure 10 the elastomeric and flex-beam rotor is compared to the BO 105 rotor system.

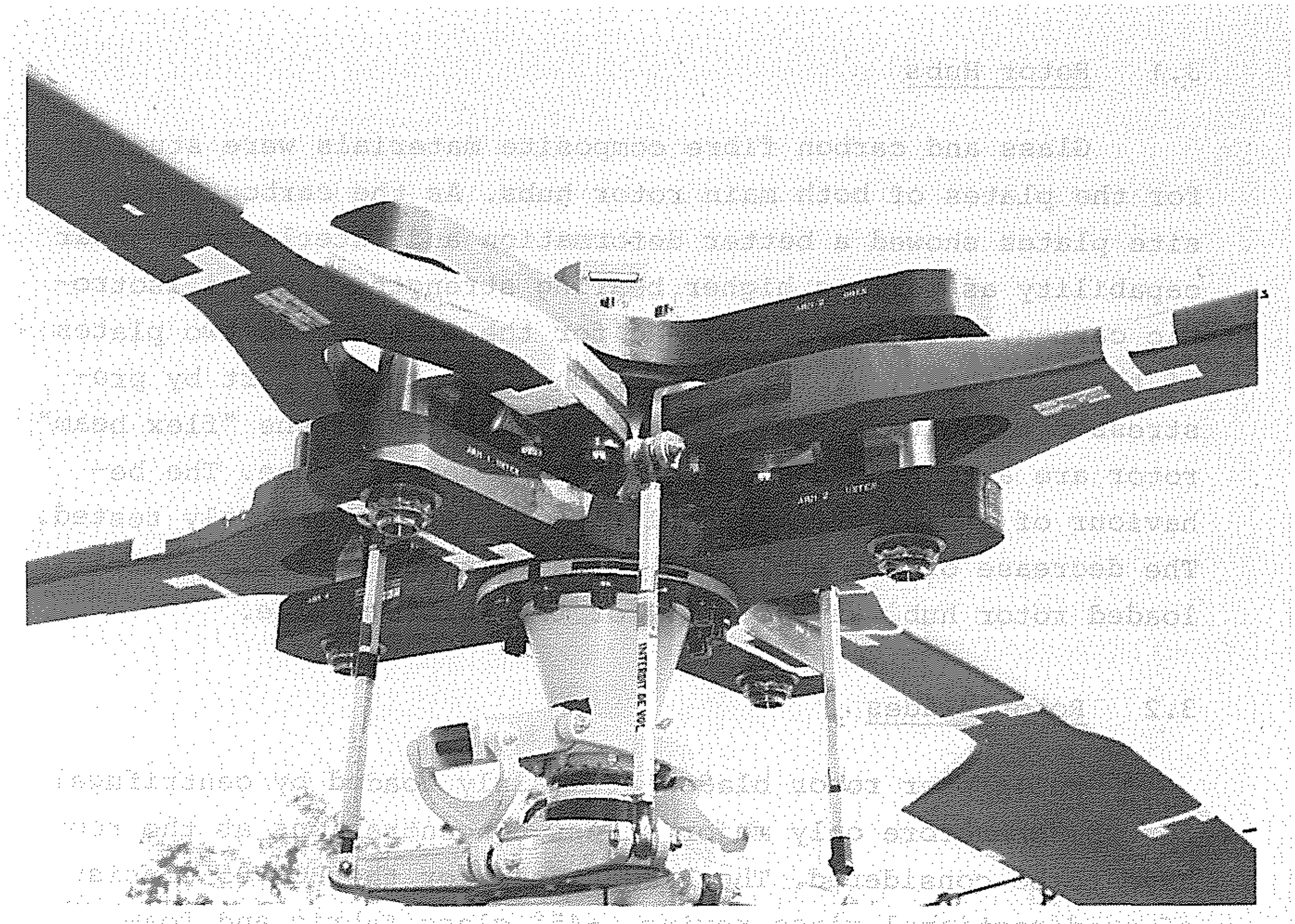
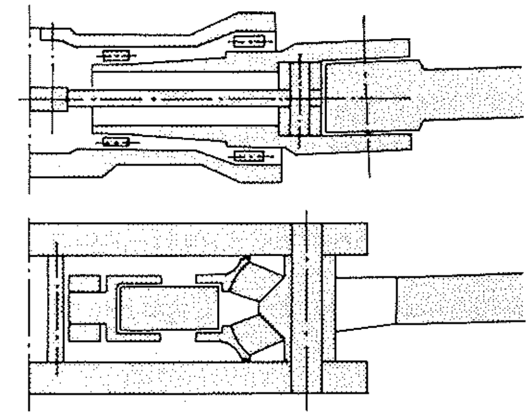


Fig. 9: Rotor system with elastomeric bearing



Hub	Titanium stiff	2 FRG plates stiff	Steel stiff
PITCH	2 LUBRICATED BEARINGS	2 ELASTOMERIC BEARINGS	BEARINGLESS
CENTRIFUGAL LOADS	BENDIX ELEMENT	ELASTOMERIC BEARING	2 ATTACHMENT BOLTS
FLAPPING LEAD LAG	FLEXIBLE HINGE	FLEXIBLE HINGE	FLEXIBLE HINGE

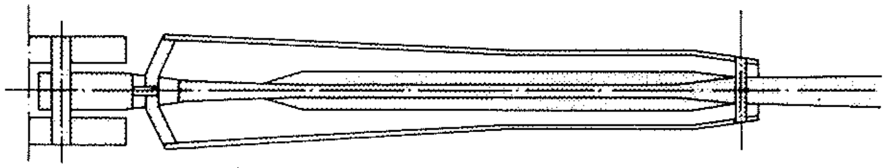


Fig. 10: Comparison of different rotor systems

3.1 Rotor Hubs

Glass and carbon fibre composite materials were studied for the plates of both main rotor hubs. As the carbon composite plates showed a better deformation and interlaminar shear capability as well as higher bearing strength, a quasi isotropic carbon fibre fabric is used for the plates. The two plates of the elastomeric rotor are attached to a metal part by prestressed titanium screws, whereas the plates of the "flex beam" rotor are attached to a carbon fibre composite tube. The behaviour of the prestressed bolted joint was intensively tested. The decrease of pretension of the screws due to the dynamically loaded rotor hub was about 10% of the initial value.

3.2 Rotor Blades

Helicopter rotor blades are mainly loaded by centrifugal forces, therefore only major stress concentrations at the root have to be considered. The blades used for the BO 105 consist of unidirectional glass roving, ±45° glass fabric and foam. Several studies were made for using Kevlar- and carbon fibre and Nomex honeycombs for the design of blades, which will be used in the future. In addition to the helicopter blades, wind tunnel blades (EMMEN and DNW) and wind energy converter blades (WEC and WEA) were designed and manufactured /8/,/9/. All blades were designed for infinite life and are running for several years. Typical cross sections of various designs are shown in Figure 11.Special attention has to be paid to the curing and bending procedures.

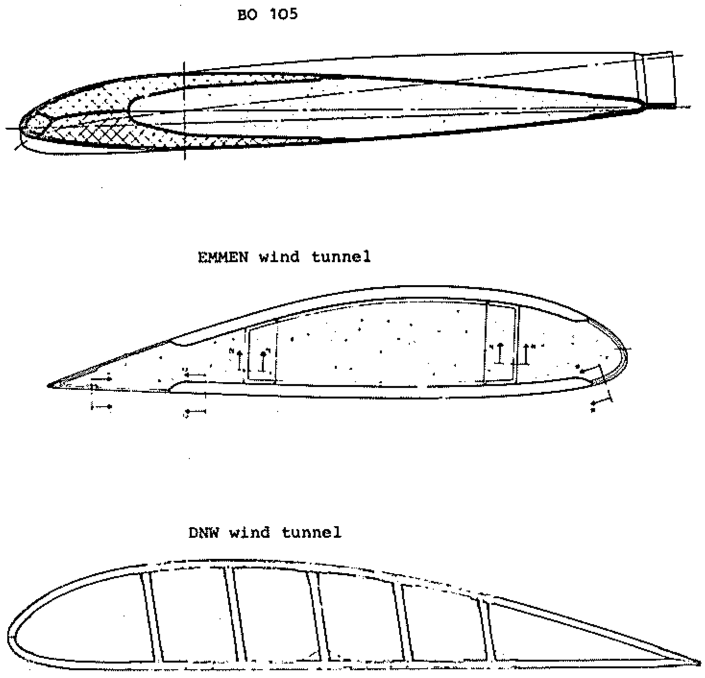


Fig. 11: Cross section of blades

As shown in Figure 12 the nose of the blade and blade itself could have a different curvature after individual curing. The bonding of both parts will create high shear stresses in glued areas. At MBB usually the stresses and deformations induced by differences in thermal expansion coefficients or different temperatures of the two parts are considered /10/. Special lay up of the fibre composite laminates then minimizes the differences in curvature of the precured parts. The joining of the leading edge to the blade at elevated temperatures will also create shear stresses, which have to be added to the stresses included by centrifugal forces and bending moments.

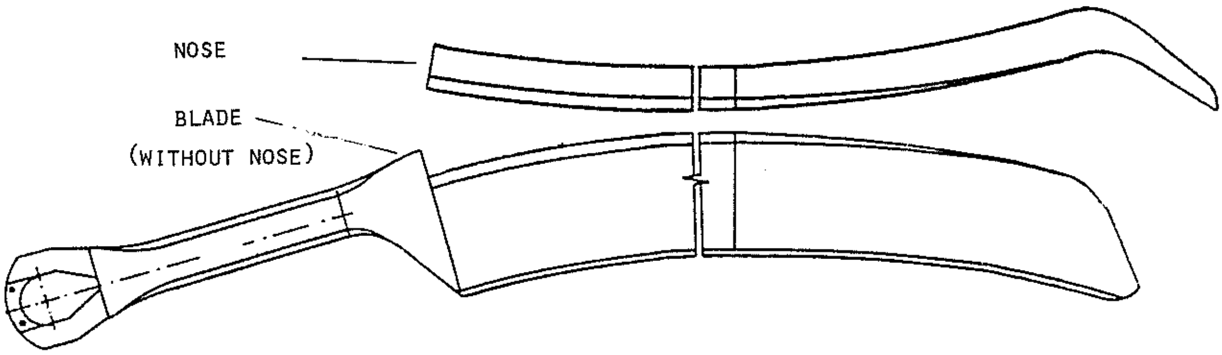


Fig. 12: Leading edge and rest of blade after separate curing cycle before bending together

The calculation of shear stresses with the help of FEM or "Shear lag" methodes makes it possible to avoid critical peak stresses by appropriate designs.

For the two fibre composite mainrotors described here, different load attachment concepts were chosen. For the "flex beam" rotor two bolts are fastening the blade with the help of glassfibre composite lugs whereas for the "elastomeric" rotor four bolts and two titanium fittings transfer moments and forces from the quasi-isotropic laminate to the rotor hub. As the load transfer at the blade attachment and the stresses cannot be predicted by simple methods, a three dimensional finite element idealization was performed. The material characteristics for the three dimensional anisotropic elements were established and confirmed with test results /11/. The idealization is shown in Figure 13. Figure 14 shows the stress distribution due to the centrifugal force. The highest stresses are created in the inner area. The stresses are not distributed constantly across the root, as the centrifugal force causes local bending moments. The highest stresses due to flapping are located in the area of the outer bolts (Figure 15).

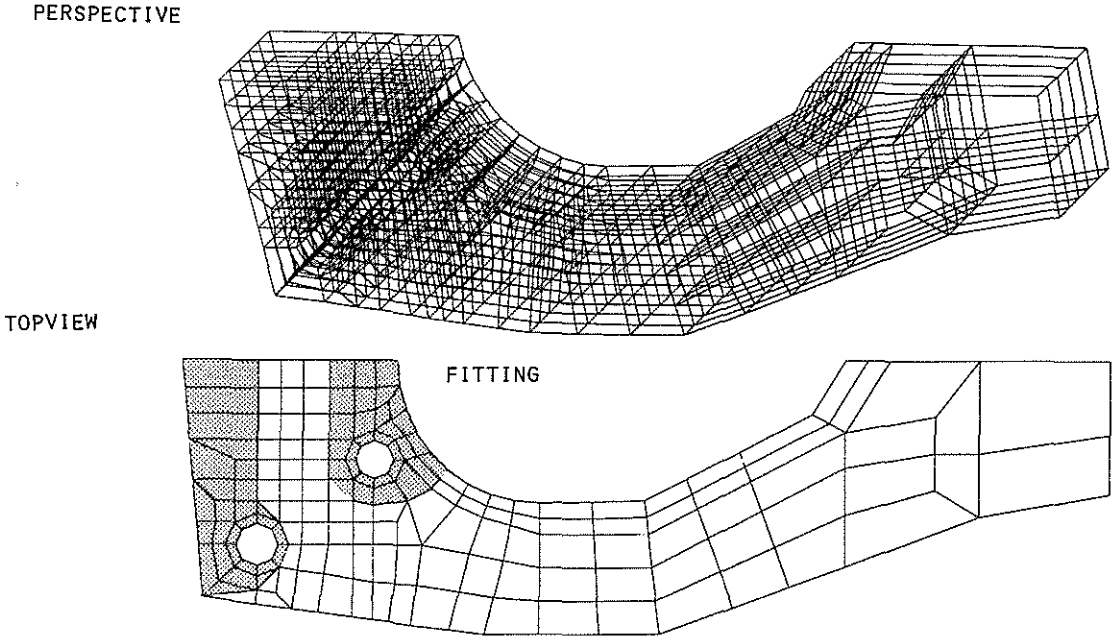


Fig. 13: FEM idealization of root attachment

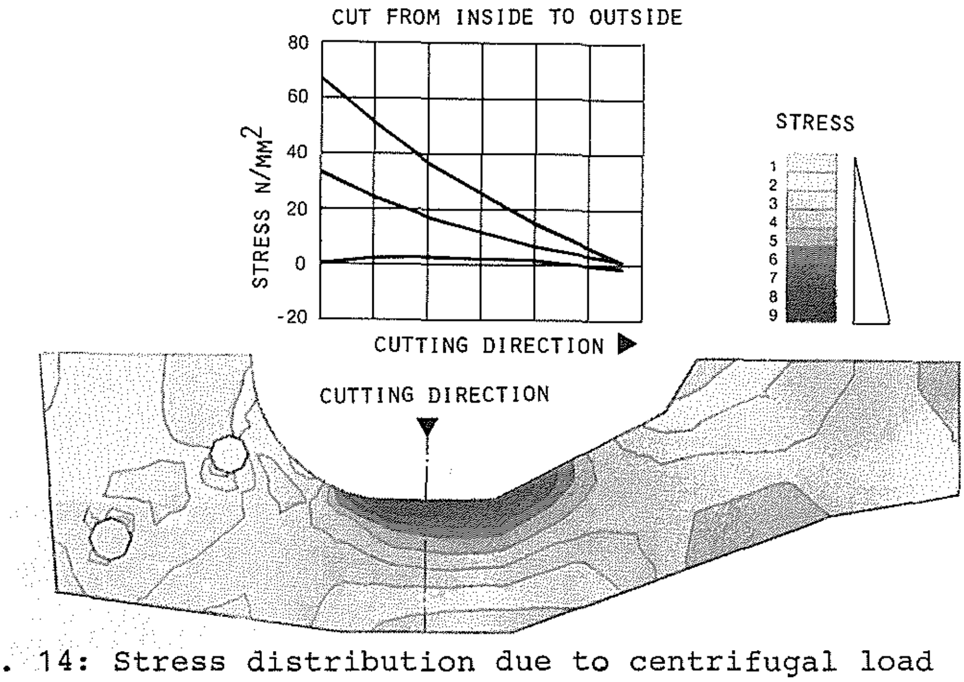


Fig. 14: Stress distribution due to centrifugal load

The stresses due to lead-lag bending moments are low. The predicted stresses were confirmed by strain gauge measurements of a root attachment component (Figure 16). In order to establish ultimate dynamic bending and shear strength values, test specimens were cut from manufactured comoponents. The calculated stresses are smaller than the material strength derived by test samples.

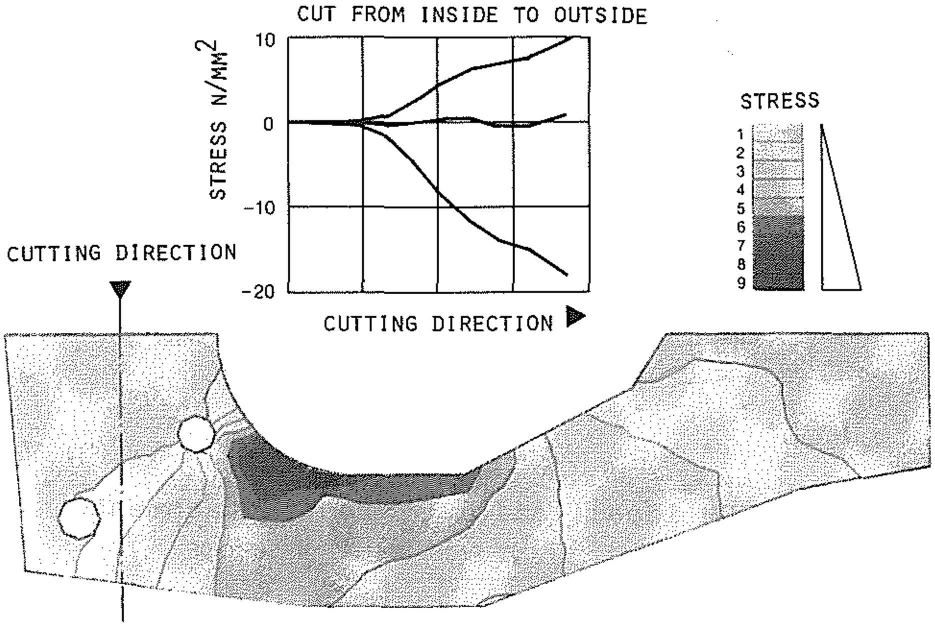


Fig. 15: Stress distribution due to flap bending

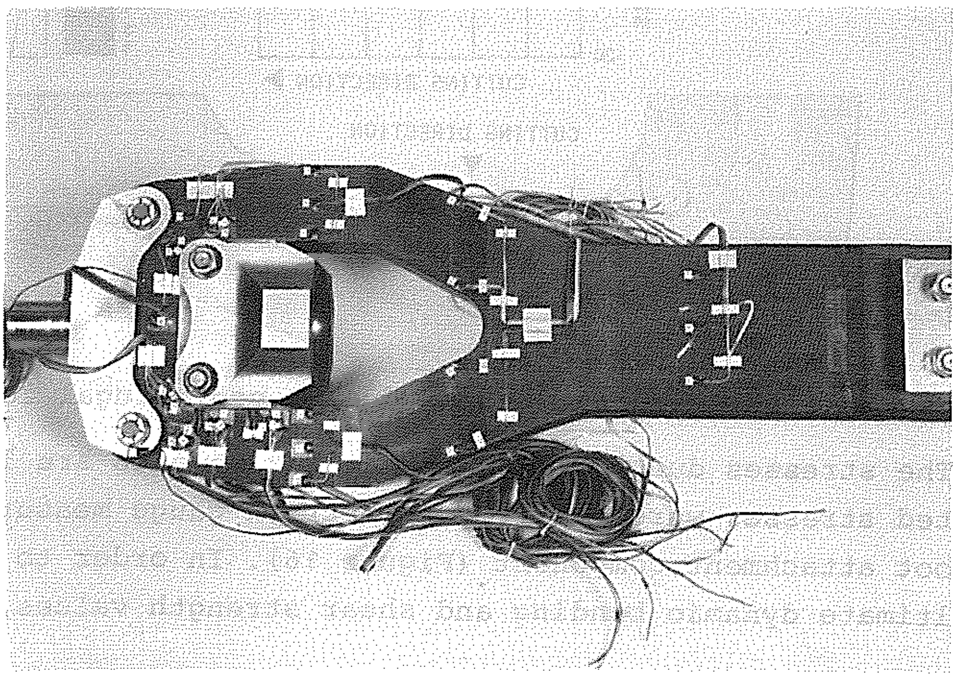


Fig. 16: Test component of the root attachment

4. COMPONENTS OF DYNAMICAL SYSTEM

4.1 Drive shafts

Drive shafts are in helicopters commonly used between main gear box and intermediate gear box (often called "long drive shaft") and between intermediate gear box and tail rotor gear box (often called " short drive shaft"). Figure 17 gives a schematic view of the complete drive shaft system of the BO 105.

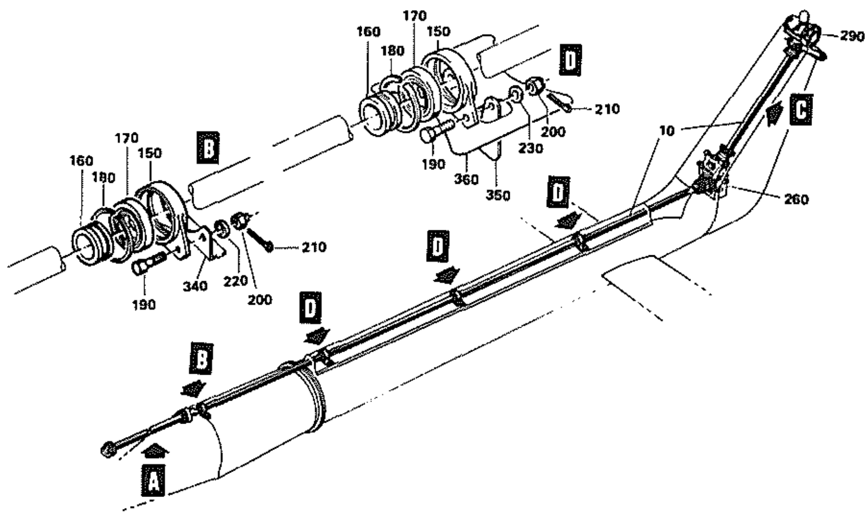
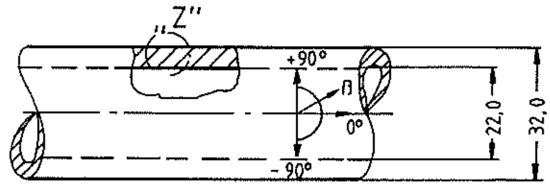


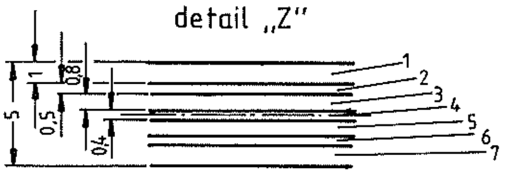
Fig. 17: Drive shaft system of the BO 105

The reasons for a possible substitution of metal drive shafts by composite drive shafts in future projects are

- saving service costs by freedom of corrosion and improved fatigue life
- saving manufacturing costs by reduction of number of parts
- saving mass by using profitable stiffness or strength to density ratios of composite materials

Figure 18 shows a typical lay-up for drive shafts.





layer	ß [°]	material
1, 7	±45	CFC (GFC or PRD/3:1)
2, 4, 6	0	CFC
3, 5	±45	CFC

Fig. 18: Typical lay-up for drive shafts

The ±45 layers have to provide the appropriate torsional stiffness and strength, the 0° layers have to provide appropriate bending stiffness.

In some cases a unique intermediate angle (ß < ±45°) is the optimum for mass and cost saving, but as the tuning is easier performed in the shown "split" design, the latter was chosen for the experimental version of the CFC drive shafts at MBB. Highly mechanised filament winding turned out to be the best process for manufacturing the homogenous shaft.

As an area, where the reduction of number of parts could be demonstrated, the flexible couplings were investigated. These couplings have to shim angular and axial mismatches between drive shaft system elements.

Figure 19 shows the finite elemente (half-) model of a composite coupling, which substituted a steel lamella coupling in several test specimen. The most suitable manufacturing process was press-moulding of fabric prepregs over metal cores, which were melted out at comparatively low temperatures (similar to WOOD's alloy).

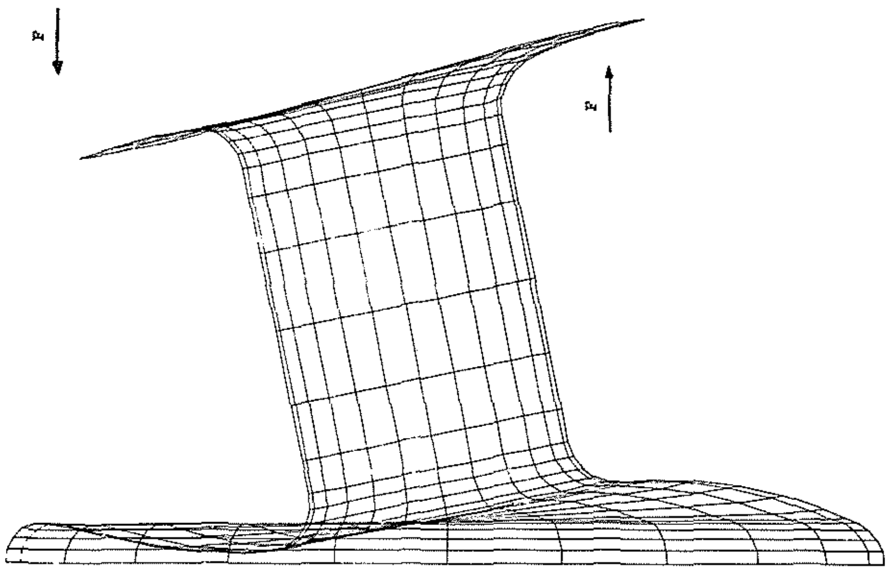


Fig. 19: FEM (half-model) of composite coupling

In an experimental production and qualification programme it could be demonstrated, that the CFC shafts can sustain loads equivalent to 1200 flight hours, see Figure 20. The mass saving was determined to be 4 kg for the long and 1 kg for the short drive shaft.

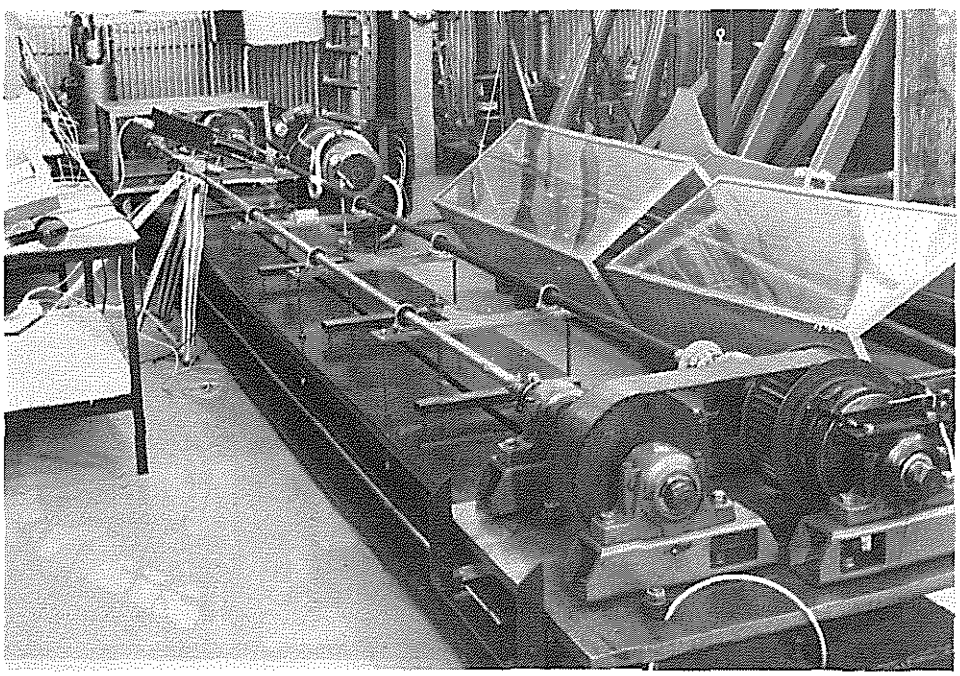


Fig. 20: Long drive shaft on endurance test stand

A 10% saving in the manufacturing costs was predicted for a possible serial production. Long time experience and estimates for life cycle cost saving should be derived from future flight tests.

The introduction of composite drive shafts is most probable for future helicopter projects in combination with composite tail booms, which have a similar coefficient of thermal expansion. For more details see /12/.

4.2 Control Elements

A control tube and several control rods were developed and tested in experimental programmes. Figure 21 shows the arrangement of the control tubes of an experimental bearingless mainrotor.

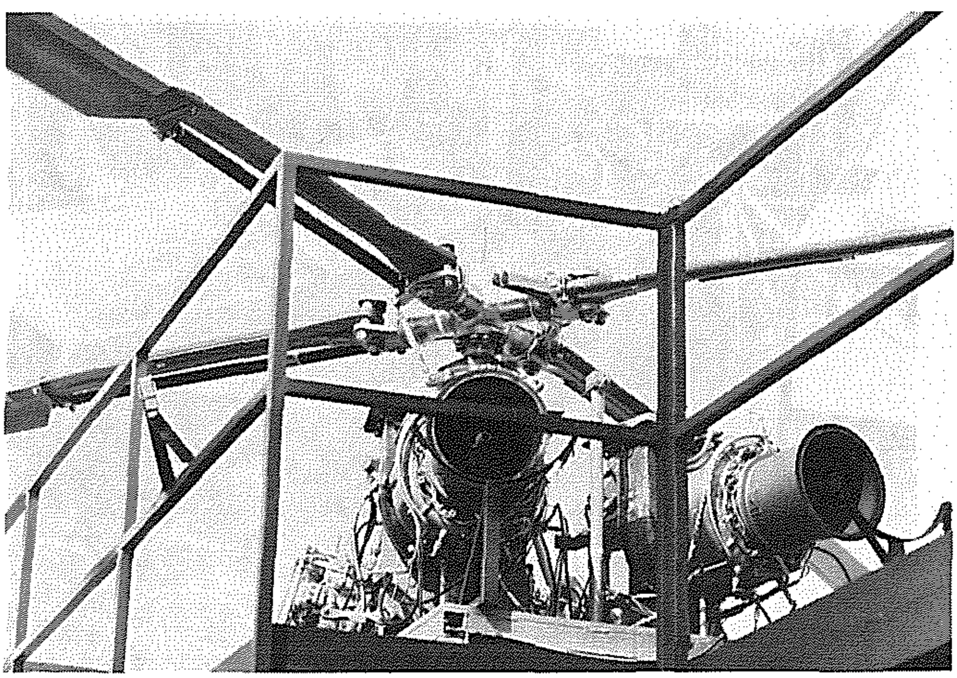


Fig. 21: Control tubes of experimental bearingless main-rotor in whirl tower test

The blade root of the rotorblade has to be stiff in bending and soft in torsion motion. The control tube, however, has to be soft in bending and stiff in torsion motion. Consequently a lay-up of ±45° carbon fibre was chosen in a filament winding process.

Figure 22 shows a typical load introduction to the test flange: Collar bushes to which the load is transferred by bearing pressure from the composite parts.

The control rod, Figure 23, is similarly connected to its end fitting, using blind rivets.

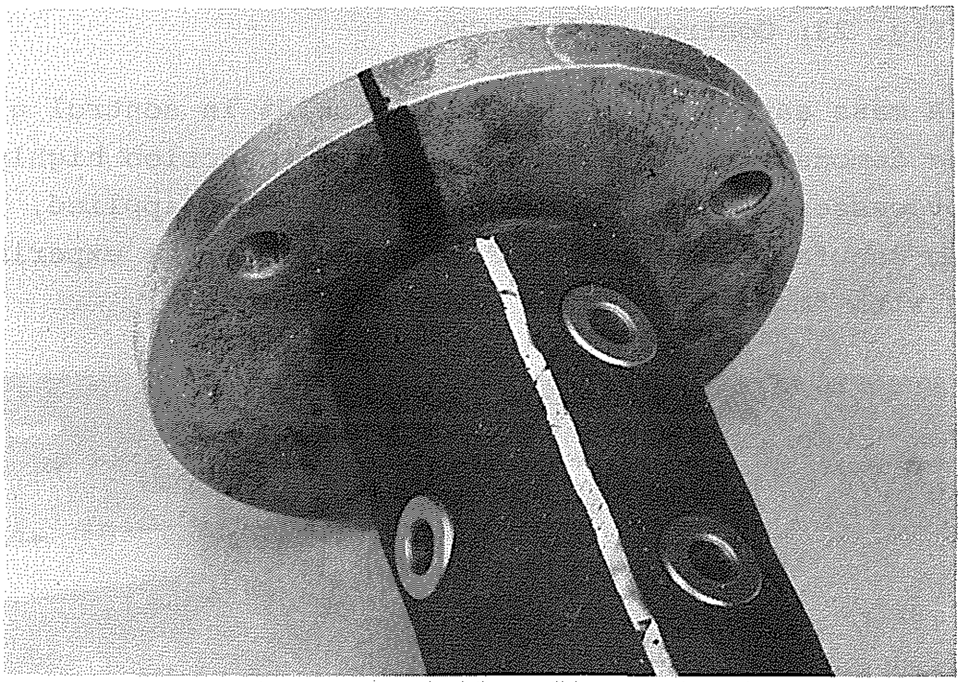


Fig. 22: Load introduction to control tube with collar bushes

The lay-up is mostly unidirectional CFC,only the inner- and outermost layers are thin filament wound ±45° GFC (protection against scratches).

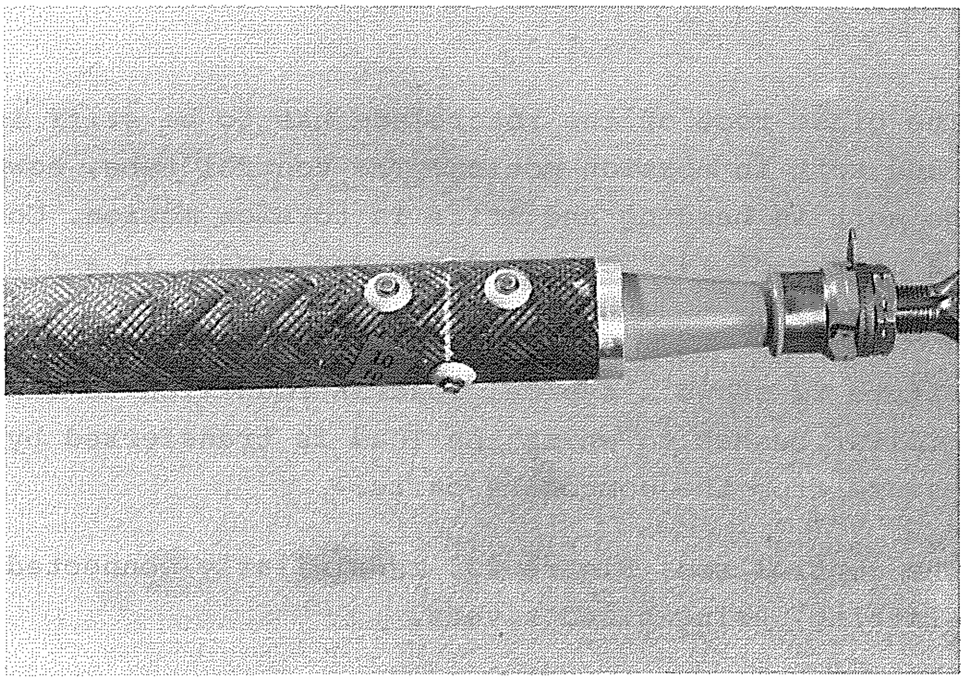


Fig. 23: Control rod of CFC

A mass saving potential of 25 to 30% in control elements could be demonstrated.For future serial production highly mechanized processes of filament winding have to be applied, in order to lower manufacturing costs. Figure 24 shows the experimental winding with "multi-eye" ring device.

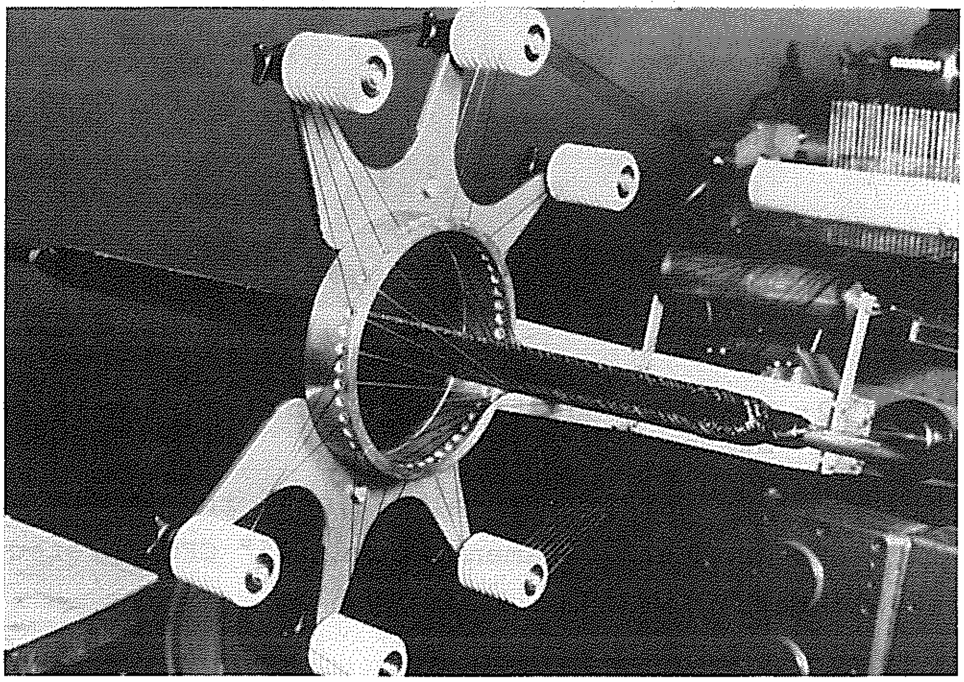


Fig. 24: Filament winding with ring device

4.3 Vibration absorbing elements

These are to be found in passive systems (e.g. vibration absorbers with leaf springs of composite) and active systems (e.g. ARIS-system between main gear box and fuselage). The reason for the choice of composites (predominatly GFC) is the high fatigue life at comparatively low stiffness of these components. Figure 25 shows a filament wound rod of the ARIS-system. The waisted zones at both ends act as "quasi-hinges".

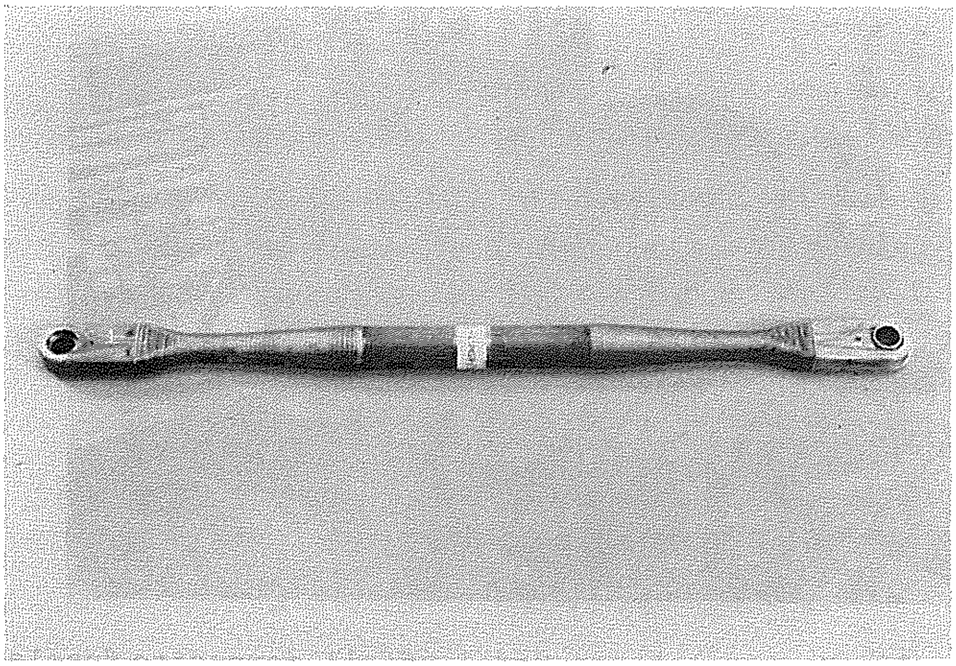


Fig. 25: ARIS rod of GFC

5. AIRFRAME

5.1 Primary Structure

In order to demonstrate the feasibility of an all-composite airframe for future transport helicopters, a primary structure of AFC and CFC is presently under development for a BK 117 helicopter. It consists only of 7 major units

- conopy LH and RH
- side shell LH and RH
- underfloor structure
- bottom shell
- turbine floor (in experimental version metal)

Figure 26 shows the master pattern model for production of the "soft" prototype moulds. Syntactic foam elements are arranged on a rectangular centre tube. The latter can be turned and locked in the base rig into every position, thus easing manufacturing steps.

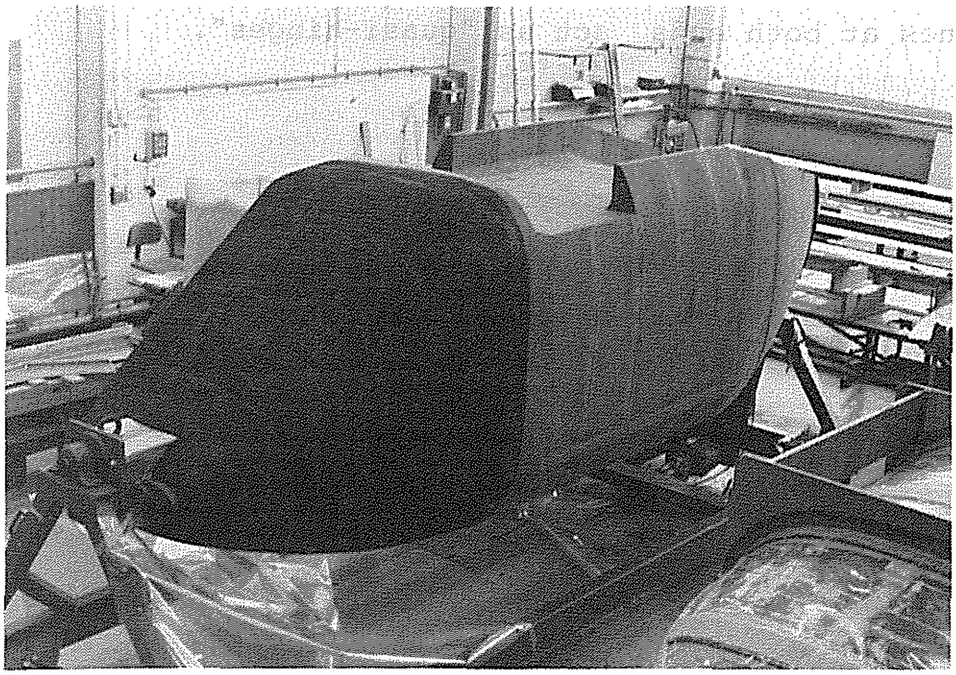


Fig. 26: Master pattern model of all-composite fuselage

With several manufacturing studies it could be demonstrated that one-shot curing of fabric prepregs for typical primary structures with integrated edges and reinforcements is possible - see Figure 27.

Predictions for mass and cost saving range from 10 t0 20%. The lower limit is typical for light, the upper for medium and heavy transport helicopters. The mass saving could be demonstrated in component manufacturing, the cost prediction will be verified after production of complete airframes.

An experimental tail boom was filament wound using CFC "grid pattern". This construction offers an advantage concerning vulnerability - see Figure 28 and /13/.

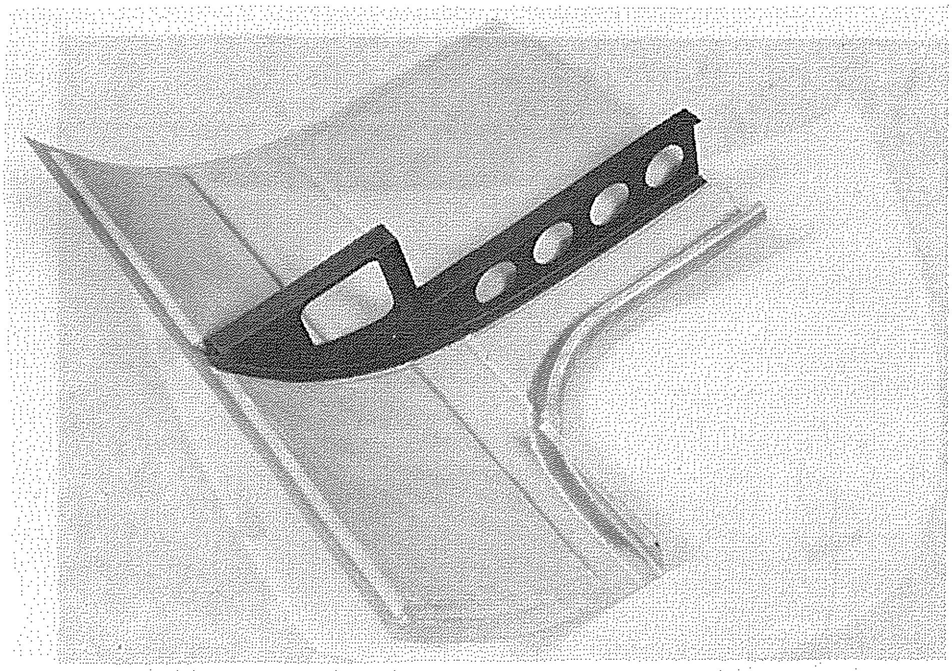


Fig. 27: Side panel with integrated door frame (one shot) connected with CFC frame (second step)

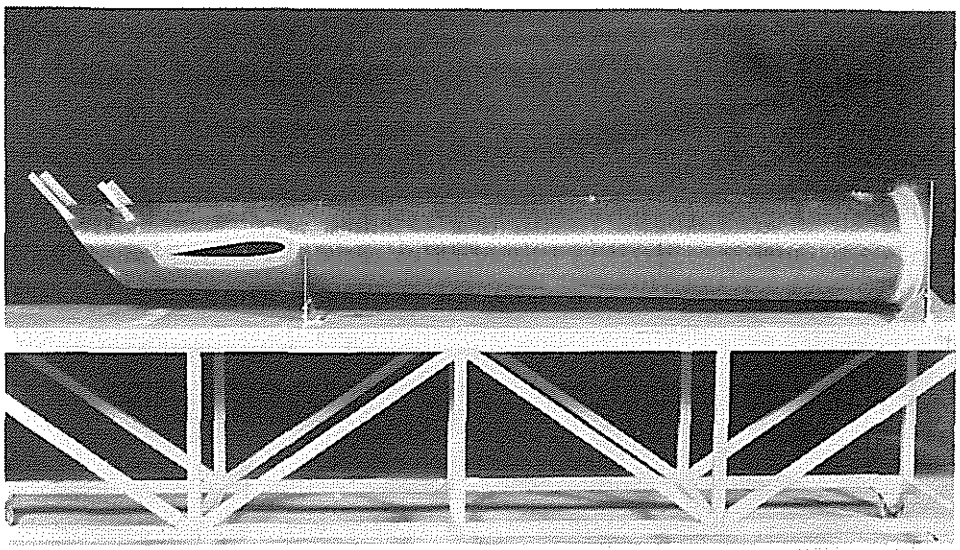


Fig. 28: Filament wound tail boom

5.2 Empennage and secondary structure

In this field of typical sandwich structures the design goals for pirmary structures are already verified in serial production. Figure 29 shows a rear door assembly of the BO 105, coated with powder primer and ready for painting.

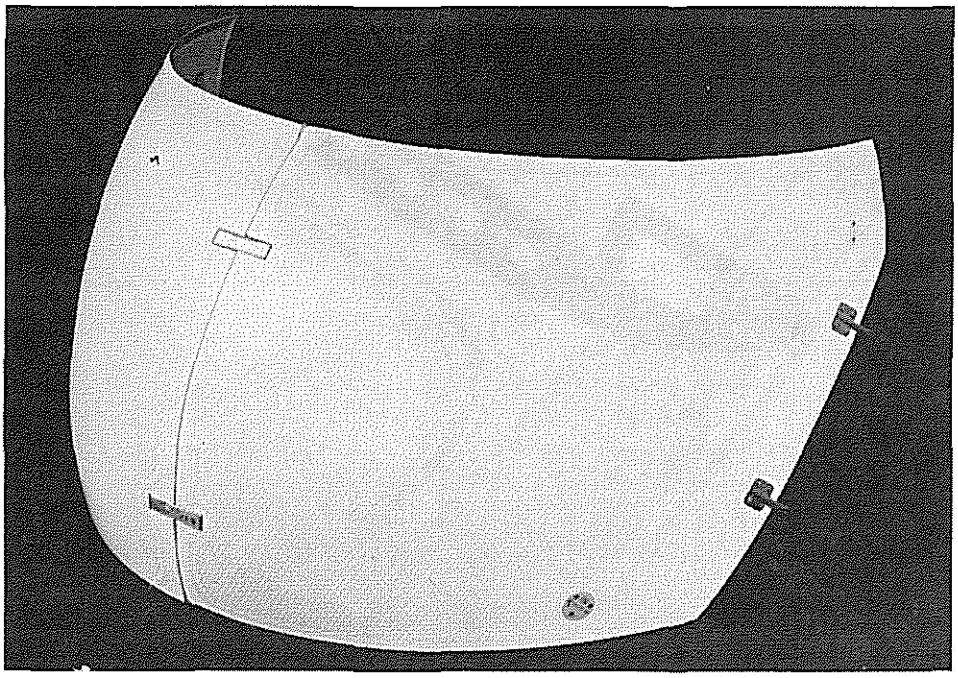


Fig. 29: Rear door of BO 105

In Figure 30 the two shells with integrated spar of the horizontal stabilizer BK 117 are depicted together with the "hard" serial mould

In the domain of manufacturing secondary structures process mechanizations primarily concerning cutting steps and material flow help to lower the manufacturing costs.

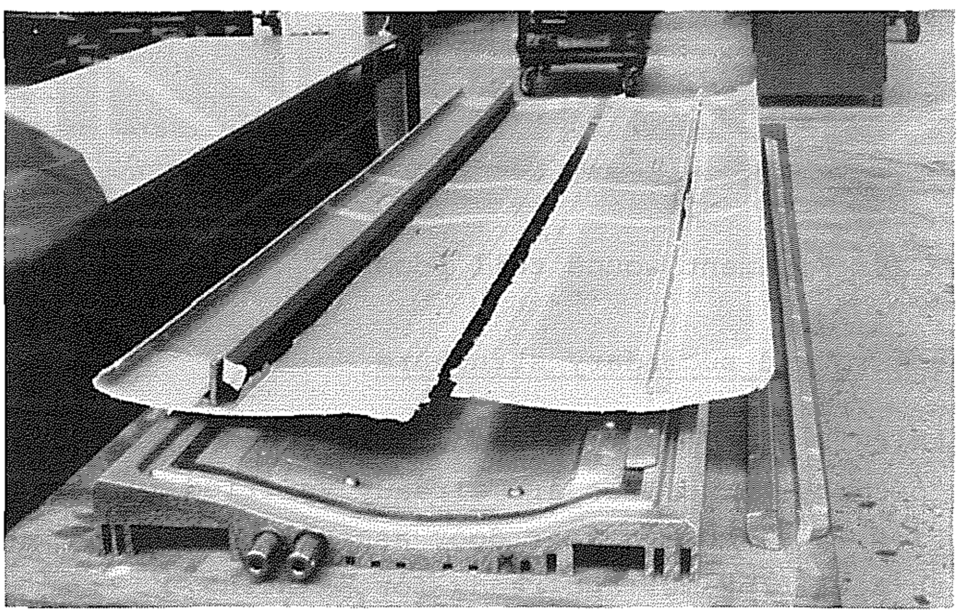


Fig. 30: Horizontal stabilizer BK 117

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