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# R & D ON COMPOSITE ROTOR BLADES AT AGUSTA

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SUMMARY

The achievement of improved methodologies for the construction of composite rotor blades requires an extensive and exhaustive research activity, which is being carried out by AGUSTA Company in cooperation with Istituto di Ingegneria Aerospaziale of Politecnico di Milano.

The research plan includes the development of a unique Finite Element Program (HANBA 2) for blade section analysis and the working-out of reliable models for the study of behavior and failure criteria of composite materials.

Program HANBA 2 is based on finite element discretization on section plane only, thus allowing the computation of "beam solutions" for any shape and material anisotropy and inhomogeneity of the section concerned. Particularly the program allows the evaluation also of the interlaminar and joint stresses of non-linear material models with unbalanced anisotropy.

The identification of composite material models requires a large number of experimental data to be obtained from the testing, to complete failure, of several flat and cylindrical specimens in biaxial stress state.

By this tools composite rotor blades have been designed and manufactured and are being submitted to static and fatigue tests as described herein.

## 1. INTRODUCTION

The design of a GRP (Glassfiber Reinforced Plastics) rotary wing is generally based on well-established metalwork criteria and procedures. An initial plan for a metal rotor is often performed, and the GRP elements are then designed so as to have equal stiffness and inertia properties.

This method ensures the accomplishment of rotors that are considerably more fatigue resistant and damage tolerant than the metal ones, although the outstanding potentials of composite materials cannot be fully exploited.

One of the most typical features of such materials is anisotropy, which can be restrained, within broad bounds, by the designer through the choice of the proper ply layup, such as it would be, for example, for the optimazation of the anisotropy of elastic and fatigue properties. In other words, as far as the rotor blade is concerned, the designer can avail himself of a greater number of project variables, which could be used for the attainment of special properties, which would otherwise be impossible to fulfill with metal blades. For instance, such advantageous matches of the bending stress with the torsional stress of the blade could be worked out as to bring about beneficial effects as regards weight and vibration level. This advanced type of designing requires a more thorough knowledge and more powerful tools than the ones available at present.

The developments that appear to be absolutely needed are the following :

a. material models to be supported by substantial experimentation and to be capable of providing an accurate performance of the non-linear behavior of multilayer FRPs, complete of failure criteria regarding all possible failure modes;

b. effective static analysis procedures for the evaluation of the stiffness properties and stress state of elements; they shall employ the material models as per item a.;

c. Versatile procedures for the analysis of rotor dynamics and stability, capable of utilizing the stiffness values obtained with the procedure as per item b.

The above objectives form the framework of a four-year research and development plan which AGUSTA Company started carrying out two years ago. A cooperation relationship between the company and Politecnico di Milano was set up, wherefore the following contracts were undersigned:
nos. 432, 781, and 782.

A plan of this kind clearly requires also a considerable development of production and quality control technologies supplemented with that of design technologies. One of its aims is the production of the main rotors of helicopter A109B, as sketched in Fig. 1, and helicopter A129.

The present paper outlines the activities performed in relation to items a. and b. as per above. As regards the activity related to item c., it is fully reported in another paper (1) to be delivered to this Forum.

## 2. PRELIMINARY TESTS ON MATERIALS

Uniaxial tensile stress tests were performed on standard shape flat specimens, with material axes at $0^{o}$, $45^{o}$, and $90^{o}$ to specimen axis.

All specimens were manufactured with different glass-epoxy prepreg warps of various makes. Unidirectional fiber specimens, as well as specimens with differently oriented multilayered laminates, though in smaller number, were used. For each material and fiber orientation six identical specimens were made and employed.

Specimen strains were measured by chip gages, and low strain levels only were recorded by bonded strain gage rosettes.

## 3. PRELIMINARY IDENTIFICATION OF MATERIALS FOR THE DESIGN OF BEAM ELEMENTS (BLADES)

As regards blades, which are in a moderately biaxial stress state, except for the root area, materials were indentified by the following procedure :

- polynomial best fit of stress-strain data of each group composed of six identical unidirectional-fiber specimens;
- computing of the tangent moduli of unidirecitional laminae as derivatives of the best fit polynomials;
- computing of the properties of multilayer laminates as the resultant of the superposition of lamina properties.

Figs. 2 and 3 illustrate two examples of polynomial interpolation of the experimental data related to two different specimens. A proper selection of the order of the polynomial involved has always brought about a good approximation of experimental points. Unfortunately this extremely simple method can be applied only in case of uniaxial stress states and cannot provide the characteristics of the interactions occurring between layers. Such restrictions are particularly rigorous, when material behavior is strongly non-linear.

## 4. PRELIMINARY MATERIAL IDENTIFICATION FOR TRIDIMENSIONAL ANALYSES

For the performance of finite element analyses based on the codes available at present a material model was first determined which was formed by the superposition of the following two different materials :

A - an elastic anisotropic material displaying the characteristics of fibers alone;

B - an elastic-plastic isotropic material with a behavior very close to that of the resin in the composite.

In relation to each unidirectional fiber layer, material A is defined as an orthotropic material having all moduli equal to zero, except for the normal modulus $E_F$ along fiber direction.

Material B is a strain hardening elastic-plastic material obeying von Mises' plasticity law; its characteristics are therefore defined by Young's modulus $E$ and by Poisson's coefficient $\nu$ as related to elastic behavior, and by yield stress $\sigma_Y$ and plastic modulus $E_T$, both to be measured by a tensile stress test.

The identification of composite material therefore requires the definition of the five constants $E_F$, $E$, $\nu$, $\sigma_Y$, $E_T$, which shall be such as to ensure the closest possible approximation of the experimental data of both unidirectional and multidirectional fiber specimens.

Clearly material B of this model does not display resin behavior, but rather shows all that should be added to material A for the attainment of the best approximation for the laminate. Although the model thus identified is rather elementary, it does offer some basic advantages which make it interesting at least for the preliminary stages, as

- it is a consistent model requiring a limited number of parameters;
- it can be employed with the finite element codes available at present, for which no modification would be required as the indication of two coinciding elements for each element - one regarding material A, the other material B - is sufficient;
- it allows a separate, though approximate and somewhat conventional evaluation of stress in the resin and fibers.

Figs. 4 and 5 draw comparison between experimental data and the results of specimen finite element analyses performed on the basis of Program ADINA. The two specimens shown were made of the same material with different ply layups.

This two-phase material model was used in several tridimensional analyses mostly performed by code ADINA and, to a smaller extent, by NASTRAN MSC.

Fig. 6 shows the exploded view of one of the meshings used for the analyses of 1/8 of the hub of A109B main rotor. The idealization employs parabolic isoparametric elements having several different fiber arrangements.

## 5. UNIAXIAL FATIGUE TEST

Several fatigue tests on flat specimens were carried out, to complete failure, under cyclic synusoidal tensile load in load control mode. The tests were performed on different glass-epoxy laminates of various makes. The cause and kind of the various damage types met during testing were also thoroughly studied. The results of such investigation were amply reported at a previous meeeting.

Fig. 7 shows the test rig consisting of four independent hydraulic cylinders which can be controlled both in load and in displacement modes.

Fig. 8 shows an example of the results obtained in terms of S-N curves.

## 6. FURTHER EXPERIMENTAL INVESTIGATION

For a better identification of materials additional experimental results are required as related to laminates in biaxial stress states induced by both stress and static load conditions.

Several authors regard tube specimens as the most adequate for this type of tests, as they can easily be submitted to axial tensile/compressive stresses, internal pressure and torsional stress (3,4).

For an initial investigation thin walled tube specimens have been used, which are subject to torsional and axial tensile static load and are made in such a way that the laminate reference direction is at $0^{o}$, $90^{o}$, and $\pm 45^{o}$ to the axis of the specimen. This way a considerable range of biaxial stress states can be obtained. In fact, let us assume that $\sigma$ and $\tau$ are the normal and shear stresses respectively, which act on a specimen section perpendicular to the axis, and $R$ is $\tau/\sigma$ ratio. Moreover, assuming $x$ and $y$ are the two mutually orthogonal reference axes, then in type a, b, c, and d specimens axis $x$ of the laminate is at $0^{o}$, $90^{o}$, $45^{o}$ and $-45^{o}$, respectively, to specimen axes (see Fig. 9). It will then be clear that within the space of stresses, $\sigma_x$, $\sigma_y$ , $\tau_{xy}$ , as related to laminate axes, along with any variation in value $R$ , the stress states of specimens a and b lie on planes $\sigma_x - \tau_{xy}$ and $\sigma_y - \tau_{xy}$ respectively (Fig. 10). It can then be easily proved that the stress states of specimens c and d lie on two planes intersecting plane $\sigma_x - \sigma_y$ along the bisecting lines of the second and forth quadrants and form angles equal to $\pm \tan^{-1}(1/\sqrt{2}) = \pm 35.26^{o}$ (Fig. 10).

Through the seven values selected for parameter $R$ , it is then possible to determine, in the three specimen types, the 28 stress states which, as shown in Fig. 10, appear well distributed over the half space where tensile stress prevails.

The first tests will then be performed on two laminate types, where the layers are arranged as indicated in layouts 1 and 2 of Fig. 9 and are 1.2 and 2.4 mm thick. It can be noticed that for an orthotropic laminate (e.g. laminate 1), if $x$ and $y$ are orthotopy axes, the stress states present on one side of plane $\sigma_x - \sigma_y$, such as the ones with $\tau_{xy} \geq 0$, are sufficient. Therefore, the number of the specimens required for an orthotopic laminate is cut to 15, whereas those required for a non-orthopic one are still 28.

The test program provides 258 tube specimens, corresponding to two laminates, two thickness measures, and three identical specimens per stress state. In Fig. 11 one of the cylinder specimens is drawn while Fig. 12 shows the testing machine, by which a 120,000 kg maximum tensile stress load can be applied; this means that thicker specimens can be employed too.

This initial series of tests aims at a fareful consideration of material models, as well as of the failure criteria applicable to FRP laminates with different fiber arrangements. The specimens have been completed and tests have been commenced in the past few days.

The program provides also tensile stress tests on flat specimens composed of the same laminates as the tube specimens, with axis of the laminate at an angle of $0^{o}$, $90^{o}$, and $\pm 45^{o}$ with the specimen axis. The purpose of this series of tests is the consideration of the correlation existing between the results of tests on flat specimens and those of tests on tube specimens, as well as the evaluation of the effect brought about by specimen width. For this reason a total of up to 168 specimens was made having 1", 1.5", 2", and 2.5" widths.

Fig. 13 shows a flat specimen and Fig. 14 the stress states of these four specimen types. For the attainment of the shear strain caused by tensile stress when orthotropy axes are not aligned to specimen axis, some swinging grips were constructed to be utilized with a standard tensile stress testing machine (Fig.15).

For a complete record of the strain suffered a rosette clip gage was also planned (Fig. 16), which in the past few days has been submitted to calibration tests.

## 7. COMPUTER CODES FOR BEAM SECTION ANALYSES

As it has previously been remarked (5), accurate analyses of slender beams, such as rotor blades are, can be properly performed by finite element discretization of the section concerned and by analytic solution on axis direction.

This approach allowed the development of Program HANBA which takes into account only the axial and shear stresses acting on the section, like in the classical theory of homogeneous beams.

With Program HANBA only linear materials can be considered, but they can be, to any extent whatever, anisotropic and different one from the other in various parts of the cross section.

The elements available for section idealization are indicated in Fig. 17.

Program HANBA, which is at present operational, ha proved so flexible and effective as to be used as analysis module in automatic optimization procedures.

To overcome the limitations of Program HANBA, a new, more comprehensive formulation had to be worked out, which would take into account complete stress states and non-linear behaviors of materials. In addition to beam center solutions, i.e. solutions that are valid at a certain distance from the ends and are determined only by beam section forces and moments, by this new formulation also beam end solutions can be otanined, which are the solutions to an eigenproblem where matrices are the same as in the beam center problem (de Saint Vénant problem).

From the above formulation Program HANBA2 was derived, which is inclusive of the elements indicated in Fig. 18 in addition to HANBA elements. It should be noted that the lamina element (which can be in a complete stress state), makes it possible for a laminate to be subdivided into its component elements, as well as for a thin resin layer bonding two section portions to be modeled.

The laminate idealized with several lamina elements can then be connected to a single element idealized laminate by means of proper transition elements. This property makes the program considerably flexible and therefore suitable for many uses.

Program coding and module tests have so far been completed and system tests are about to be started.

## 8. OPTIMIZING OF BLADE DESIGNS

For the achievement of an optimum design of a GRP rotor blade, a conventionally designed metal blade was initially worked out. A GRP blade was subsequently designed, which had its torsional stiffness and C.G. location very close to those of the metal blade.

This design was then utilized as starting point in a non-linear mathematical procedure which optimizes weight and natural frequencies and keeps both torsional stiffness and C.G. location as close as possible to the initial ones by submitting design variables to one-sided constraints.

Fig. 19 shows a flow design for the automatic optimizing procedure, of which

Program HANBA is an essential module.

Fig. 20 shows the cross sections of the metal blade, the initially designed GRP blade, and the final result for the optimizing procedure, namely helicopter A129 blade.

Table 1 shows the main data of all three designs.

## 9. ELASTIC TESTS ON BLADE COUPONS

The reliability of the material models, and of Program HANBA procedure as well, was verified by means of elastic tests performed on blade coupons subject to bending, shear, and torsional stresses.

Fig. 21 shows one of such coupons as equipped with gages on the test rig.

Tables 2 and 3 collate esperimental surveys and the results of HANBA analysis. Their consistency is usually satisfactory; the stronger discrepancies are mainly due ti HANBA restrictions regarding shear stress distribution in large flanges and to non-linear behavior of the materials.

As previously said, both restrictions will be removed by Program HANBA2.

## 10. FATIGUE TESTS ON BLADE COUPONS

Alternate constant-amplitude bending tests were carried out on blade coupons corresponding to the center (Fig. 22) and root areas (Fig. 23).

The last coupons tested, which incorporated the advantages of the technological improvement achieved, could bear 20 load Mcycles without undergoing either any considerable damage or any negligible degradation of their elastic properties.

## 11. BULLET IMPACT TESTS

Several impact tests were performed which utilized 12.7 mm bullets shot so as to provide different impact angles and points.

Figs. 24 and 25 show the considerably different effects brought about by the test to GRP and to the metal edging.

Subsequent to impact test, some coupons were submitted to fatigue tests and proved to be considerably damage tolerant from the view point of both elastic property decay and crack propagation.

## 12. CONCLUSIONS

At the end of the second year of research and development activity regarding GRP materials for rotary wings, the following remarks can be made :

- The identification of FRP materials requires numerous, long, and costly experimental tests, as other authors already pointed out. Actually only the results of such tests would ensure an adequate exploitation of the outstanding potentials of the materials involved.
- The development of suitable computing codes provides high advantages on condition that it be supported by an adequate experimental basis.

## 13. REFERENCE


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(2) Brivio A., Parenti G., Samanni G., Wagner V., Zanotti C. Consideration on the Fatigue Damage of Specimens Used for Composite Critical Components Qualification, USA-Italy Joint Symposium on Composites, Capri June 15-19, 1981.

(3) Hütter U., Schelling H., Krauss H. An Experimental Study to Determine Failure Envelope of Composite Materials With Tubular Specimens Under Combined Loads and Comparison Between Several Classical Criteria, AGARD CP 163 (1975) 3-1, 3-11.

(4) Owen M.J., Rice O.J. Biaxial Strength Behaviour of Glass Fabric Reinforced Polyester Resins, Composites, January 1981, 13-25.

(5) Giavotto V., Borri M., Puccinelli L., Mussi F., Caramaschi V. Evaluation of Section Properties for Hollow Composite Beams, Fifth ERAPLAF, Paper No. 35, Amsterdam, Sept. 4-7, 1979.

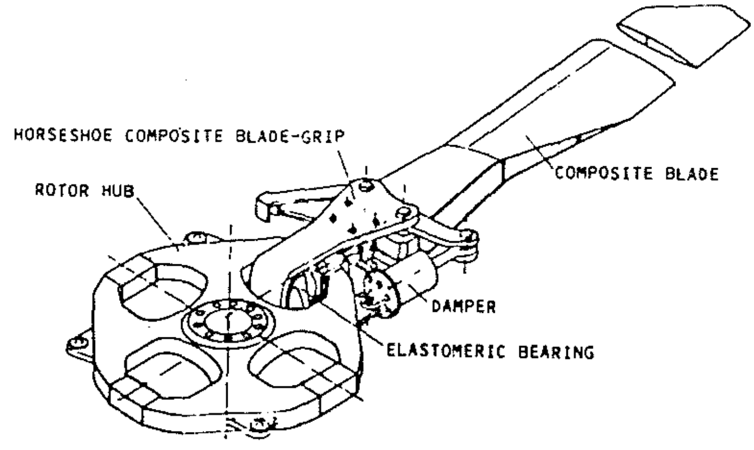
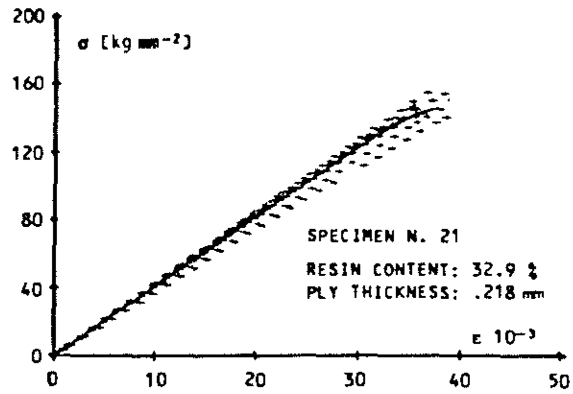



FIGURE 1 - A109B MAIN ROTOR ASSEMBLY




FIGIRE 2 - POLYNOMIAL BEST FIT; σ-ε CURVE

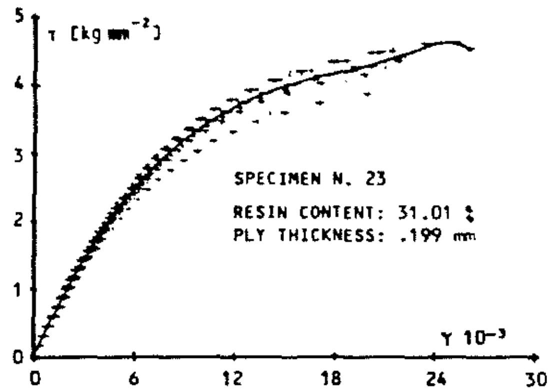



FIGURE 3 - POLYNOMIAL BEST FIT; τ-γ CURVE

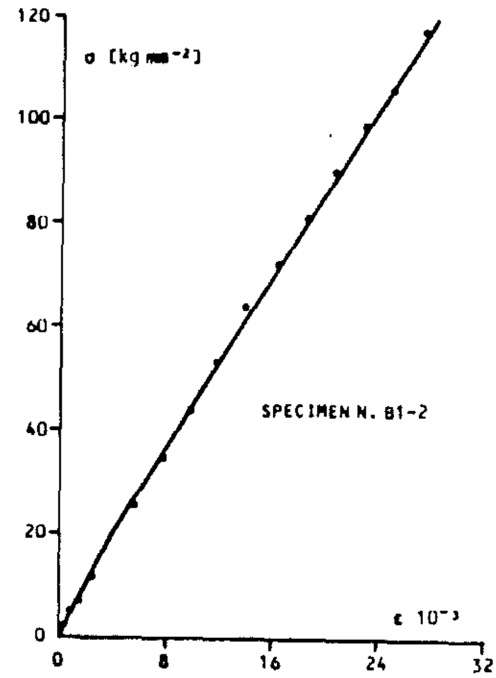



FIGURE 4 - TWO PHASE MATERIAL MODEL
COMPARISON OF F.E. WITH EXPER. DATA

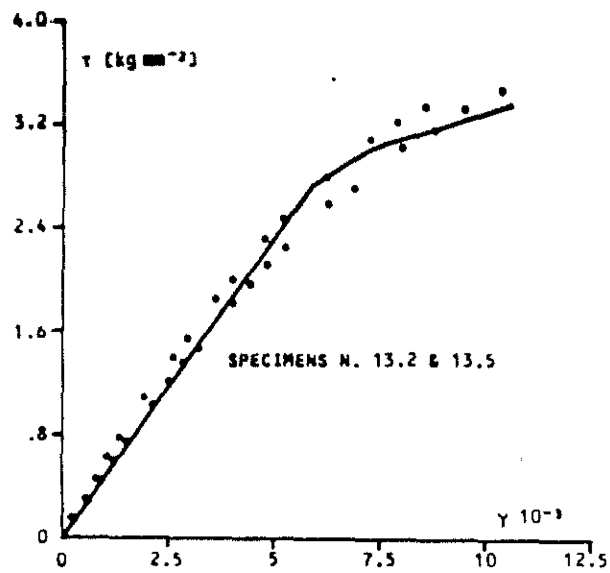



FIGURE 5 - TWO PHASE MATERIAL MODEL
COMPARISON OF F.E. WITH EXPER. DATA

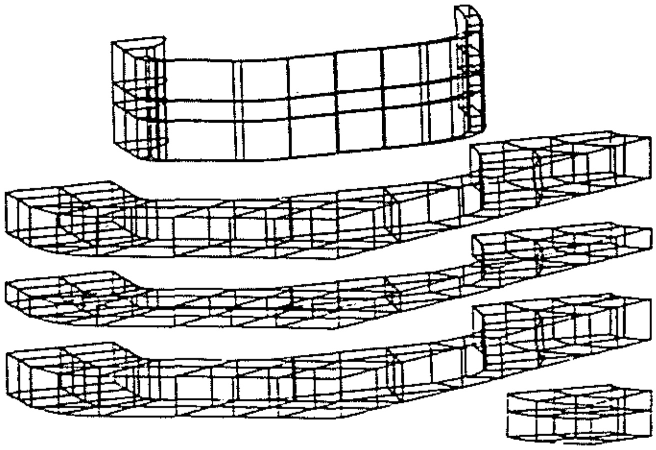


FIGURE 6 - 3D F.E. MESH OF 1/8 ROTOR HUB

FIGURE 7 - TENSILE FATIGUE TEST PLANT

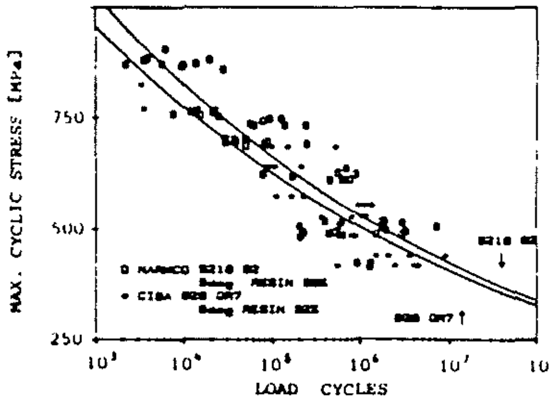
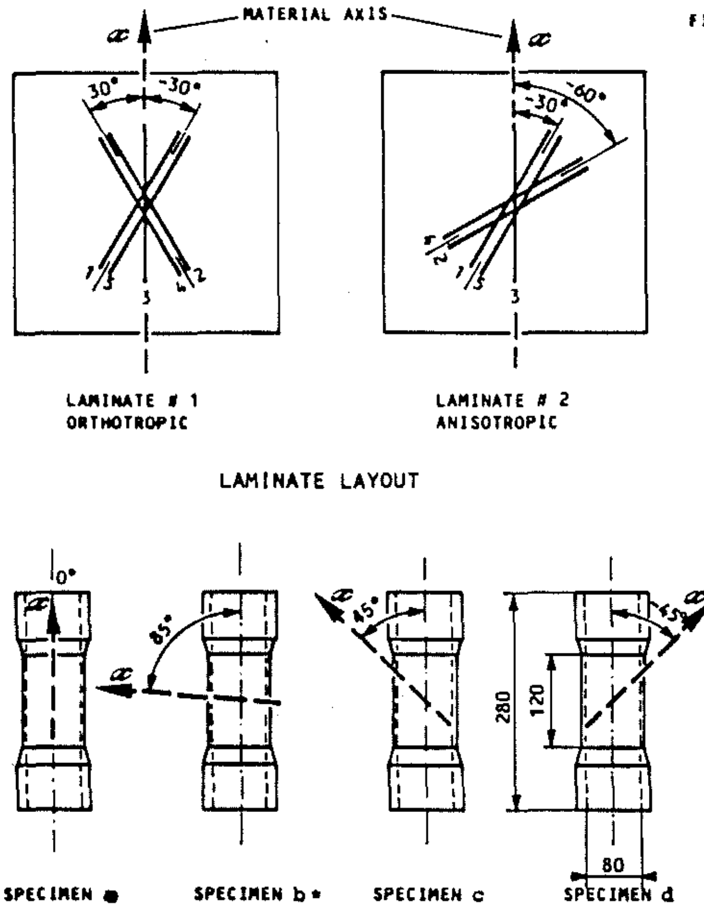



FIGURE 8 - S/N CURVES ( 3 PARAMETERS BEST FIT ) FOR R/S GLASS/EPOXY LAMINATES, FROM (2)




* 85° INSTEAD OF 90° TO AVOID OVERLAPPING JOINT

FIGURE 9 - LAMINATE LAYOUT AND TUBULAR SPECIMENS

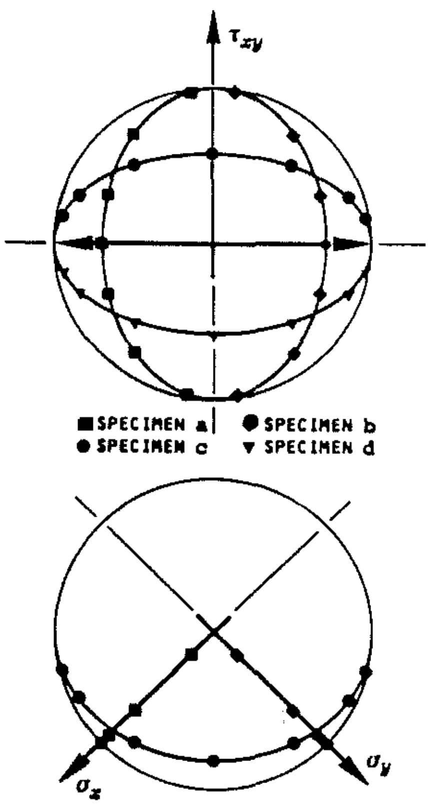



FIGURE 10 - STRESS CONDITIONS OF TUBULAR SPECIMENS

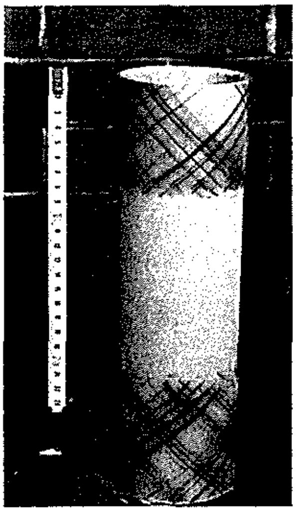


FIGURE 11 - TUBULAR SPECIMEN

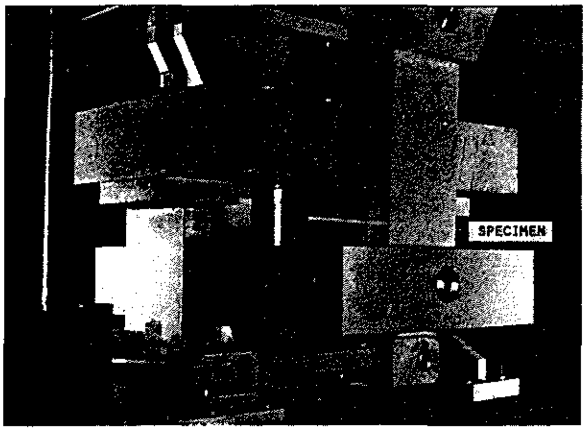



FIGURE 12 - LOADING MACHINE (TENSION & TORSION)

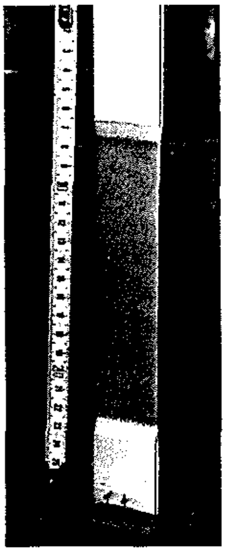


FIGURE 13 - FLAT SPECIMEN

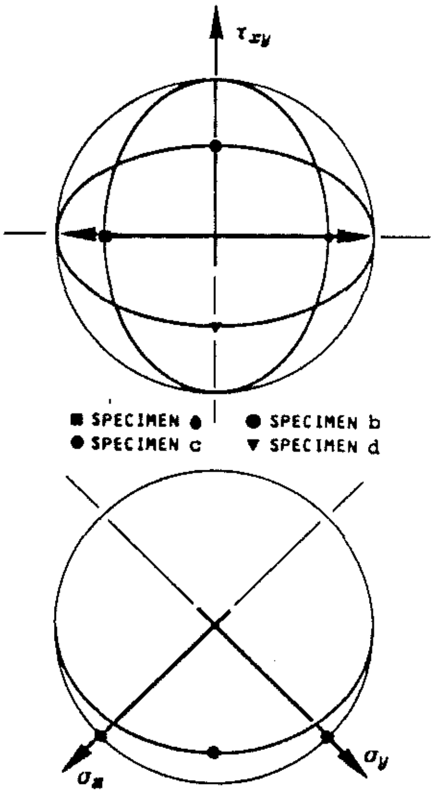



FIGURE 14 - STRESS CONDITIONS OF FLAT SPECIMENS

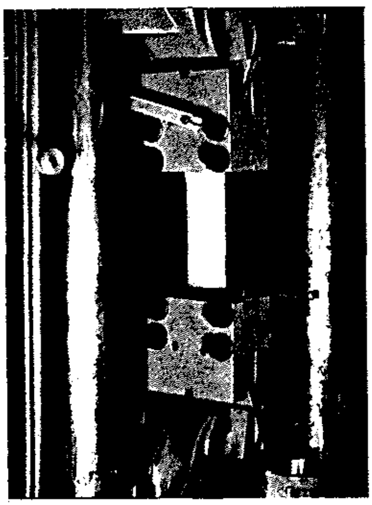


FIGURE 15 - SWINGING GRIP FOR FLAT SPECIMEN

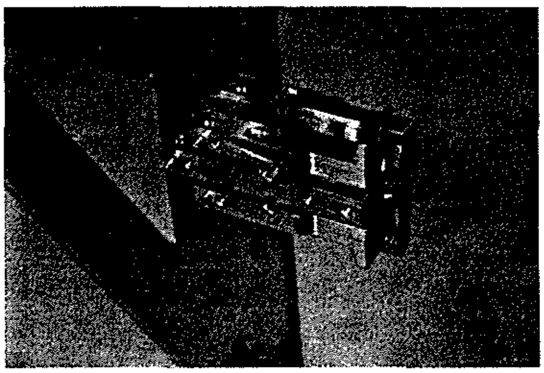


FIGURE 16 - ROSETTE STRAIN GAGE

## PROGRAM H A N B A

PURPOSE : FINITE ELEMENT BEAM SECTION ANALYSIS
MATERIALS: LINEAR, ANISOTROPIC

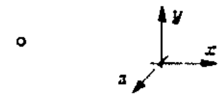
| ELEMENT | | STRESS COMPONENTS | NODES |
|---|---|---|---|
| ISOPARAMETRIC PANEL |  | $\sigma_z$ , $\tau_{zn}$ | 2 TO 4 |
| LUMPED MASS FLANGE |  | $\sigma_z$ | 1 |
| TWO NODE JOINT |  | $\tau_{zn}$ | 2 |

FIGURE 17 - ELEMENTS AVAILABLE IN PROGRAM HANBA

## PROGRAM H A N B A 2

PURPOSE : BEAM ANALYSIS BY F.E. DISCRETIZATION OF CROSS SECTION AND ANALYTICAL FORMULATION SPANWISE

CAPABILITY: NON LINEAR BEAM SECTION ANALYSIS (BEAM CENTER SOLUTIONS)

LINEAR BEAM END SOLUTIONS (FROM AN EIGENPROBLEM HAVING THE SAME MATRICES OF THE BEAM CENTER PROBLEM)

MATERIALS : NON LINEAR, ANISOTROPIC

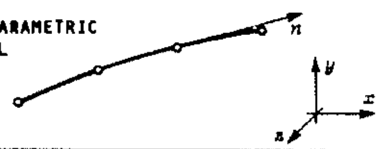
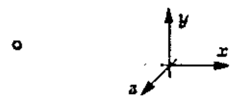
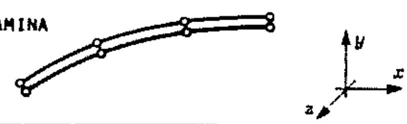
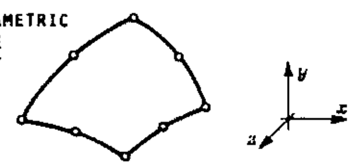
| ELEMENT | | STRESS COMPONENTS | NODES |
|---|---|---|---|
| ISOPARAMETRIC PANEL |  | $\sigma_z$ , $\tau_{zn}$ | 2 TO 4 |
| LUMPED MASS FLANGE |  | $\sigma_z$ | 1 |
| TWO NODE JOINT |  | $\tau_{zn}$ | 2 |
| LAMINA |  | ALL : $\sigma_x$ , $\sigma_y$ , $\sigma_z$ $\tau_{xy}$ , $\tau_{yz}$ , $\tau_{zx}$ | 2 TO 4 COUPLES |
| ISOPARAMETRIC SURFACE ELEMENT |  | ALL : $\sigma_x$ , $\sigma_y$ , $\sigma_z$ $\tau_{xy}$, $\tau_{yz}$, $\tau_{zx}$ | 3 TO 8 |

FIGURE 18 - ELEMENTS AVAILABLE IN PROGRAM HANBA2

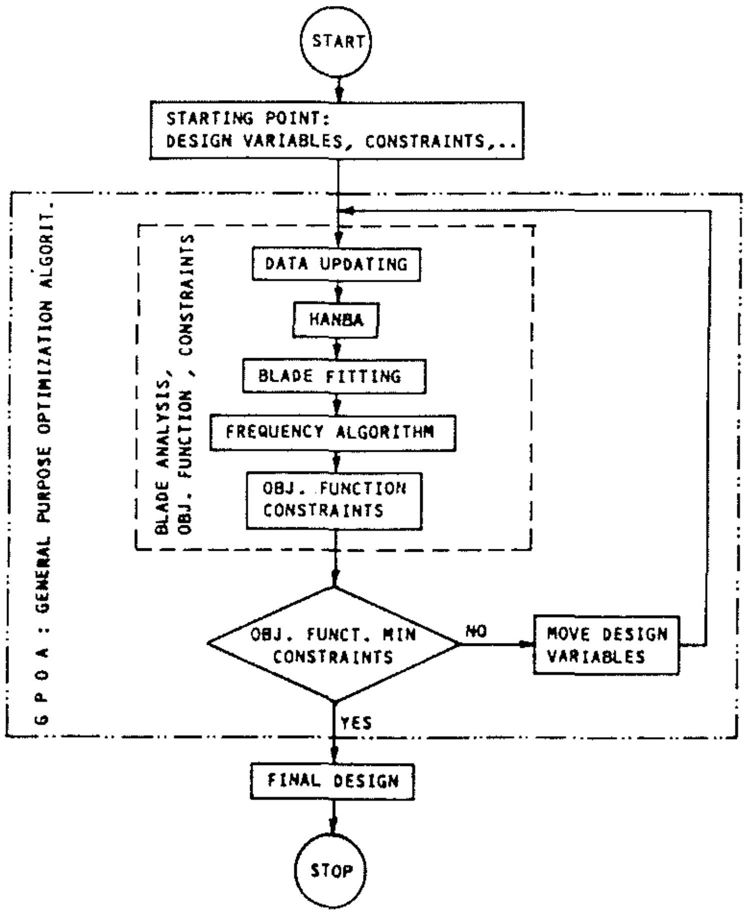
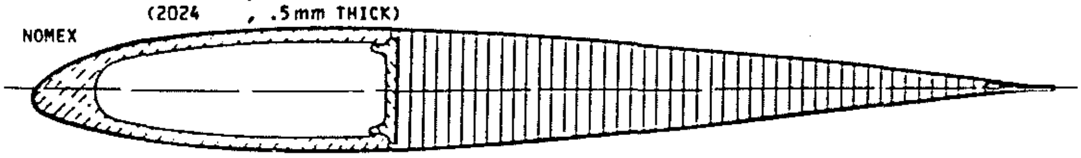



FIGURE 19 - GROSS FLOW DIAGRAM OF BLADE OPTIMIZATION

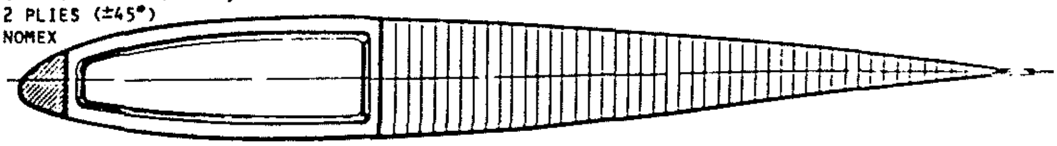
METAL DESIGN

CHORD 390
SPAR EXT. 34% CHORD (2014)
ANTIABR. STRAP 21% CHORD (AISI 301, .9mm THICK)
SKIN (2024 , .5mm THICK)
HONEYCOMB NOMEX



FIRST COMPOSITE DESIGN

CHORD 390
SPAR EXT. 34 % CHORD, 2 PLIES (±45°), 22 (0°), 3 (±45°)
ANTIABR. STRAP 21 % CHORD (AISI 301, .9 mm THICK)
SKIN 2 PLIES (±45°)
HONEYCOMB NOMEX



OPTIMIZED COMPOSITE DESIGN

CHORD 390
SPAR EXT. 38.5% CHORD, 3 (±45°), 16 (0°), 1 (±45°)
ANTIABR. STRAP 24 % CHORD (AISI 301, .8mm THICK)
SKIN 1 PLY FABRIC, 2 PLIES (±45°)
HONEYCOMB NOMEX

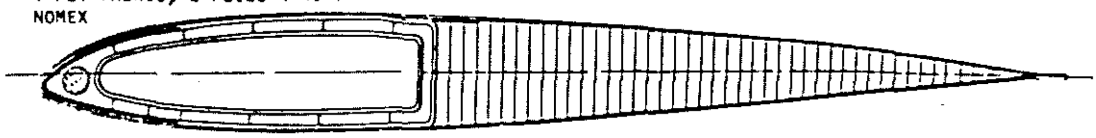


FIGURE 20 - DESIGN DEVELOPMENT OF A129 MAIN ROTOR BLADE

TABLE 1 - Design development of A129 main rotor blade

| | METALLIC BLADE SECTION | FIRST COMPOSITE BLADE SECTION | OPTIMIZATION COMPOSITE BLADE SECTION |
|---|---|---|---|
| WEIGHT (KG/M) | 5.8 | 7.9 | 6.7 |
| CHORD OFFSET OF C.G. (MM) | 88.3 | 116.5 | 93.3 |
| FLAPWISE BENDING STIFFNESS $(Kg \cdot MM^2)$ | .3099 E 10 | . 2709 E 10 | . 245 E 10 |
| CHORDWISE BENDING STIFFNESS $(KG \cdot MM^2)$ | .9214 E 11 | . 1055 E 12 | .4470 E 11 |
| TORSIONAL STIFFNESS $(KG \cdot MM^2)$ | .2532 E 10 | .2538 E 10 | .2127 E 10 |
| CHORD OFFSET OF SHEAR CENTER (MM) | 97.7 | 79. | 57.2 |
| CHORD OFFSET OF NEUTRAL AXIS (MM) | 82.2 | 99.7 | 77. |
| BLADE NATURAL FREQUENCIES (CYCLES/RPM) AT NOMINAL RPM . | | | |
| 1 ST | 2.72 (FLAP) | 2.64 (FLAP) | 2.61 (FLAP) |
| 2 ND | 3.53 (CHORD) | 4.37 (CHORD) | 4.22 (CHORD) |
| 3 RD | 4.78 (FLAP) | 4.84 (FLAP) | 4.72 (FLAP) |
| 4 TH | 5.78 (CHORD) | 5.9 (TORSION) | 5.61 (TORSION) |
| 5 TH | 6.11 (TORSION) | 7.88 (CHORD) | 7.44 (CHORD) |

TABLE 2 - Comparison between HANBA end experimental results
Spar section tests

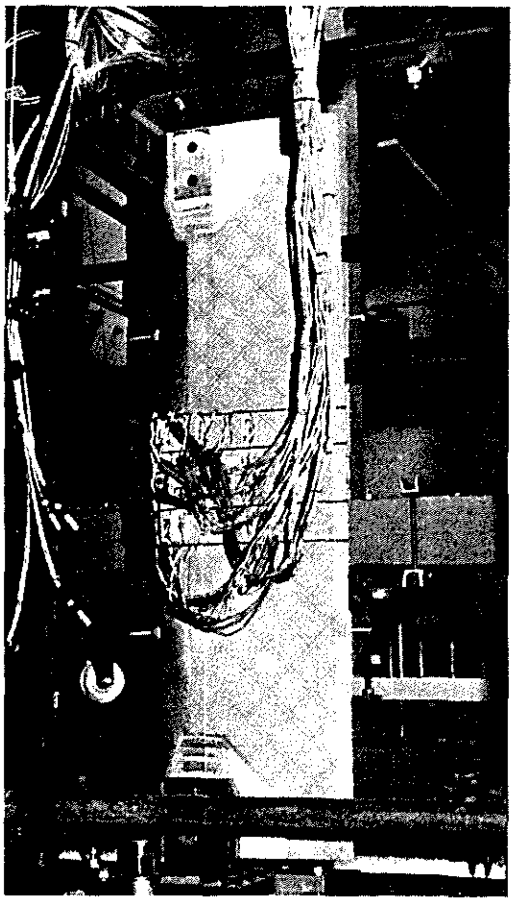
| | | TYPE A | TYPE B | TYPE C | TYPE D |
|---|---|---|---|---|---|
| FLAPWISE BENDING STIFFNESS (KG * MM²) | EXPERIMENTAL | .854 E 9 | .1 E 10 | .818 E 9 | .797 E 9 |
| | HANBA | .8433 E 9 | .1162 E 10 | .8008 E 9 | .7968 E 9 |
| CHORDWISE BENDING STIFFNESS (KG * MM²) | EXPERIMENTAL | .605 E 10 | .847 E 10 | .561 E 10 | .579 E 10 |
| | HANBA | .5965 E 10 | .8353 E 10 | .5808 E 10 | .5693 E 10 |
| TORSIONAL STIFFNESS (KG * MM²) | EXPERIMENTAL | .35 E 9 | .625 E 9 | .499 E 9 | .457 E 9 |
| | HANBA | .3359 E 9 | .6052 E 9 | .4750 E 9 | .4454 E 9 |
| AXIAL STIFFNESS (KG * MM²) | EXPERIMENTAL | .539 E 7 | .798 E 7 | .486 E 7 | .497 E 7 |
| | HANBA | .5311 E 7 | .7898 E 7 | .5208 E 7 | .5105 E 7 |
| CHORD OFFSET OF SHEAR CENTER (MM) | EXPERIMENTAL | 45 | 58.8 | 48.8 | 49.3 |
| | HANBA | 40.6 | 56.3 | 46.3 | 47.1 |
| CHORD OFFSET OF NEUTRAL AXIS (MM) | EXPERIMENTAL | 45.3 | 52.4 | 43.6 | 43.6 |
| | HANBA | 46.3 | 52.3 | 44. | 46.3 |

* A = Narmco 5216 S2 12 PLY 0°
* B = 3M SP 250 S2 2 (± 45°), 12 (0°), 2 (±45°)
* C = Narmco 5216 S2 2 (± 45°), 12 (0°), 2 (±45°)
* D = Ciba F 920 GR7 2 (± 45°), 12 (0°), 2 (±45°)

TABLE 3 - Comparison between HANBA and experimental results
complete blade section tests

| | | B 1 | D 1 |
|---|---|---|---|
| FLAPWISE BENDING STIFFNESS (kg * MM²) | EXPERIMENTAL | .136 E 10 | .995 E 9 |
| | HANBA | .1247 E 10 | .9422 E 10 |
| TORSIONAL STIFFNESS (KG * MM²) | EXPERIMENTAL | .1174 E 10 | .965 E 9 |
| | HANBA | .1034 E 10 | .8805 E 9 |
| AXIAL STIFFNESS (KG * MM²) | EXPERIMENTAL | .9046 E 7 | .6 E 7 |
| | HANBA | .9204 E 7 | .6275 E 7 |
| CHORD OFFSET OF SHEAR CENTER (MM) | EXPERIMENTAL | 73.1 | 69.9 |
| | HANBA | 72. | 67.6 |
| CHORD OFFSET OF NEUTRAL AXIS (MM) | EXPERIMENTAL | 73.8 | 74. |
| | HANBA | 72.1 | 73.2 |

* B1 SPAR TYPE B + SKIN (2 plies ± 45°)
* D1 SPAR TYPE D + SKIN (2 PLIES ±45°)



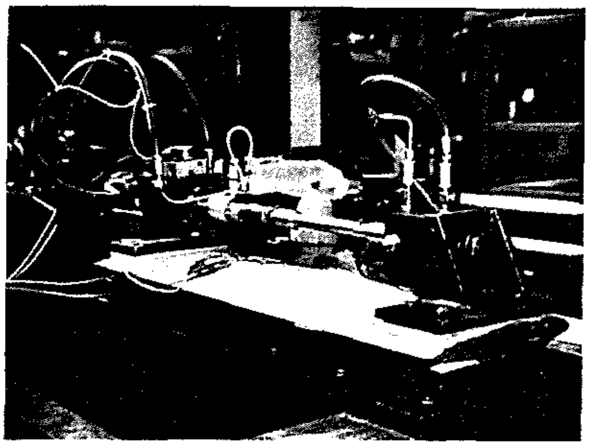


FIGURE 22 - BLADE COUPON FATIGUE TEST

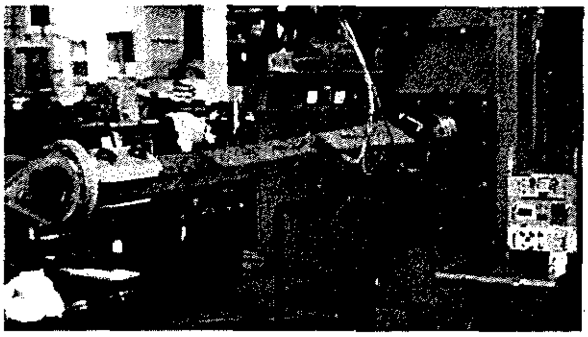
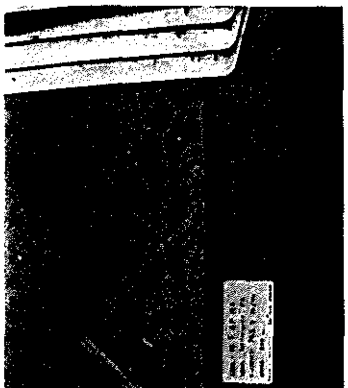


FIGURE 21 - ELASTIC TEST EQUIPMENT

FIGURE 23 - BLADE ROOT FATIGUE TEST



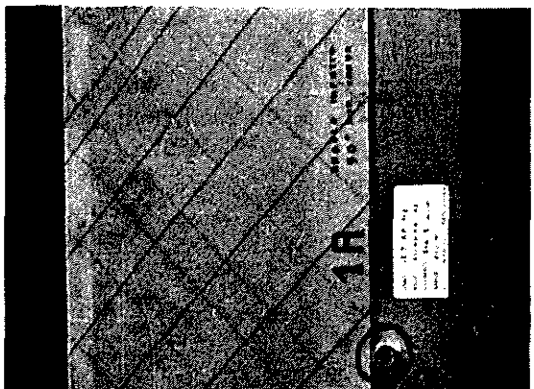



FIGURE 24 - EFFECT OF BULLET IMPACT ON GRP

FIGURE 25 - EFFECT OF BULLET IMPACT ON L.E. COVERING