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BALLISTIC AND IMPACT RESISTANCE OF COMPOSITE ROTORBLADES

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SUMMARY

The BO 105 Helicopter is fitted with composite rotorblades, both for main and tail rotor. After the superiority of those blades with reference to fatigue life had been proven the impact resistance was investigated. Main rotor blades were ballistically impacted by .30 APM bullets. Then fatigue tests with loads experienced in flight were run. Test loads had to be increased dramatically to cause crack propagation. Even with increased loads crack propagation was only slow.

FOD-Tests were performed with BO 105 tail rotorblades. Wooden rods up to 65 mm thick were impacted by tail rotorblades, again composite rotorblades performed better than those out of metal. The results of all the tests mentioned above are presented.

From the experience available today, a final conclusion can be drawn, saying that the combination of both excellent fatigue and impact strength make composite rotorblades the favorite candidate for any helicopter, but especially for military helicopters.

1. INTRODUCTION

Composite rotorblades have been state of the art for several years. Within the investigation of materials and design concepts wide scattered tests were performed in laboratory and field. The material behaviour of GRP, CRP, and mixed modulus coupons was found to be very well qualified for high loaded dynamic components like rotorblades.

The information about material and component stress in field operations and those about service conditions are showing that the majority of rotorblade component failures found until now are caused by unexpected defects or damage (Ref. 1, 2)

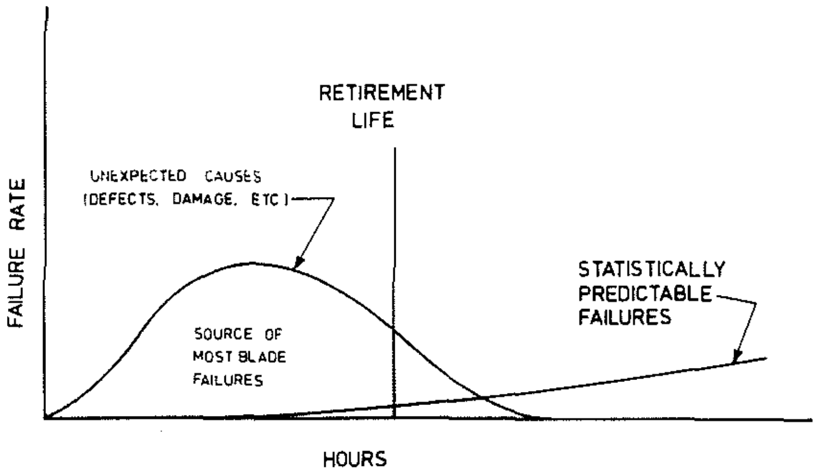

Figure 1 PREDICTABLE AND UNPREDICTABLE BLADE FAILURES

Especially for rotorblades, the impact and postimpact behaviour was found very important for civil and military missions. Impact includes a great variety of damage possibilities. e.g. moving and solid barriers, birds, bullets, hail and small particles. The impact damage causes a reduction of fatigue life and remaining flight time. The fatigue behaviour of small damage similar to notches and cracks is investigated theoretically and by tests predictions based on calculations are possible.

A comparison of the material properties employed for rotorblades on dynamic resistance shows the superiority of FRP-materials over metals. The most critical material properties for dynamically high loaded components are fatigue resistance and crackpropagation. In the figures 2 and 3 a comparison between metals and GRP is given.

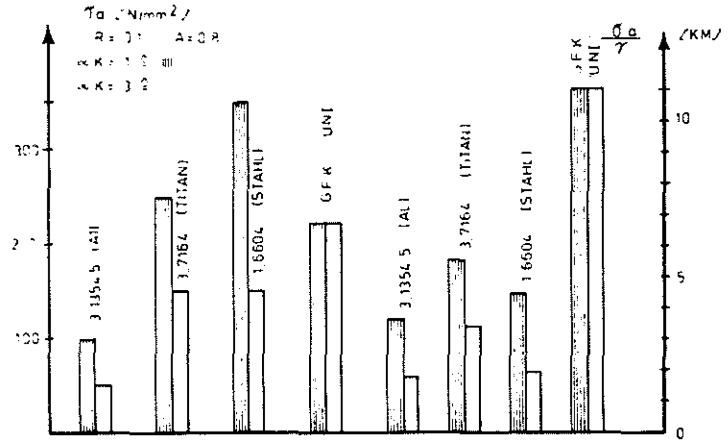

Figure 2 DYNAMIC RESISTANCE OF SPAR-MATERIALS FROM ROTORBLADES

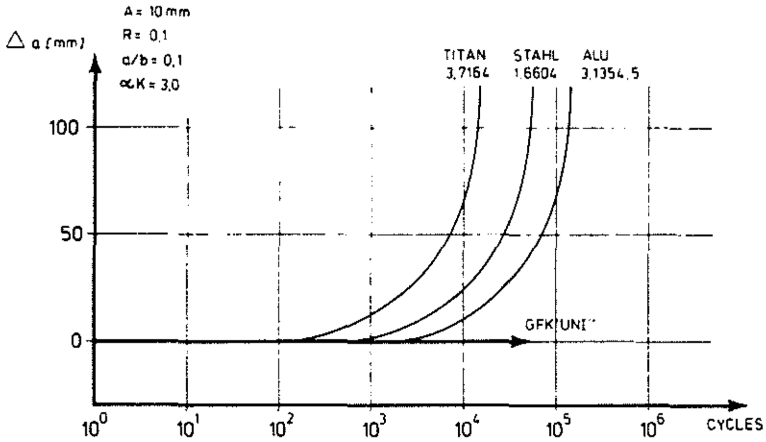

Figure 3 CRACKPROPAGATION ON SPAR-MATERIALS OF ROTORBLADES

Large area impacts essentially are investigated by component tests, because primarily structural (fail safe) problems are dominant to material problems.

2. DESIGN AND PRODUCTION TECHNOLOGY

The essential difference between fiber reinforced composite (FRC) and metal structures is that within the production process the component and the component material is created. Hence production technology severely influences the materials peoperties and this must be fed in the basic design very carefully.

As an example the dynamic shear resistance of glass fiber reinforced Epoxy produced by three different processes is shown in Fig. 4.

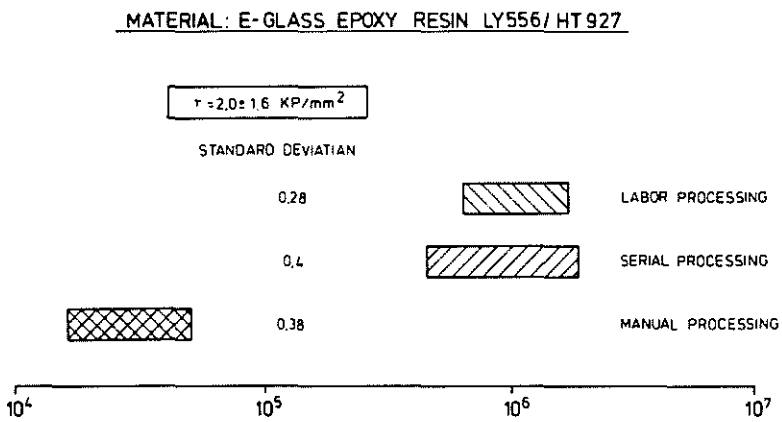

Figure 4 INFLUENCE OF PRODUCTION PROCESS ON FATIGUE LIFE

For component design one must ensure that the material properties evaluated on test specimens and used for dimensioning can be realised by the production process of the component. A simple way to do so, is to use test specimens for data compilation which were cut out of full-scale component sections.

3. INFLUENCE OF STRESS CONCENTRATION ON ROTORBLADE FATIGUE LIFE

The basis for fatigue life predictions are the fatigue bending tests with unnotched and notched specimens. In the case of the BO 105 - rotorblades, the specimens were cut out of the blade spar. In Fig. 5 the results are given for glass reinforced Epoxy composites and aluminium.

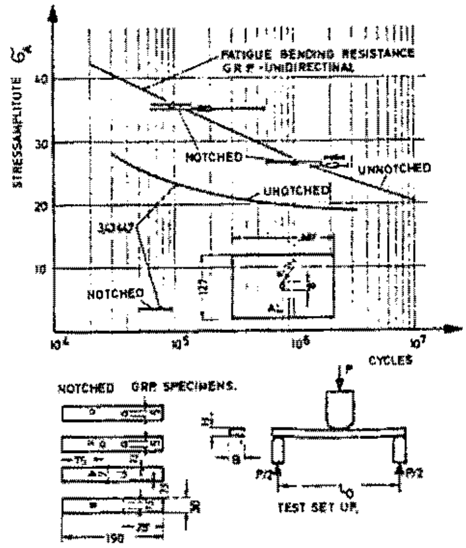

Figure 5 FATIGUE STRENGTH OF GRP AND ALU

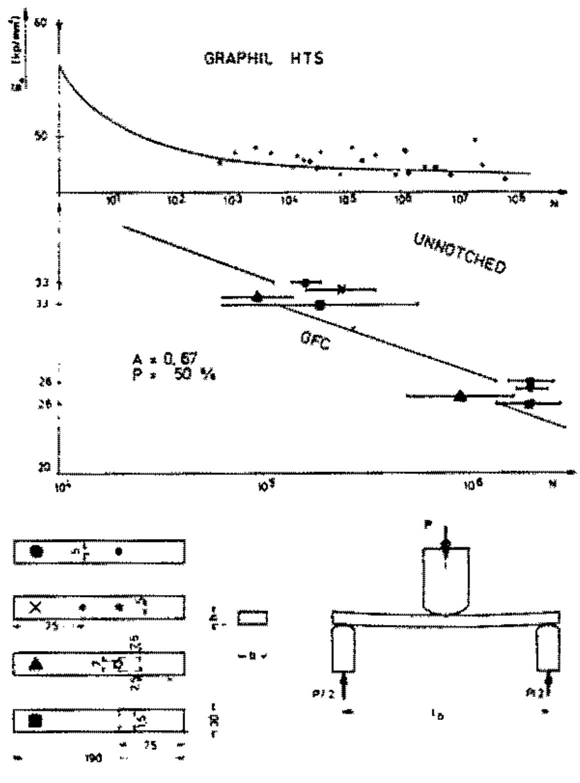

Figure 6 FATIGUE STRENGTH OF GRP AND CRP

For aluminium a drastic strength reduction by notches can be seen. For GRP, however, the average values of notched and unnotched unidirectional laminates (UD-Laminates) correspond very well. This is a very different sensitivity to stress concentration relative to that known from metals, see Fig. 6. This means that FRP has generally favourable behaviour to stress concentration which is unaffected by notches of different shapes. The direction of crack propagation of notched UD-Laminates under static or dynamic bending loads is parallel to the fiber direction. The failure is initiated by local shear stress concentration.

For the remaining cross-section the maximum of possible stresses is the same as for unnotched specimens.

Furthermore the impact behaviour of cloth laminates were investigated and some results are given in Fig. 7 and Fig. 8.

In Fig. 7 test results of Charpy impact are given for glass-Epoxy laminates.

Laminates orientated lateral to the direction of impact absorb more energy than parallel orientated laminates. Notches are initiators for failure mechanisms with normal and shear stresses. If the notched and unnotched cross-sections in the impact area are of equal size, the notched specimen has a higher energy absorbtion than the unnotched.

Since the last few years hybrid fiber composites have become of great interest in the aeronautical and space industry. The impact sensitivity of high modulus fibers limits their application on exposed surfaces. A good possibility for reducing this is the combination of high modulus and high strength fibers, see Fig. 8.

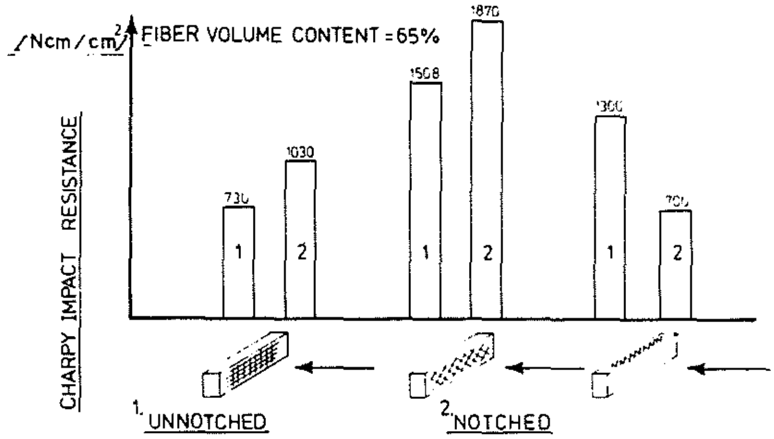

Figure 7 CHARPY IMPACT ON GLASS LAMINATES

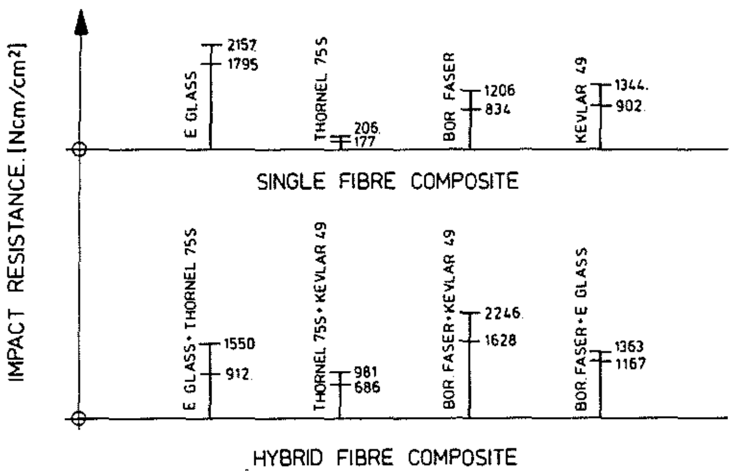

Figure 8 IMPACT RESISTANCE

4. PROPAGATION OF CRACKS CAUSED BY IMPACT ON ROTORBLADES

In contrast to the many favourable properties composites lack nearly any plastic deformation capability. Glass fiber composites (GFC's) at least compensate for this disadvantage by comparatively good damage tolerance. This damage tolerance clearly became evident by fatigue testing GFC rotorblades after ballistic impact.

Some of the tests that have been carried out with BO 105 main rotorblades and armour piercing ammunition .30 APM 2 are discribed here. Impact velocity of the bullets was always, approximately, 750 m/sec. The damage caused by such an impact is shown in figures 9, 10, 11, 12, 13, 14, 15, 16. All specimens shown have been fatigue tested after impact.

4.1 Tests with alternating flexural load

The number 1 specimen was tested with .06% alternating strain both at impact area 1a and 1b for 2 million cycles without damage propagation. Then the load was increased to 0.18% at area a and 0.185% alternating strain at area b. After .35 million cycles again no crack propagation had become evident. The test was shut down and the specimen cut in pieces to allow visual inspection of the impact areas. Figure 17 shows those areas.

The number 2 specimen was tested for 45.6 million cycles at different loads. The spanwise distribution of alternate flexural deformation is shown in Fig. 18. The test conditions at which the maximum alternating deformation was 0.125, 0.25, 0.4 and 0.5% are referred to conditions 1,2,3 and 4 respectively.

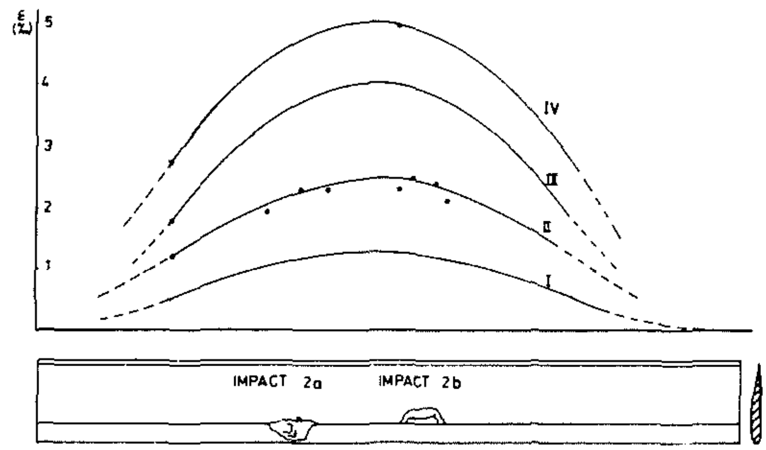

Figure 18 IMPACT TEST, STRAIN DISTRIBUTION

Condition 1	30 million cycles, crack in titanium nose cap starting from 2a impact area
Condition 2	6.8 to 11.8 million cycles, three additional cracks in titanium and carbon
Condition 3	0.5 million cycles, cracks in titanium nose cap propagated into unloaded area towards leading edge. Partial debonding of nose cap in 2a area were bullet left blade
Condition 4	.017 million cycles, further cracks in nose cap. Slow growth of delaminated 2b area. 0.5 million cycles, two additional cracks in nose cap.

.0775 million cycles, failure of the blade skin in the 2b area (figure 19). The most amazing fact is that the 2a area damage showed no growth although loaded to about 0.37% (condition 3) and 0.47% strain (condition 4).

Cross sections of the areas 2a and 2b are shown on figures 20, 21.

4.2 Test with combined tensile and flexural load

A blade root section was hit by .30 APM 2 again and then fatigue tested, see Fig. 22, 23. This - from here on number 3 specimen was loaded with constant tension and alternating bending, both in flap- and chordwise direction. The 12 t tensile load introduced by cable resulted in a .135% strain. The flexural deformations being applied by excentries and push-pull rods resulted in additional .15% alternating strain. After application of 7.5 million cycles with bending load the test was completed. The damage again had not propagated at all. The no. 3 test specimen also was cut through the impact area for visual inspection , see Fig. 24.

Within 80.000 flight hours of BO 105 equivalent to nearly .5 million blade flight hours no incident has happened to cause damage only half as severe as the damage caused by bullet impact that were discussed.

5. FATIGUE TEST WITH BULLET IMPACTED TAIL ROTORBLADE

Together with the main rotorblades a tail rotorblade was shot with the same test set up and gun ammunition, (see Fig. 25 and 26). This damaged tail rotorblade was fatigue tested by the following load case with a test set up shown in Fig. 27:

simulated static zentrifugal force	3×10^{4} N
flapwise bending moment	$\pm$ 100 Nm
chordwise bending moment	$\pm$ 200 Nm.

After 30×10^{6} cycles an increase of failure area was not to be found.

Then the dynamic load was increased to

flapwise bending moment	$\pm$ 200 Nm
chordwise bending moment	$\pm$ 420 Nm.

After $35{,}1 \times 10^{6}$ cycles the blade failed in the homogeneous part, see Fig. 28, 29. This type of failure is known from undamaged rotorblades.

6. IMPACT TEST WITH TAIL ROTORBLADES ON WOODEN RODS

During the service life of helicopters in civil and military missions collisions with trees or other objects cannot be avoided. To demonstrate the impact resistance of tail rotorblades a test programme was realized.

Test blades were impacted on wooden rods in the tip area. The rate of revolution was the same as used on the BO 105-helicopter.

Figure 30 shows the test maschine used. The deviation of the impact point was within 5 mm at a distance of 90 mm from tip.

Figure 30

The first run with test blade 1 should demonstrate how many strokes the blade can resist with full action capability. This was found up to the point where a safe landing becomes impossible. Test blade 1 resisted a total of 10 strokes, see fig. 31 and after a visual inspection by design- and stress people and by pilots a "safe landing possibility" was attested. During all tests the test blade 1 had nochange in its ballance properties. The damage is to be seen in Fig. 32, 33, 34.

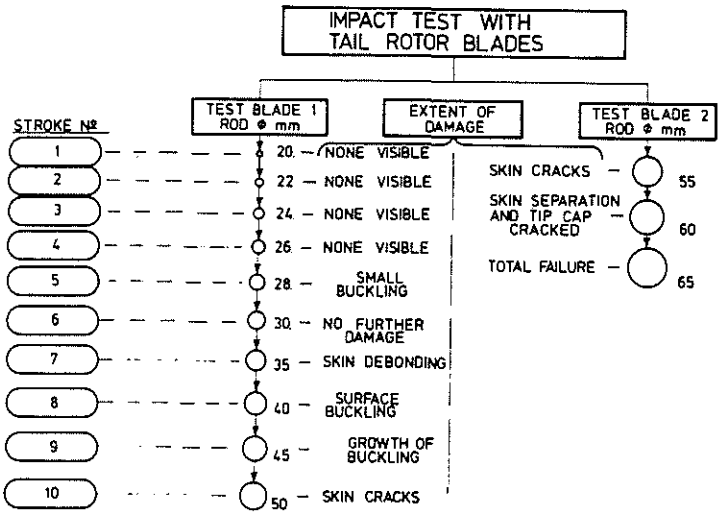

Fig. 31 ROTOR BLADE IMPACT TESTS

With test blade 2 there were three strokes, see Fig. 31. The first on a 55 mm rod initiated the same failure as the test blade 1 had after 10 strokes. The figures 35, 36, 37, 38, 39 are showing the damage increase up to total failure. After the 60 mm rod test an immediate landing seems to be possible although an imballance initiated by the loss of skin and core parts was detected. A normal landing after the last 65 mm rod impact is impossible because the imballance initiated by the lost parts will cause secondary failures in tailboom components.

7. CONCLUSIONS

1. The requirements for fatigue loaded components like rotorblades are fulfilled by FRP-materials with the maximum possible "no crack propagation probability". The result of a comparison done by Boeing Company between metal- and GRP-rotorblades, see Fig. 40, confirms our statement and gives an impressive view to the different material behaviour of metals and FRP.

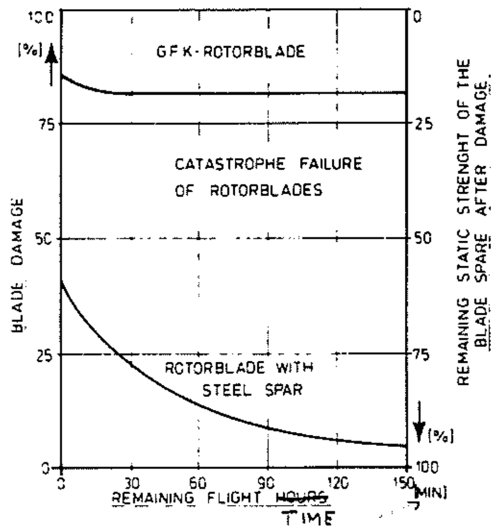

Figure 40 FATIGUE LIFE AFTER DAMAGE

2. In addition to fracture mechanic investigation on composite materials already performed up to now considerable research is desirable. Mixed modulus laminates should also be considered.

Acknowledgement:

The authors wishes to thank BMVG and BWB, Germany, for permittance to publish impact test results.

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9. BLADE TEST, DAMAGE PHOTOGRAPHS

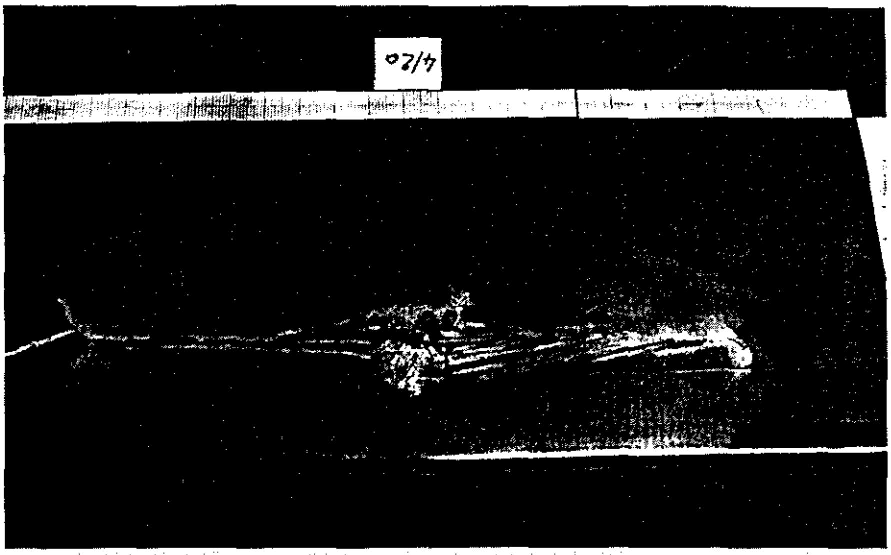

Figure 9 NUMBER 1 TEST SPECIMEN
AREA "a" BULLET ENTRY

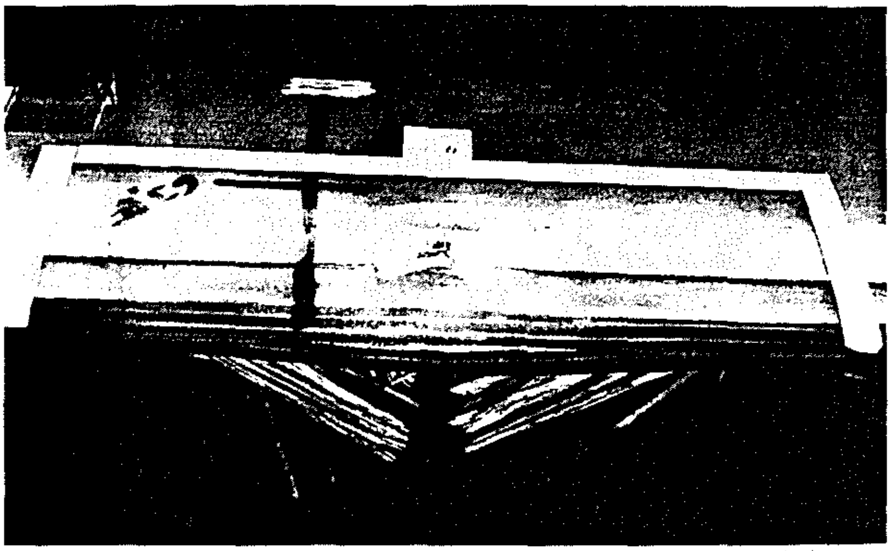

Figure 10 NUMBER 1 TEST SPECIMEN
AREA "a" BULLET EXIT

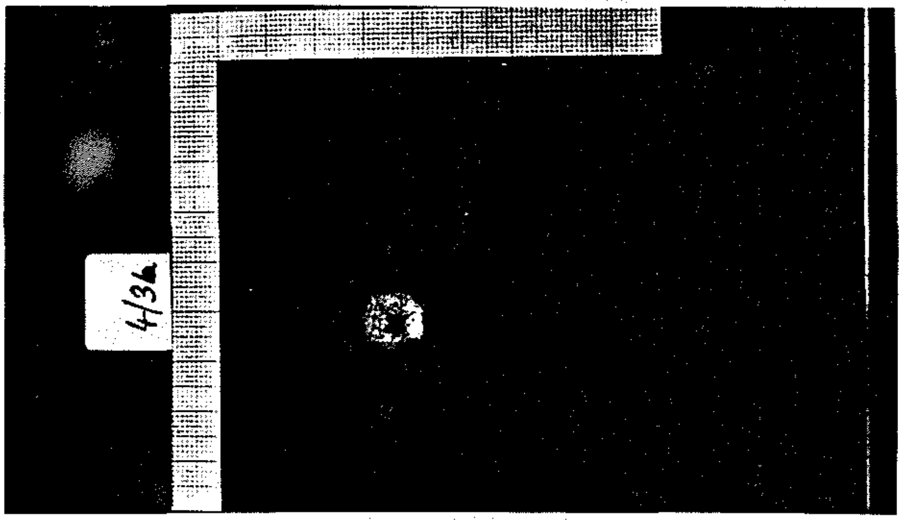

Figure 11 NUMBER 1 TEST SPECIMEN
AREA "b" BULLET ENTRY

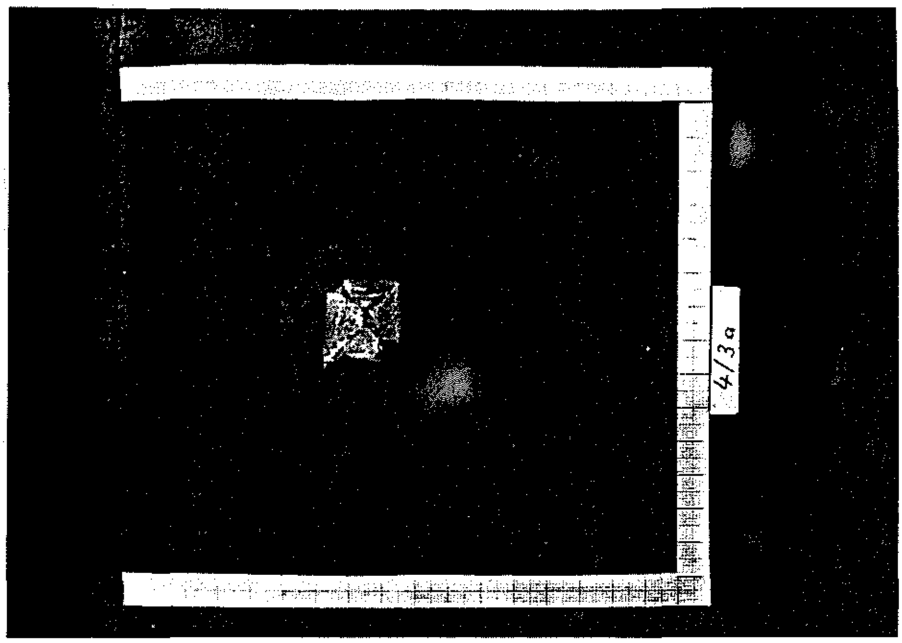

Figure 12 NUMBER 1 TEST SPECIMEN
AREA "b" BULLET EXIT

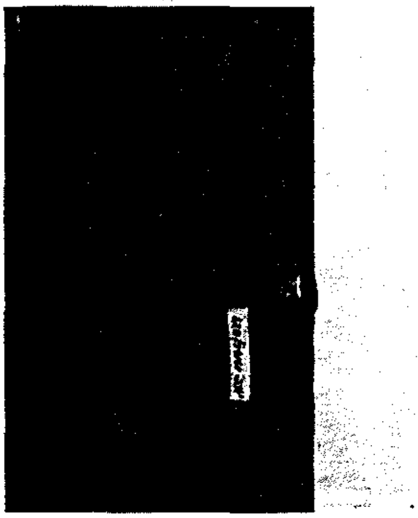

Figure 13 NUMBER 2 TEST SPECIMEN
AREA "a" BULLET ENTRY

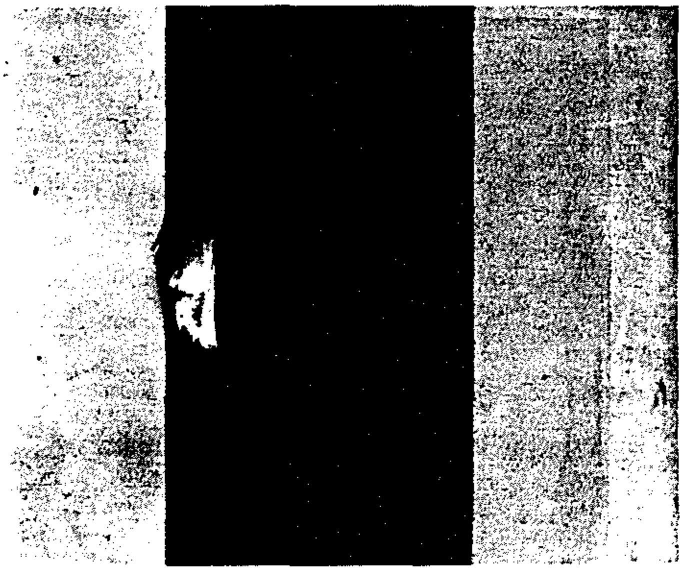

Figure 14 NUMBER 2 TEST SPECIMEN
AREA "a" BULLET EXIT

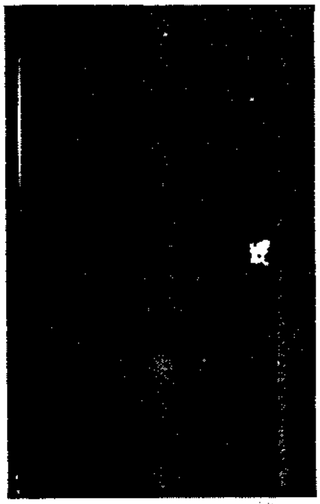

Figure 15 NUMBER 2 TEST SPECIMEN
AREA "b" BULLET ENTRY

Figure 16 NUMBER 2 TEST SPECIMEN
AREA "b" BULLET EXIT

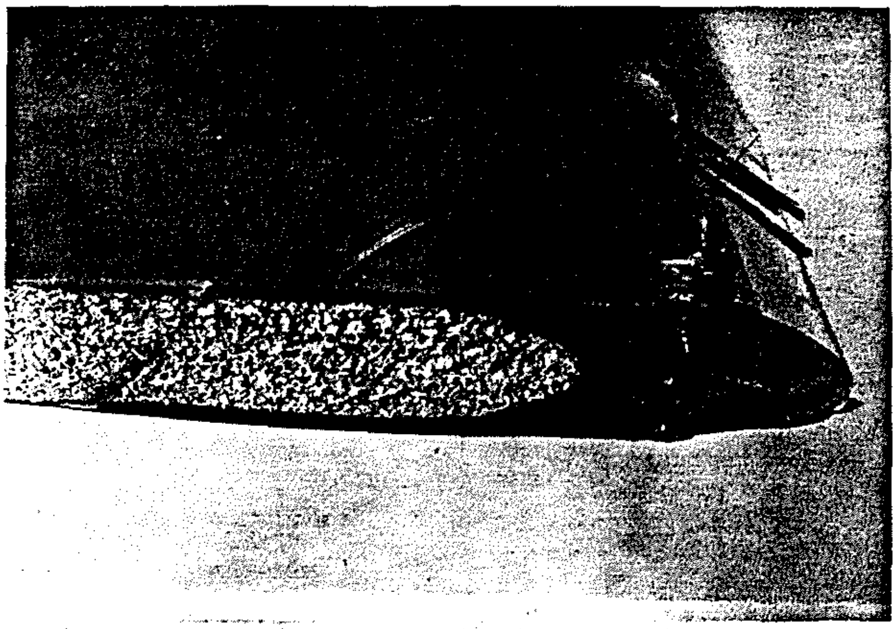

Figure 17 CROSS SECTION OF PENETRATION AREA "1a"

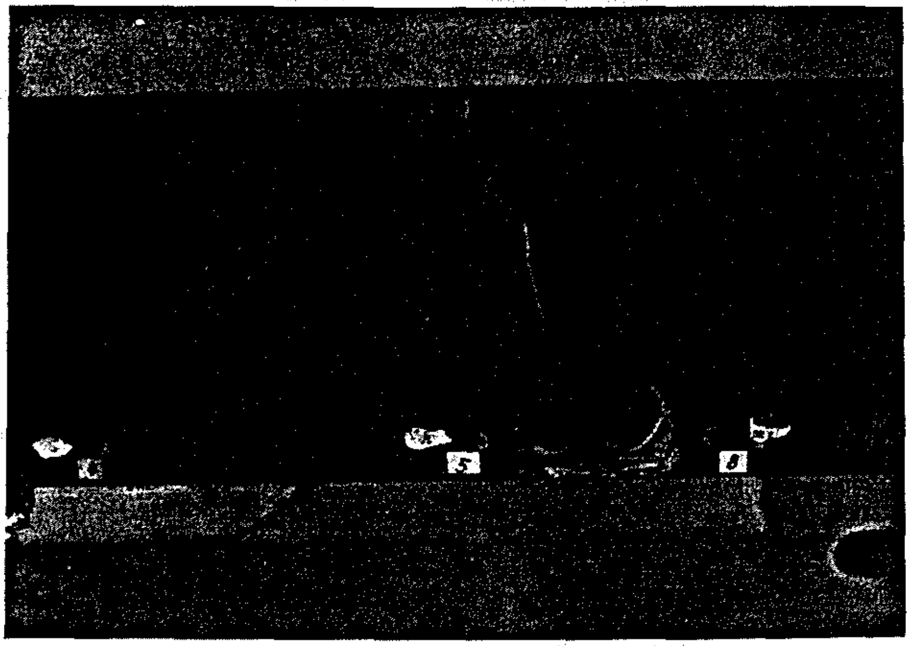

Figure 19 VIEW OF FAILED ROTORBLADE

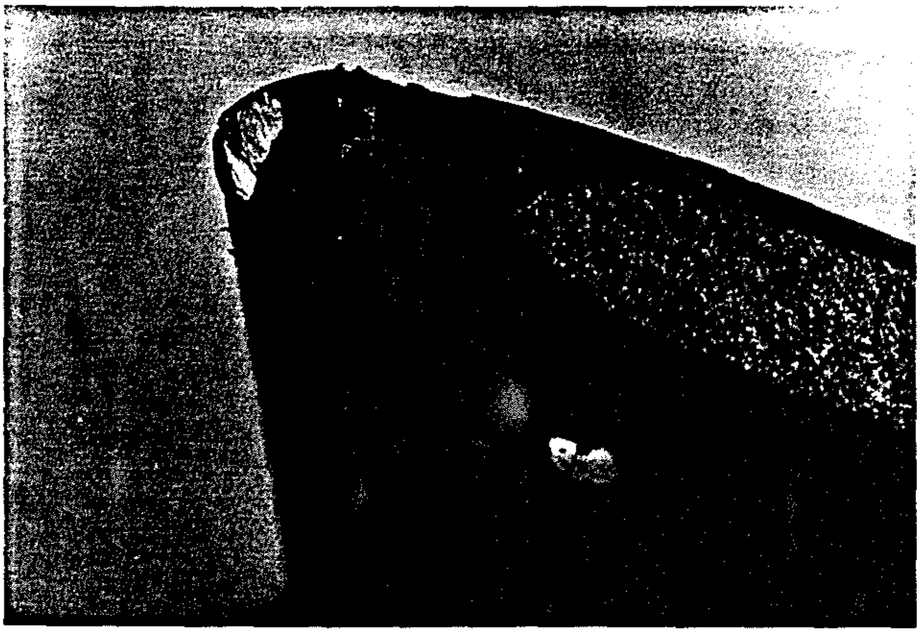

Figure 20 CROSS SECTION OF PENETRATION AREA "2a"

Figure 21 CROSS SECTION OF PENETRATION AREA "2b"

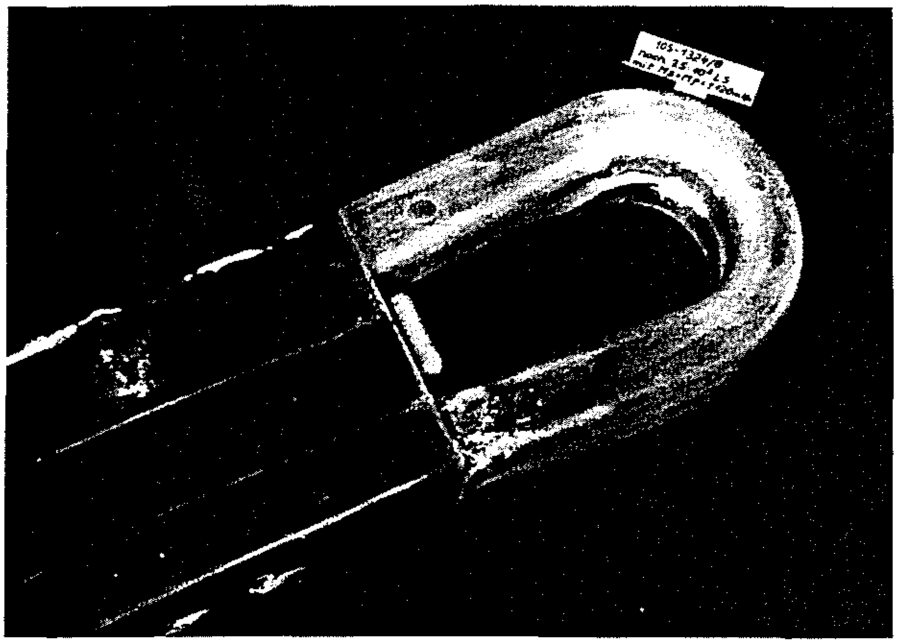

Figure 22 NUMBER 3 TEST SPECIMEN
BULLET ENTRY

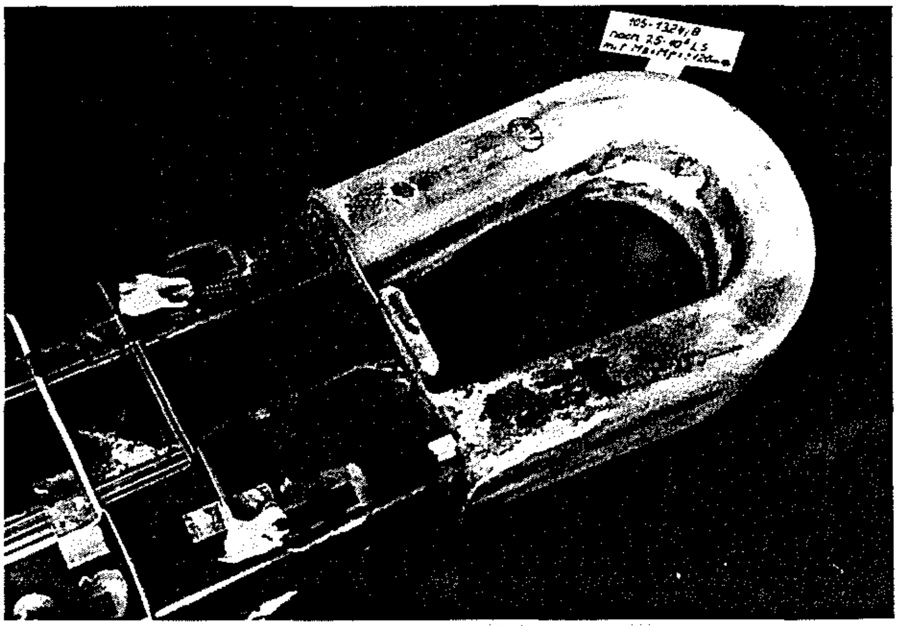

Figure 23 NUMBER 3 TEST SPECIMEN
BULLET EXIT

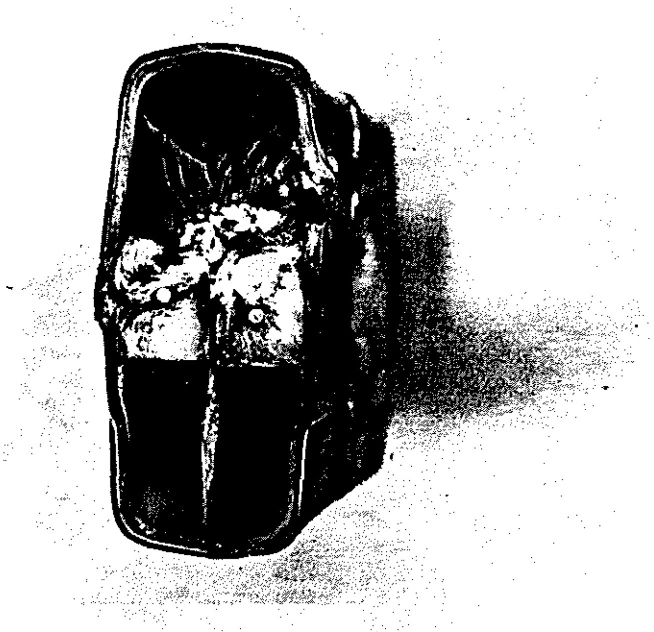

Figure 24 CROSS SECTION OF PENETRATION AREA "3"

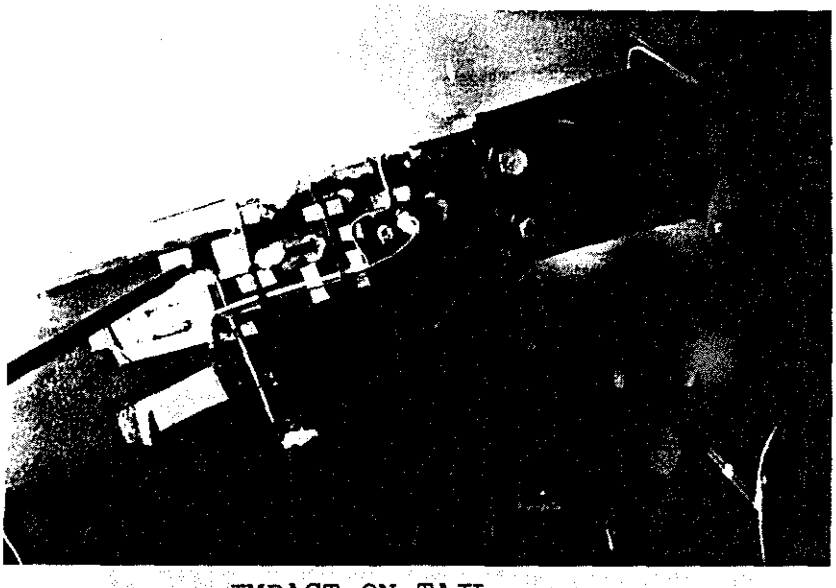

Figure 25 IMPACT ON TAIL ROTORBLADE BULLET ENTRANCE

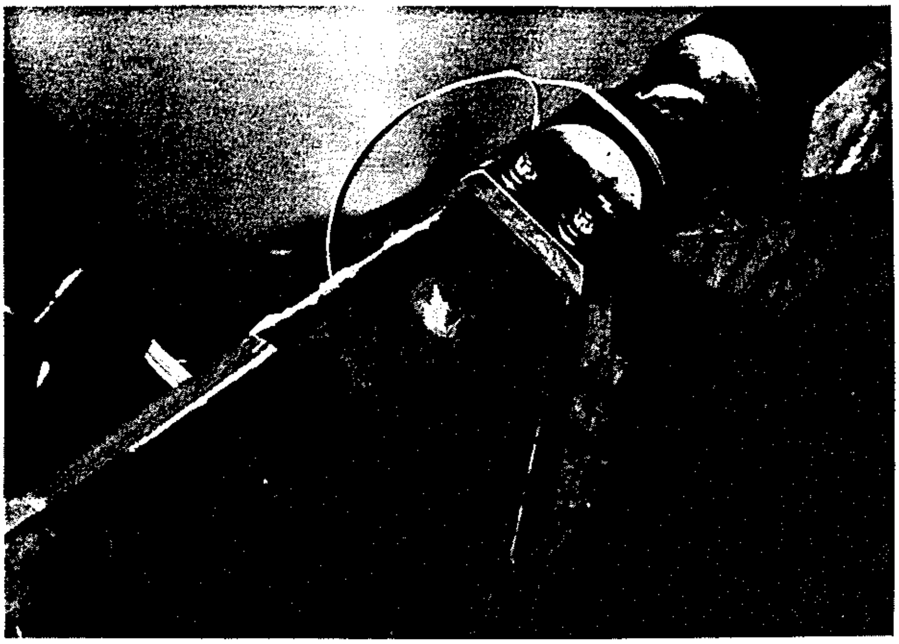

Figure 26 IMPACT ON TAIL ROTORBLADE BULLET EXIT

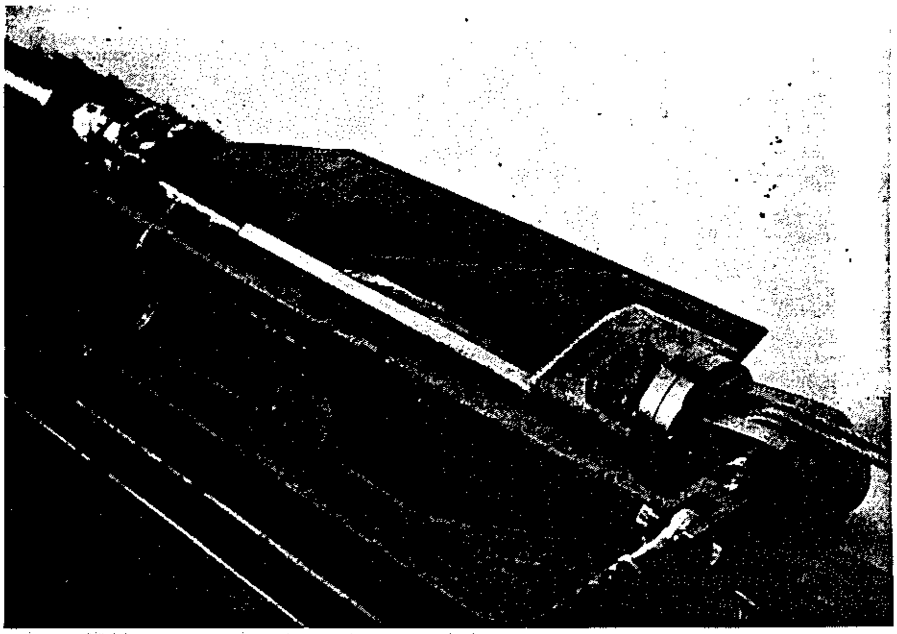

Figure 27 FATIGUE TEST SET UP FOR TAIL ROTORBLADES

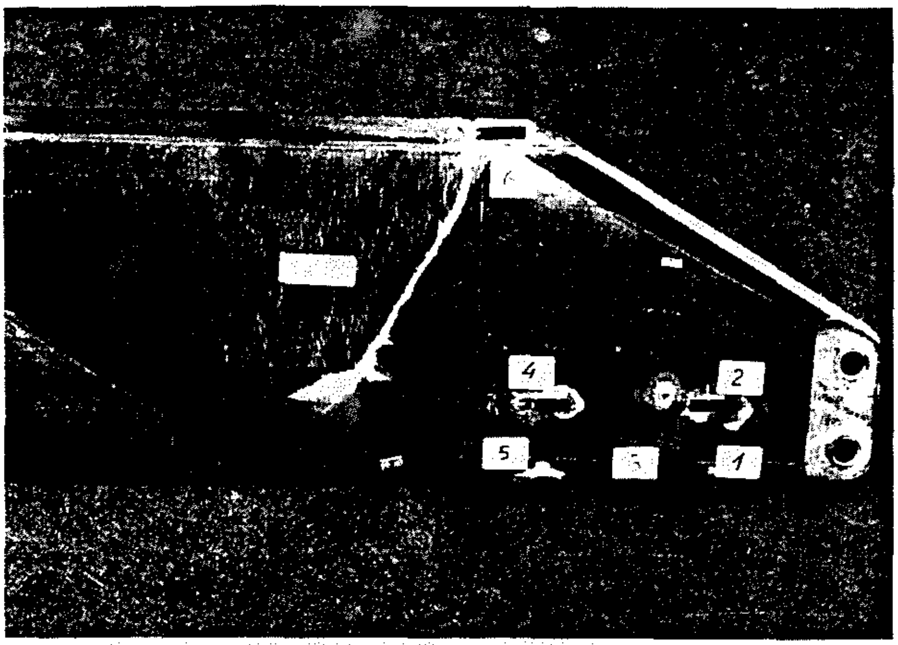

Figure 28 FATIGUE TESTED TAIL ROTORBLADE BULLET ENTRANCE

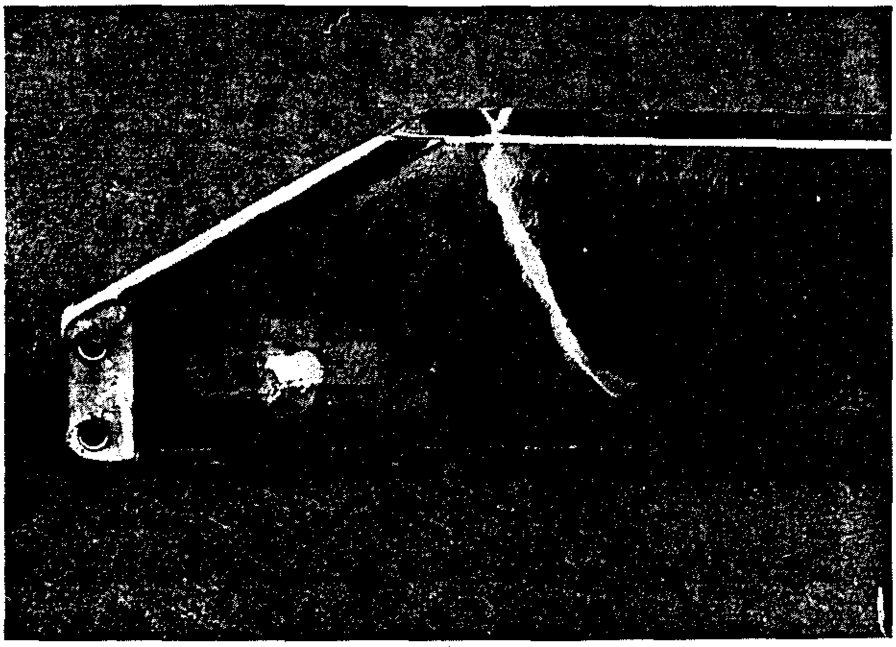

Figure 29 FATIGUE TESTED TAIL ROTORBLADE BULLET EXIT

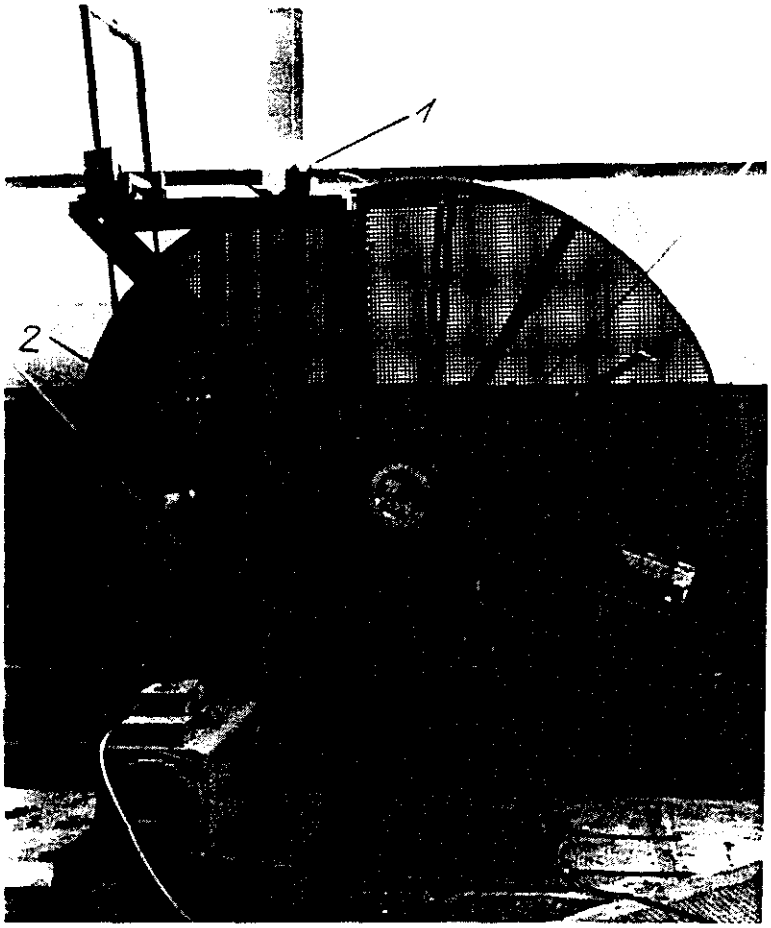

Figure 30 IMPACT TEST MASCHINE FOR TAIL ROTORBLADES

1. Magnetic mechanism for releasing
2. Pendulum catch mechanism
3. Fastening for rods

Figure 32 IMPACT OF TAIL ROTORBLADE ON WOODEN ROD NO VISIBLE DAMAGE

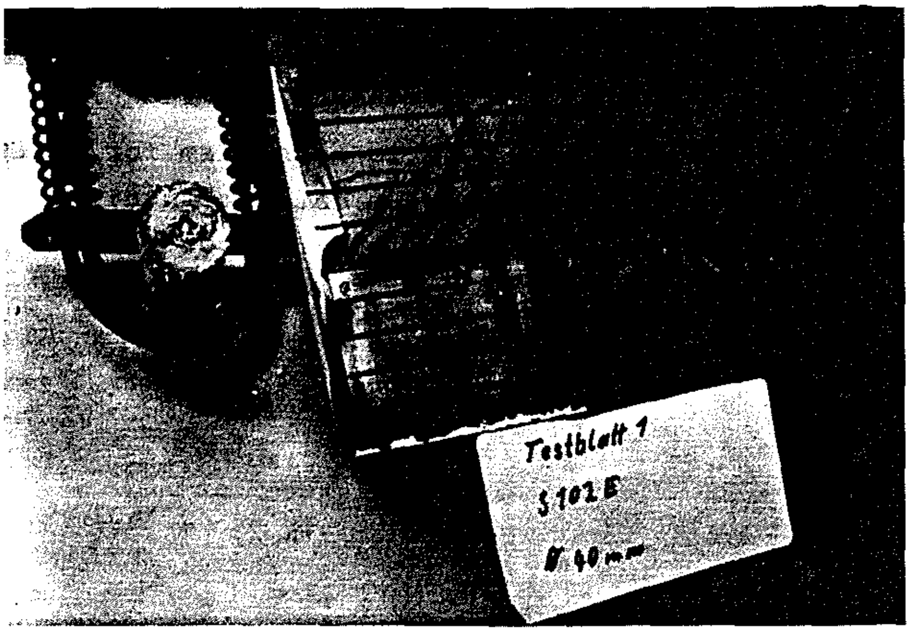

Figure 33 IMPACT OF TAIL ROTORBLADE ON WOODEN ROD FIRST SURFACE BUCKLING

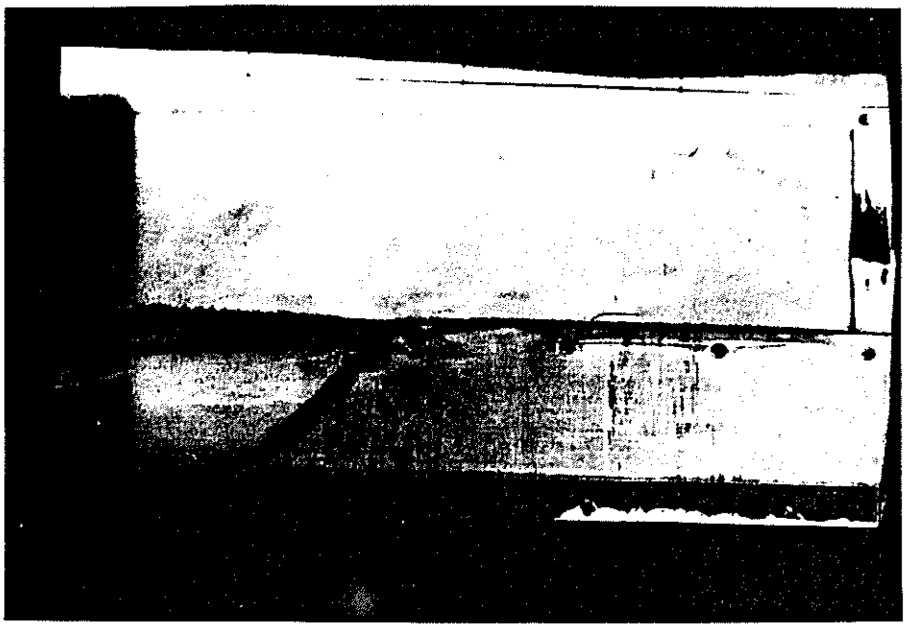

Figure 34 IMPACT OF TAIL ROTORBLADE ON WOODEN ROD ø 55 mm

Figure 35 IMPACT OF TAIL ROTORBLADE ON WOODEN ROD
SKIN SEPARATION, TIP CAP CRACKED

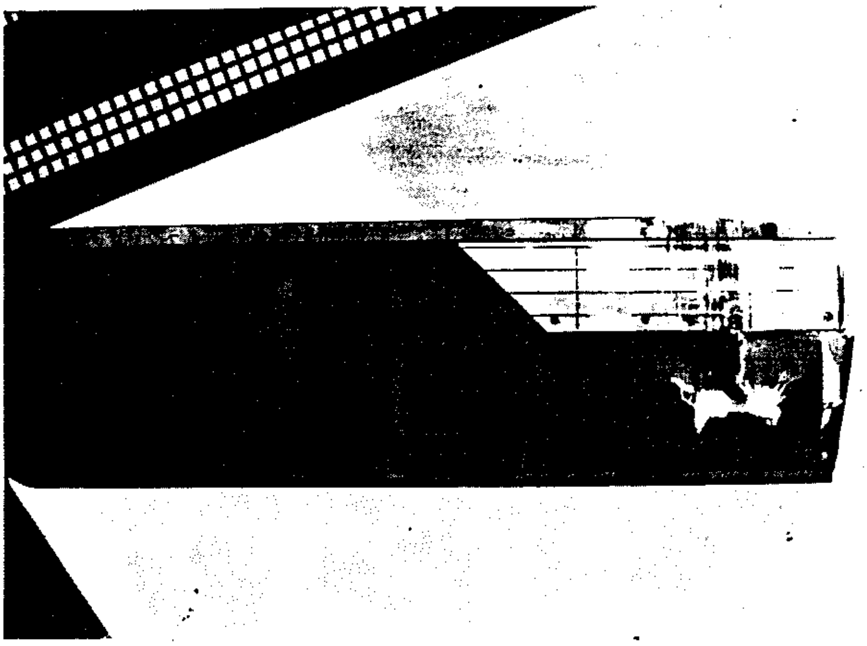

Figure 36 — IMPACT OF TAIL ROTOR BLADE ON WOODEN ROD ø 60 mm
SKIN SEPARATION, TIP CAP CRACKED

Figure 37 — IMPACT OF TAIL ROTORBLADE ON WOODEN ROD
TOTAL FAILURE

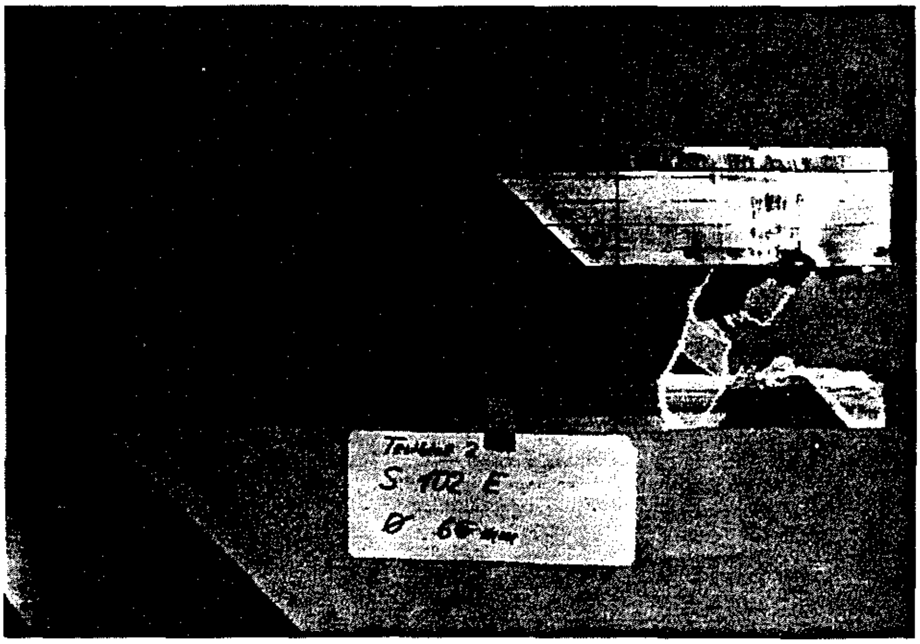

Figure 38 IMPACT OF TAIL ROTORBLADE ON WOODEN ROD TOTOAL FAILURE

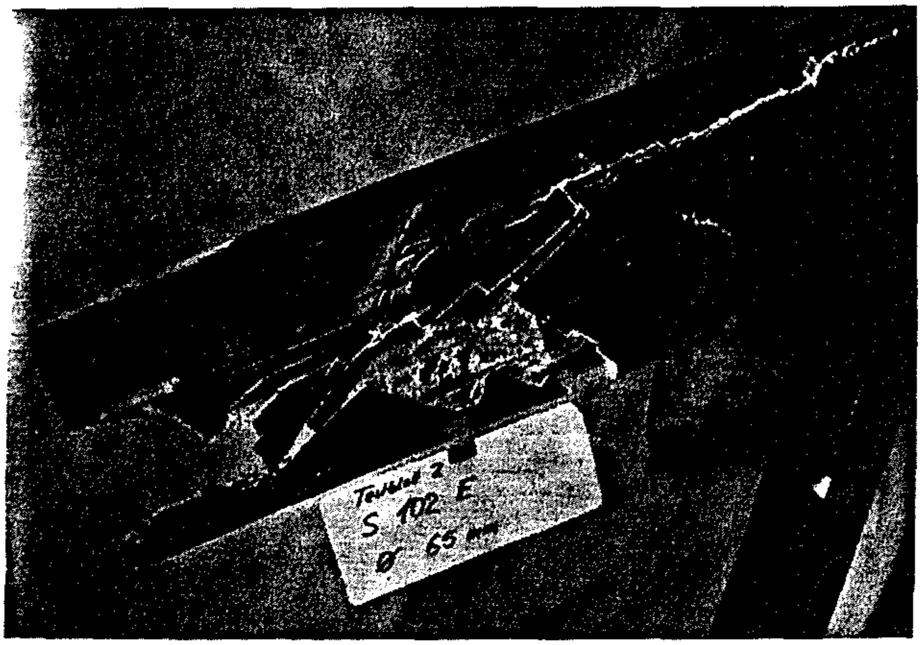

Figure 39 IMPACT OF TAIL ROTORBLADE ON WOODEN ROD TOTAL FAILURE