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EVALUATION OF SECTION PROPERTIES FOR HOLLOW COMPOSITE BEAMS

by

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Abstract

The paper describes the plan and the first results of a joint research project, aiming at the development and the validation of design procedures for composite beam-like structures and structural components.
Analytical as well as experimental results are reported; one of the most significant of such results has been the development of the program HANBA (Hollow Anisotropic Beam Analysis) which, based on an original displacement method approach, allows the evaluation of section stiffnesses and stresses. The program works on a finite element idealization of the beam section and computes the stresses from the resultant forces and moments acting on the particular section, as the usual engineer's beam theory.
Experimental results are mainly concerning the identification of elastic properties for composite laminates, at relativevely low stress levels, and the validation of the results of the program HANBA. The latter has been planned through the evaluation of a large number of bending and torsion tests to be performed on blade spars and on complete blades.
Analytical results compare very well with experimental ones, the largest differences in section stiffenesses so far evaluated being of the order of 1%.
The plan is still going on and future activities are also outlined in the paper.

1. INTRODUCTION

The continuous evolution of composites materials is bringing them among the most interesting and the most studied materials for the manufacturing of aircraft, and of course also of helicopter.
Among their most significant features, besides having, quite obviously, a favourable strength to weight ratio, composites promise a high fatigue resistance and a good damage tolerance.
AGUSTA, following this trend, has undertaken a plan for composite application development, which will lead, in the near future, to the use of composites in the manufacturing of primary structural components, as rotor hubs and blades, and in that of secondary components, as doors, fairings etc..
Figure 1 shows the potential of composite application in the structure of a modern Agusta helicopter.
Such development plan brought up the need of reliable analysis procedures for primary structural subassemblies made from composites.
Besides being sufficiently reliable such procedures must also be:

- sufficiently efficient and simple in use to be employed from the early design stages, in interactive modes by the designers as well as integrated in optimizing routines;
- sufficiently sophisticated to take into account the presence of different materials in the same section, non-orthotropic materials and non-linear coupling between shear and normal stresses, as it may be needed in the more advanced designs;
- sufficiently flexible to be able to compute the inertia and stiffness properties of rotor blades, to be used in dynamics and dynamic instability

analysis of rotors.

For such reasons a cooperation has been undertaken between AGUSTA and IASP (Istituto di Ingegneria Aerospaziale del Politecnico di Milano) for the development and the validation of experimental and computational procedures pertaining the analysis and design of composite beams, with particular emphasis on rotor blades.
The cooperation has been a complete success, partly due to good planning and effective management; undoubtedly it has been a new evidence of the tremendous potential of the cooperation of different ad complementary competencies, as the ones of University and Industry.
It may be enough to note that, the first contract having been signed the 27th sept. 1978, now a significant amount of experimental work has been completed, and the first version of the program HANBA is being used for design purposes. Such version, which in fact is a medium size code, has already been validated trough the evaluation of a certain number of theoretical test cases, i.e. cases where exact solutions based on monocoque or semi-monocoque schemes were available.
Besides, the first results of HANBA compare very well also with the results of ad-hoc measurements made on blade spars in bending and torsion.

2. THE RESEARCH PLAN

The main activities of the plan are listed below, grouped according to methodologies.

A. BASIC THEORETICAL DEVELOPMENTS

A1 Formulation of a displacement method procedure for the analysis of a beam section

A2 Finite element formulation of the same procedure for linear elastic materials; element formulation

A3 Critical statement of the problem of identifying non-elastic behaviour of composite materials at high stress levels

A4 Development of non-elastic material models and of failure criteria

A5 Formulation of finite element procedures employing the models developed by activity A4, based on the general formulation stated in A1

B EXPERIMENTAL ACTIVITIES

B1 Evaluation of techniques for the direct measurement of elastic properties of composite laminates, in uniaxial stress states, at low stress levels

B2 Development and evaluation of techniques for the direct measurement of elastic properties of composite laminates in pluriaxial stress states

B3 Observation of failure conditions and failure modes for composite laminates in pluriaxial stress states

B4 Deflections and stiffness measurements on blade spars and complete blade sections in various bending and torsion load conditions, in the elastic range

B5 Observation of strength properties and of failure characteristics of longerons and complete blade sections in various combined load conditions

C DEVELOPMENT OF COMPUTER CODES

C1 Drafting of the general specifications of the program

C2 Detail specifications of the linear version

C3 Coding, test and validation of the linear version

C4 Detail specifications for an extended version of the program including non-elastic material behaviours and strength evaluations

C5 Coding, test and validation of the extended version specified by activity C4.

The logical flow of the activities of the plan, showing also dependance connections, is reported in figure 2.

At the present time the activities A1, A2, B1, B3, C1, C2 and C3 have been completed.

3. ANALITICAL APPROACH

The approach is based on the hypothesis that the solid can be considered as a "beam", i.e. that, with a good approximation, it has the shape of a cylinder of any cross section, loaded only on its end sections. In other words the basic hypothesis of De Saint Vénant are supposed to hold, and we seek a solution which is correct only in a certain distance from the end sections, where loads and/or constraint may be applied.
In this case it is well known that the stress and/or the strain state can be determined on a cross section of the beam, only from the resultant forces and moments acting on the same cross section, ignoring the situation of the neighboring sections.
Let us consider a solid that can be assumed to be a beam, or shortly a beam, and let Oxyz be an orthogonal reference set having the z axis paralell to the generatrices of the cylinder; the point O is a point of the cross section that has been choosen as a reference point.
If the beam is moderately bent the z axis is only locally parallel to the generatrices, or, more precisely, parallel to the straight lines tangent to the generatrices at the cross section considered.
So z can also be considered an abscissa measured along the line connecting the points O of the cross sections of the beam.
Let us immagine that the set Oxyz moves during the deformation in such a way that z axis remains tangent to the deflected axis of the beam and x and y axis rotates around z axis by and angle $\theta = \theta(z)$ corresponding to the torsion of the section (x).
If $\underline{w} = \underline{w}(z)$ is the displacement of the points O, in the case of small deflections, the rotation $\underline{\beta} = \underline{\beta}(z)$ of the set Oxyz has the components:

$$\underline{\beta} = \begin{cases} -w'_y \\ w'_x \\ \theta \end{cases} \qquad (1)$$

(x) In general this definition would require a further specification about torsion: in the case of hollow sections the projection of the section on xy plane can be assumed to remain undeformed and torsion is uniquely specified.

where the apex means derivation respect to the abscissa z.
The displacement $\underline{s}$ of any point P of the cross section can then be regarded as the sum of the rigid displacement of the reference set plus the follows:

$$\underline{s}\ (P,z) = \underline{W}(z) + \underline{\beta}\ (z) \wedge (P-O) + \underline{g}\ (P,z) \qquad (2)$$

The third component g_z of the relative displacement $\underline{g}$ is generally known as the "warping" of the points of the cross section.
The decomposition (2), within the specification (1) of the rotation $\underline{\beta}$ gives the following formulations for the significant strain components:

$$\begin{aligned} \varepsilon_z &= w'_z - x w''_x - y w''_y \\ \gamma_{nz} &= 2\,\Omega_{(n)}\ \theta' + \frac{\partial g_z}{\partial n} \end{aligned} \qquad , (3)$$

where:

$$2\,\Omega_{(n)} = (P-O) \wedge \underline{n}.\underline{k} = xn_y - yn_x \qquad (4)$$

is the double of the area dashed in figure 4 [1], [2].
It may be noted that the significant components of strain, from (3), depend on the 4 global deflection parameter of the cross section w'_z, w''_x, w''_y and θ', and on the warping g_z.
If the constitutive laws of the materials are specified, stresses, virtual work of deformation, and anything else usable for studying equilibrium, can be erpressed as functions of the 4 global deflection parameters and of the function g_z.
In this case the desplacement method implies that the above global deflection paramaters and the warping function are assumed as the unknown of the equilibrium equations.
An efficient solution procedure can be obtained by means of finite element techniques, i.e. by dividing the cross section surface in a certain number of finite elements, each element being characterized by a certain number of nodes or grid points; the unknown, discrete in number, are then assumed to be the 4 global desplacement parameters, plus the values Γ_i $(i = 1,2,\dots,m)$ of the warping function g_z in the m grid points of the cross section.
The basic element types that can be useful for idealizing the section of aeronautical beams and beamlike structures seem to be the following:

a) panel elements, i.e. elements thin enough to be representable on the cross section by a suitable mean line;

b) flange elements that on the cross section must be considered as surface elements;

c) joint elements.

The material model can be any linear material model, and generally anysotropic model (i.e. non-orthotropic) must be allowed. So also semi-mono schemes can be reproduced just specifying for panel elements a material having only the shear modulus G non-zero, and for flange elements a material capable only of normal stress (G = o).
For the panels it has been convenient to develop isoparametric elements having 2, 3 and 4 nodes each.
The joint elements are used to represent a longitudinal joint in the beam: on the cross section a joint element is always connecting 2 grid points and has a stiffness that can be specified independently of the shape and the dimen-

sions of the joint itself.
Figure 5 shows all these types of elements with some possible way of using them.
To describe briefly the finite-element approach it is convenient to develop, as an example, the contribution, to the equilibrium of the whole cross section, of an isoparametric panel having 3 nodes idealizing a piece of laminate of thickness t.

With reference to figure 6 we define

$$p = \int_t \sigma_z \, d\bar{y} \quad ; \quad q = \int_t \tau_{\bar{x}z} \, d\bar{y} \quad ; \tag{5}$$

and in accordance with the usual approach for hollow beam we can assume that:

$$\int_t \sigma_{\bar{x}} \, d\bar{y} = 0 \qquad \text{and} \qquad \int_t \tau_{\bar{y}z} \, d\bar{y} = 0 \quad . \tag{6}$$

To shorten the notation it is convenient to denote the stress flows with the column $\{p\}$ and the significant strains in the column $\{\varepsilon\}$, i.e.:

$$\{p\} = \begin{Bmatrix} p \\ q \end{Bmatrix} \quad ; \quad \{\varepsilon\} = \begin{Bmatrix} \varepsilon_z \\ \gamma_{\bar{x}z} \end{Bmatrix} \quad . \tag{7}$$

For linear elastic materials, taking into account (5) and (6), the constitution relation can be put in the following symbolic form:

$$\{p\} = [C]\{\varepsilon\} \quad , \tag{8}$$

where $[C]$ is a symmetrical matrix summarizing the significant elastic proparties of the laminate.
$[C]$ will be a diagonal matrix only if the unidirectional laminae are so oriented that the resultant laminate is orthotropic respect to the direction of the z axis, or in other words has an orthogonal symmetry of the elastic properties respect to a direction parallel to z axis.
The significant deflection parameters, i.e. the 4 global parameters plus the 3 values $\{\Gamma\}$ of the warping at the panel nodes can be denoted by the column:

$$\{\bar{u}\} = \begin{Bmatrix} \Gamma_1 \\ \Gamma_2 \\ \Gamma_3 \\ \theta' \\ w''_x \\ w''_y \\ w'_z \end{Bmatrix} \quad . \tag{9}$$

Denoting by $\{X\}$ and $\{Y\}$ the column of the x and y coordinates of panel nodes, the idea of isoparametric element comes off into the fact that the coordinate x y and the warping function g_z of any point of the panel mean line are expressed in the same way:

$$x = \left\{ N \right\}^T \cdot \left\{ X \right\} \; ; \; y = \left\{ N \right\}^T \cdot \left\{ Y \right\} ; \; g_z = \left\{ N \right\}^T \cdot \left\{ \Gamma \right\} \quad , \tag{10}$$

where $\{ N \}$ are suitable shape functions.
From (3), taking into account (4), (9), and (10), the strains can be expressed as linear functions of displacement parameters, as follows:

$$\{ \varepsilon \} = [B] \cdot \{ \bar{u} \} \quad , \tag{11}$$

where

$$[B] = \begin{bmatrix} 0 & 0 & 0 & 0 & -x & -y & 1 \\ \frac{dN_1}{d\bar{x}} & \frac{dN_2}{d\bar{x}} & \frac{dN_3}{d\bar{x}} & xn_y - yn_x & 0 & 0 & 0 \end{bmatrix} \quad . \tag{12}$$

To derive equilibrium equations we now start writing the virtual work pertaining to a slice of the beam bound by two cross sections at the vanishing distance dz.
The contribution $\delta^* l_e$ of the isoparametric panel that we are considering to the virtual work of "external" forces (external for the elementary beam slice), with the notations of figure 7 is:

$$\delta^* l_e = dz \int_1^3 (p \, \delta \, s_{z/z} + p_{/z} \, \delta \, s_z + q\underline{n} \cdot \delta \underline{s}_{/z}) \, d\bar{x} \; ; \tag{13}$$

whence, for (1) and (2):

$$\frac{\delta^* l_e}{dz} = (\bar{T}_x + \bar{M}_y') \, \delta w_x' + (\bar{T}_y - \bar{M}_x') \, \delta w_y' + T_z' \, \delta w_z + \left\{ \delta \bar{u} \right\}^T \left\{ \bar{P} \right\} \quad , \tag{14}$$

where $\bar{T}_x$, $\bar{T}_y$ and $\bar{T}_z$, $\bar{M}_x$, $\bar{M}_y$ and $\bar{M}_z$ are, respectively, the contribution of the panel to the resultant forces and moments acting on the cross section, and:

$$\left\{ \bar{P} \right\} = \left\{ \begin{array}{c} \bar{\Phi}_1 \\ \bar{\Phi}_2 \\ \bar{\Phi}_3 \\ \bar{M}_z \\ \bar{M}_y \\ -\bar{M}_x \\ \bar{T}_z \end{array} \right\} \quad ; \quad \bar{\Phi}_k = \int_1^3 N_k \, p_{/z} \, d\bar{x} \quad . \tag{15}$$

Likewise, the contribution of the same panel to the virtual work of deformation:

$$\delta^* l_d = dz \int_1^3 \left\{ \delta \varepsilon \right\}^T \left\{ p \right\} \, d\bar{x} \quad , \tag{16}$$

for (8) and (11) can be expressed as :

$$\frac{\delta^* l_d}{dz} = \left\{\delta \bar{u}\right\}^T \left[k\right] \left\{\bar{u}\right\} \tag{17}$$

where:

$$\left[K\right] = \int_{-1}^{3} \left[B\right] \left[C\right] \left[B\right] \, d\bar{z} \tag{18}$$

Elements of other type will give contributions to external and internal virtual work formally identical to (14) and (17), even if the number of nodal unknown $\left\{\Gamma\right\}$, the shape function and the matrix $\left[B\right]$ may be different. In any case the total virtual work of the beam slice comes from the sum of the contribution of all the elements, after having arranged all the unknown parameters in the column:

$$\left\{u\right\} = \left\{\begin{matrix} \Gamma_1 \\ \Gamma_2 \\ \vdots \\ \Gamma_m \\ \theta' \\ w_x'' \\ w_y'' \\ w_z' \end{matrix}\right\} , \tag{19}$$

m being the number of nodes of the whole section.
The total external and internal virtual works come off as follows:

$$\begin{aligned} \frac{\delta^* L_e}{dz} &= (T_x + M_y')\,\delta w_z' + (T_y - M_x')\,\delta w_y' - T_z'\,\delta w_z + \left\{\delta u\right\}^T \left\{P\right\} \\ \frac{\delta^* L_d}{dz} &= \left\{\delta u\right\}^T \left[K\right] \left\{u\right\} , \end{aligned} \tag{20}$$

where the forces T, the moments M, $\left\{P\right\}$ and $\left[K\right]$ come from the summing, or assembling of all element contributions.
The principle of virtual works states that at equilibrium, for any choice of the virtual variation of the parameters, it must be:

$$\delta^* L_d = \delta^* L_e , \tag{21}$$

whence, for (20), it must be:

$$M_y' = - T_x \quad ; \quad M_x' = T_y \quad ; \quad T_z' = 0 , \tag{22}$$

and:

$$\left[K\right] \left\{u\right\} = \left\{P\right\} . \tag{23}$$

The equations (22) are the well known equilibrium equations of the resultant forces acting on the section.
The set of linear equations (23), in the unknown displacement parameters $\left\{u\right\}$

are the actual equilibrium equations of the finite element section scheme. Yet it must be noticed that not all the terms of the column $\{P\}$ are actually known. As a matter of fact the first m terms ϕ are depending on $p_{/z}$ (15), which at the moment cannot be known.
Nevertheless we may note tnat according to the basic hypothesis, stresses and strains can only be constant with z or linear function of z, while the stifness matrix $\lceil K \rfloor$ must be constant with z.
Then deriving both menbers of (23) with regard to z, the following set of equations is obtained:

$$\lceil K \rfloor \ \{u'\} = \{P'\} \qquad , \quad (24)$$

where

$$\{P'\} = \left\{\frac{dP}{dz}\right\} = \begin{Bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ -T_x \\ -T_y \\ 0 \end{Bmatrix} \qquad . \quad (25)$$

So the known terms being actually known, the (25) can be solved for u' .
Eventually deriving equations (8) and (11) with regard to z :

$$\{p_{/z}\} = \lceil C \rfloor \ \{\varepsilon_{/z}\} ; \{\varepsilon_{/z}\} = \lceil B \rfloor \ \{u'\} \qquad , \quad (26)$$

the terms Φ of the known term of (23) can be evaluated by means of (15).
It it is worth noting that the set of equations (23) and (25) have the same coefficient matrix, so the latter can be factorized once for both solutions. Once the matrix $\lceil K \rfloor$ has been factorized it will be convenient to compute separately the 6 solutions corresponding to unit values of any one of the 6 components of resultant forces and moments.
If all the elements have orthotrofic materials normal strasses and shear stresses remain unconpled. In this simpler case it is possible to define, in the usual way, the centroid of normal stresses, the principal axes for bending and the corresponding bending stiffnesses, the shear center and the corresponding torsional stiffness.
In the more general case where normal and shear stresses are coupled the above usual definitions no longer hold, and the stiffness properties of the cross section must be expressed by a matrix.
Nevertheless such general cases and the possible ways of presenting the corresponding stiffnesses deserve a further study, due to the interest inherent in the possibility of using non-orthotropic laminates to improve section properties.

4. THE PROGRAM HANBA

The finite element procedure outlined above has been implemented in the program HANBA (Hollow Anisotropie Beam Analysis).
Before the first statement of the program had been written, the design of the program has been developed, and detailed to the description of the subrouti-

nes, of data base and test cases.
This allowed different parts of the program to be developed independently by 8 persons, belonging to AGUSTA and IASP, in a pretty short time, and integra tion to be performed without any particular problem.
In particular HANBA has been designed to have an open modular structure, and with the possibility of stop and restart at intermediate points.
The first level structure of the program is done by the following modules:

- Input and Preprocessing
- Analysis
- Stress computation and output.

The input and preprocessing module reads the data given or specified by the user.
It makes use of a library of materials, laminae and laminates, with different modes of operation, at user's choice.
For instance the user may specify a laminate by choosing one of the laminates of the library, or by selecting a certain number and specifing a certain arrangement of unidirectional laminae.
Modules are also provided to unprove the library.
In addition the preprocessing module performs checks and emits diagnostic messages about input data, prepares the printed and graphic output for data check, and the input for the subseguent analysis.
The analysis module computes the inertia and stiffness properties of the beam section, and the solutions needed by the possible subsequent computations.
The stress module computes the stresses in the laminae forming the laminates, in flange elements and in joint elements, for given load conditions.
The gross flow diagram of program HANBA is depicted in figure 8.
At present the following elements have been implemented:

- panel elements, isoparametric, 2, 3 and 4 nodes; Gauss numerical integrative of order 2, 3 or 4;
- flange elements capable of working also in normal stresses;
- joint elements.

Besides the element nodes may be displaced from the grid points by a certain displacement or offset. So the grid points can be fixed on the external profile and the actual element nodes are automatically placed, in positions depending on the laminate.
Clearly the Program HANBA can be also a flexible and efficient instrument for the analysis of hollow beams of any material, and then also wings, tailplanes etc.
In particular, as it computes the beam section by section, it is much more ver satile and manageable than the usual finite element codes, especially in the early design stages.
As such it is already being used at AGUSTA.

5. EXAMPLE OF AN IDEALIZATION

To give an impression of the idealization that can be used with the program HANBA, the scheme adopted for analyzing a rotor blade is reported in figure 9.
Figure 9A shows the actual cross section of the blade, while figure 9 B shows the idealization prepared by the user, with the grid points located on the outer profile.
Figure 9C reports the element nodes, computed by the program, whose actual position defends on element thikness.

The scheme has a total of 59 degrees of freedom, 6 cubic panel elements (4 nodes), 11 parabolic (3 nodes) and 7 linear (2 nodes), plus 5 flange elements and 12 joint elements.
Despite its semplicity and relatively low cost this model is capable of representing the cross section with a very good accuracy.

6. ELASTIC PROPERTIES OF LAMINATES

The elastic moduli of laminates have been measured directly, employing a technique based on uniaxial tension tests of specimens cut from the laminate at different angles. Figure 10 shows the three types of specimens, denoted as I, II and III: the specimen longitudinal axes x form with the laminate reference direction X angles of 0°, 90° and 45°, respectively.
For non-orthotropic laminates the strain y_{xy} of specimens type III may be non negligible, and then it may be important that the end clamps allow this strain without interferences. For that reason the clamps were hinged in the specimen centerline, at the stations where the specimen emerges from the clamps, as shown in figure 11.
Each specimen have been equipped with two strain rosettes, one on each face, to eliminate possible bending effects from the measurements. So, for each stress level, three strain measures can be extracted from one specimens, and then 9 for one group of 3 specimens of the 3 types.
For an orthotropic laminate these 9 measured values are obviously redundant to determine the 4 independent elastic constants.
In the first tests these 9 strains where used to determine the 9 terms of the elastic matrix, without making any assuption on orthotropy, nor even on symmetry.
The first tests were run with 12 specimens, coming from the same sheet, 4 for each of the types in figure 10.
The sheet was done by three unidirectinal layers, material SP250 S2920, placed at 0°-90°-0°.
All the tests have been run with a Data Acquisition System, making use of a small computer, programmed to evaluate the elastic moduli from strain measurements, on line.
The first tests showed essential symmetry and orthotropy of the elastic matrix, and a rather strong dependence of the tangent modulus G on stress level.
To make easier the observation of possible stress-dependence of the moduli, a simpler processing of meassured data was programmed, accepting a priori orthotropy and symmetry. Particularly 5 moduli were directly extracted, as follows:

E_X	and	ν_X	from specimens type I
E_Y	and	ν_Y	from specimens type II
G_{XY}			from specimens type III.

This type of test was done on the same 12 specimens used before, with stress levels up to about 6 kg mm^{-2}.
Specimens type I and II showed linear stress-strain relations, while specimens type III manifested remarkable non-linearities, notably creep and hysteresis.
Figure 12 shows the decay in time of the secant modulus G_{XY}, for specimens type III at constant stress: it was also apparent that such modulus is strongly dependent on specimen temperature.
Figure 13 shows typical stress strain curves for the three types of specimens; the curve reported for specimen III was obtained with a fixed load an unload velocity of $\pm .02$ kg mm^{-2} s^{-1}.
Table I gives a summary of the most significant features and of the moduli measured with the 12 specimens; the moduli G reported for specimens III are secant moduli, measured with a stress of 5.53 kg mm^{-2}, applied for 5.5 minutes.

TABLE 1

Specimen ≠	Type	Adhesive ≠	Ex $[Kg\ mm^{-2}]$	ν_x	E_y	ν_y	G_{xy} $[Kg\ mm^{-2}]$
245	I	2	3426	.1440			
246	I	1	3397	.1645			
247	I	1	3462	.1647			
248	I	1	3473	.1649			
253	II	1			2444	.1076	
254	II	1			2347	.0989	
255	II	2			2372	.0883	
256	II	2			2387	.0847	
249	III	1					379
252	III	1					382
250	III	2					427
251	III	2					394

ADHESIVE ≠ 1 : MICRO-MEASUREMENTS type M-BOND 200
ADHESIVE ≠ 2 : H.B.M. type Z 70

From table 1 the following observation can be drawn:

-a) Moduli E_X and E_Y measured from specimens I and II show a very low scatter, below 2%.

-b) Systematic differences appear between the measurements coming from strain gages applied with the two different adhesives, at least for ν_Y, and even more for G_{XY}, which are essentially dependent on resin stiffness. In particular it appears that adhesive ≠ 2 causes an excessive stiffening of the resin.

-c) The values of E_Y ν_X are systematically lower than the values of E_X ν_Y, even comparing only the measurements taken from strain gages applied with the same adhesive. This may appear as a lack of symmetry of the elastic matrix, but most probably it is simply due to the fact that specimen width is not enough to transfer transverse contraction from the inner layer to the outer ones, for specimens II.

Nevertheless the authors think that the methodology so far tested has proved to posses a high potential accuracy; in the future larger specimens will be used, and the effect of adhesive will be carefully investigated.

7. TEST ON BLADE SECTIONS

Several experimental tests with different beam cross section and construction have been planned. Figure 14 shows typical cross sections employed in tests. The test articles have been made from different composite materials, different number of pre-preg layers, and different fiber angle.
Also the material employed come from different manufacturers.
Tests are run with a frame allowing the loads to be applied in a well defined plane, without undesired effects on other planes, and able to give good evaluations of shear center location.
Loads are applied by weights, and deflection have been measured with dials in the first tests (figure 15), and subsequently with a set of LVDT transducers (figure 16).

Strain gages have also been fit, to detect the strains of the outer layers. Figure 17 shows some typical bending and twist measurement obtained from the tests.
Figure 17b contains also results from a metal blade tested for the first evaluation of the equipment and of the results of HANBA. In torsion results it appears that the length of the specimen is sufficient to obtain a significant part of the diagram with a linear trend of the twist angle, i.e. outside the influence of end restraint.

8. EVALUATION OF HANBA RESULTS

Four types of beam sections have been so far tested, shown in figure 18. Section A was tested only in bending, in both principal planes; section D, corresponding to a typical metal blade was tested only in torsion, while the remaining sections were tested both in bending and in torsion.
In each test bending deflection and twist angles were measured at 9 stations, in different load levels.
All these measurements were then used, in an optimizing procedure, to compute the value of the stiffnesses and the values of the slope at the first station (one for each load), giving the best fit of experimental points.
Such experimental values of the stiffnesses were then compared with the corresponding values obtained analytically from the program HANBA, with the idealizations showed in figure 19.
The tables in Fig.20 report some of these comparison. Further tests are needed to draw conclusive evaluations, and probably a deeper insight into resin creep may give a better interpretation of some of torsional results. Nevertheless the agreement between analytical and experimental results seems to be extremely good.

9. FUTURE DEVELOPMENTS

The main future developments, related to the completion of the research plan, are:

- completion of the linear version of the program HANBA, trough the development of isoparametric flange elements, capable of developing both normal and shear stresses. Complete development of the stress output module, and of the interfaces for rotor dynamics programs.
- Development of a non linear version of HANBA, allowing for general non linear behaviour of materials, and including also strength evaluations. As it has been outlined above, this will require some further theoretical work and much experimental activity.

In the mean time another research project is now being planned as a joint venture between IASP and AGUSTA, concerning the development and validation of new codes for the analysis of rotor dynamics and instabilities.

10. CONCLUDING REMARKS

The results so far obtained strengthen the opinion of the authors that the application of finite element techniques to the classical problem of De Saint Vénant, can give, for many actual problems, an answer which may be more effective, more flexible and more usable then the one of usual F.E. programs.

11. BIBLIOGRAPHY

1 - MANTEGAZZA P., Analysis of semimonocoque beam sections by displacement method, L'Aerotecnica Missili e Spazio, Journal of AIDAA, 1977 N.G.

2 - GIAVOTTO V., Procedimento per il calcolo di travi a guscio in materiale anisotropo - Studio di base - 1978, IASP Research report - Restricted.

3 - CRIVELLI VISCONTI, Materiali compositi tecnologie e progettazione - Tamborini Editore - 1975.

4 - N.J. PARRAT - Fibre-Reinforced Materials technology - Van Nostrand, New York 1972.

5 - BROUTMAN L.J., KROCK R.H., Composite materials vol. 1-8, Academic Press, New York 1974.

6 - C.C. CHAMIS, Computerized multilevel analysis of multilayered composites. Computer & Structures. Jan. 1973 pp. 467-492.

7 - C.C. CHAMIS, Computer code for the analysis of multilayered fiber composites - Nasa TN D - 7013 - March 1971.

8 - J.J. KIBLER NOLIN - A nonlinear laminate analysis program - Nasa Cr. 2410 - Feb. 1975.

9 - F.W. WENDT, H. LIEBOWITZ, N. PERRONE - Mechanic of composite materials - Pergamon Press 1967.

10 - Agard specialist meeting on failure modes of composite materials - Agard CP-163.

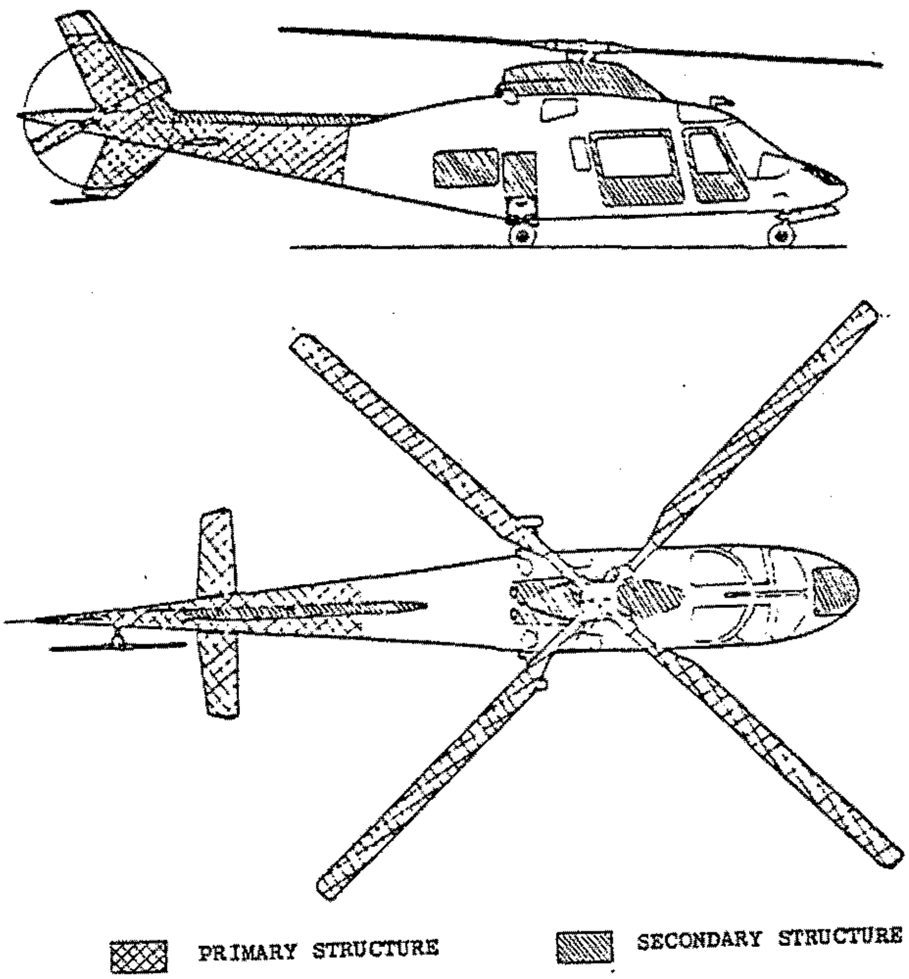


Fig. 1 -POTENTIAL USE OF COMPOSITES IN THE STRUCTURE OF A MODERN HELICOPTER.

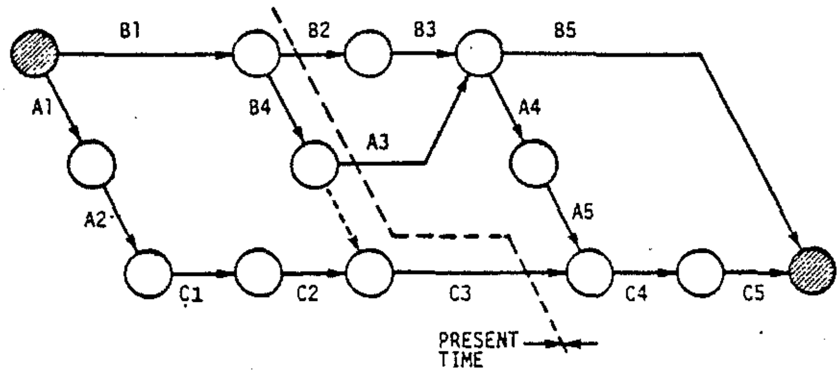


Fig. 2 - THE RESEARCH PLAN

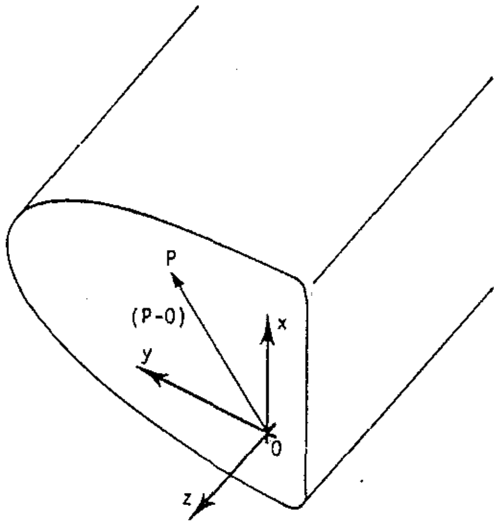


Fig. 3

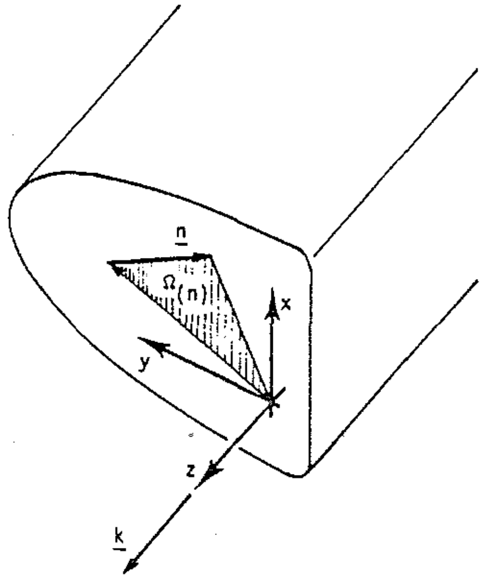


Fig. 4

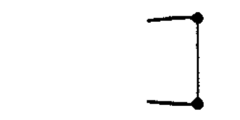
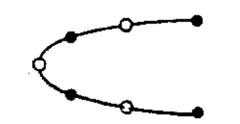
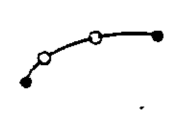
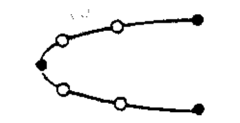
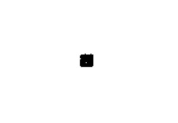
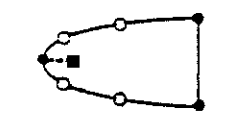
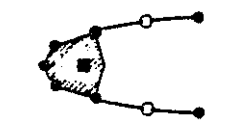
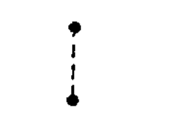
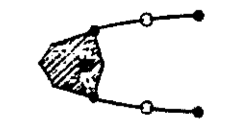
SYMBOL	ELEMENT	EXAMPLE OF USE
	PANEL 2-NODE ISOPARAMETRIC	
	PANEL 3-NODE ISOPARAMETRIC	
	PANEL 4-NODE ISOPARAMETRIC	
	FLANGE CONCENTRATED AREA	
	FLANGE NON CONCENTRATED	
	JOINT	

Fig. 5 - ELEMENTS IN PROGRAM HANBA

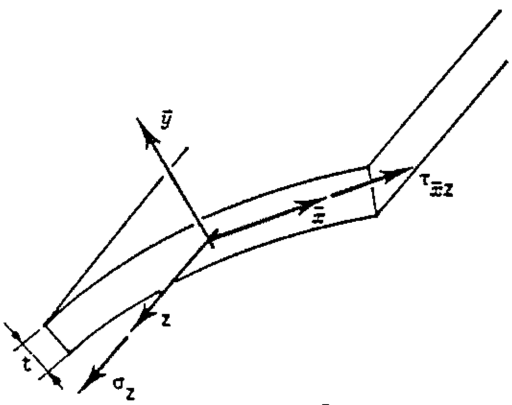


Fig. 6

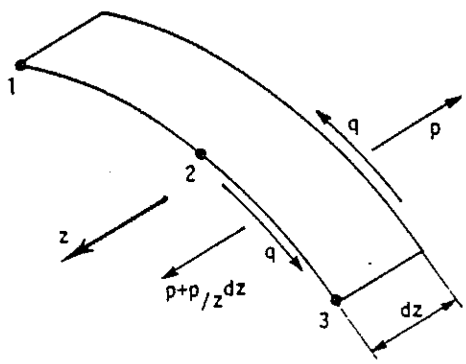


Fig. 7

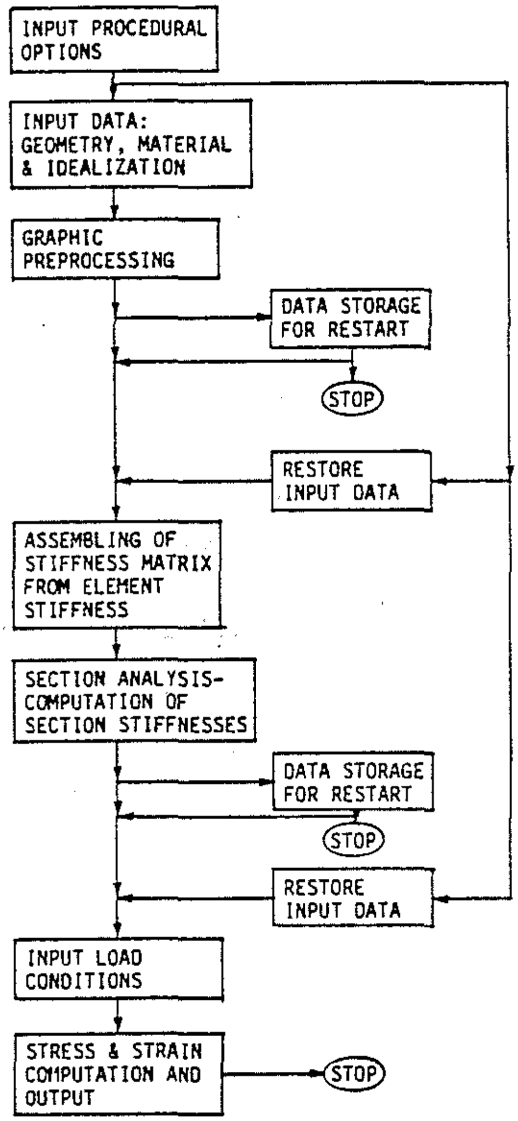


Fig. 8 - GROSS FLOW OF PROGRAM HANBA

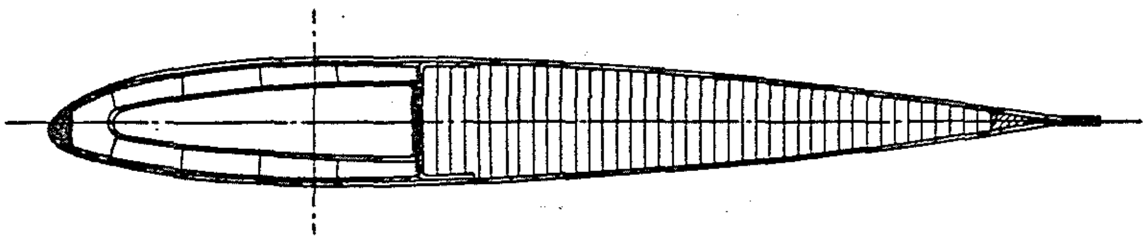


FIG. 9A. - ACTUAL CROSS SECTION

X =END NODES OF A PANEL ELEMENT

⊙ =INTERNAL NODES OF A PANEL ELEMENT

△ =FLANGES HAVING MASS AND STIFFNESS

◇ =FLANGES HAVING ONLY MASS

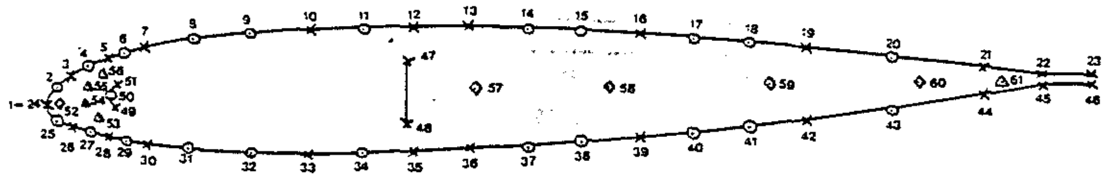


Fig. 9 B - GRID POINTS

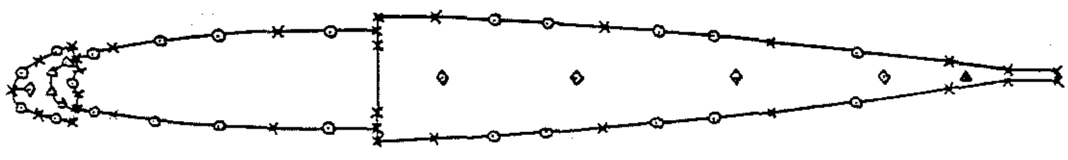


Fig. 9C. - ELEMENT NODES

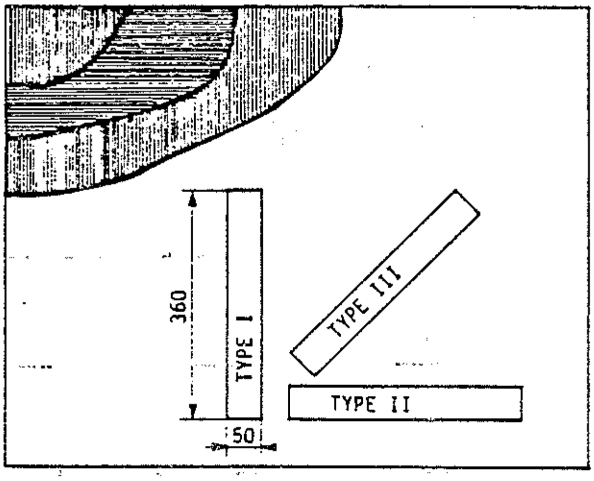


Fig. 10 - SPECIMENS FOR ELASTIC TESTS.

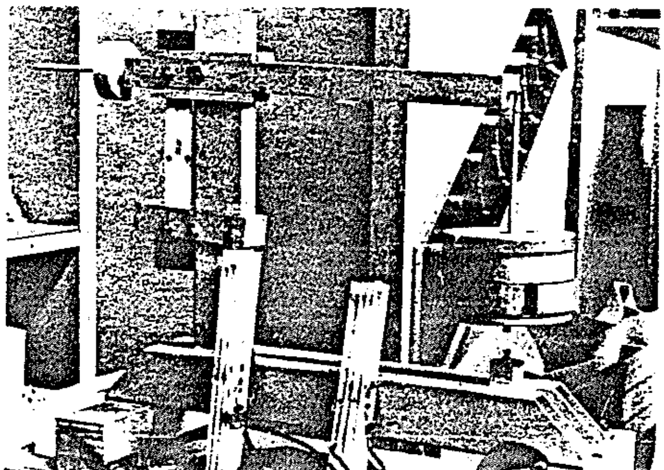


Fig. 11 - ELASTIC TESTING

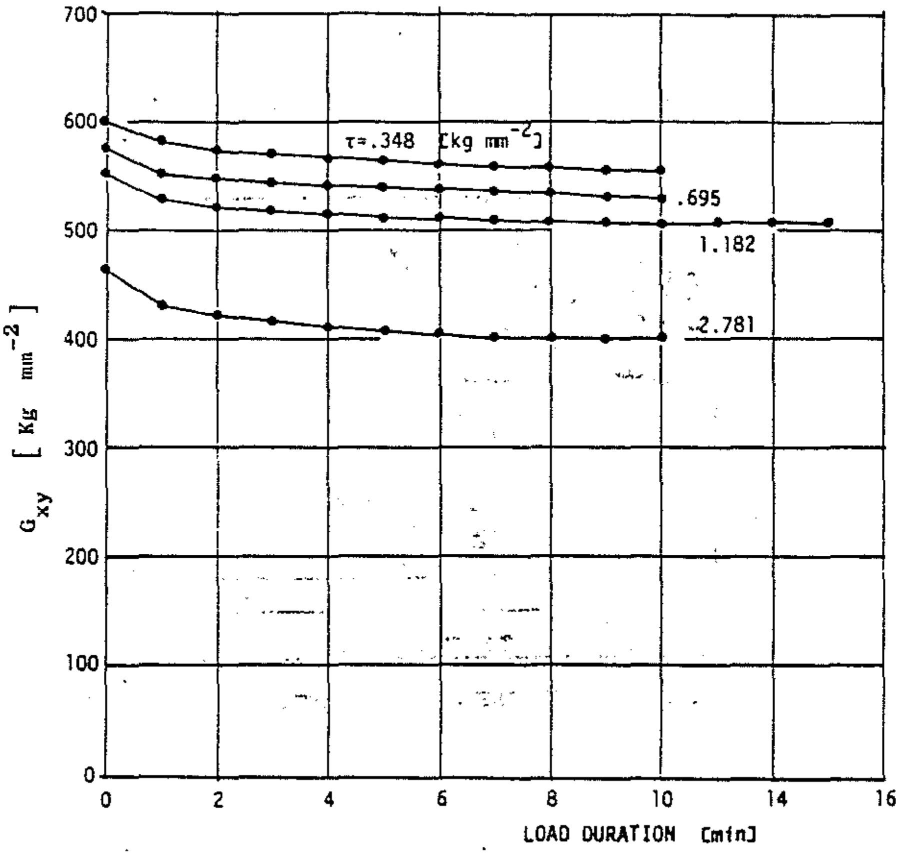


Fig. 12 - CREEP BEHAVIOUR OF SPECIMENS TYPE III.

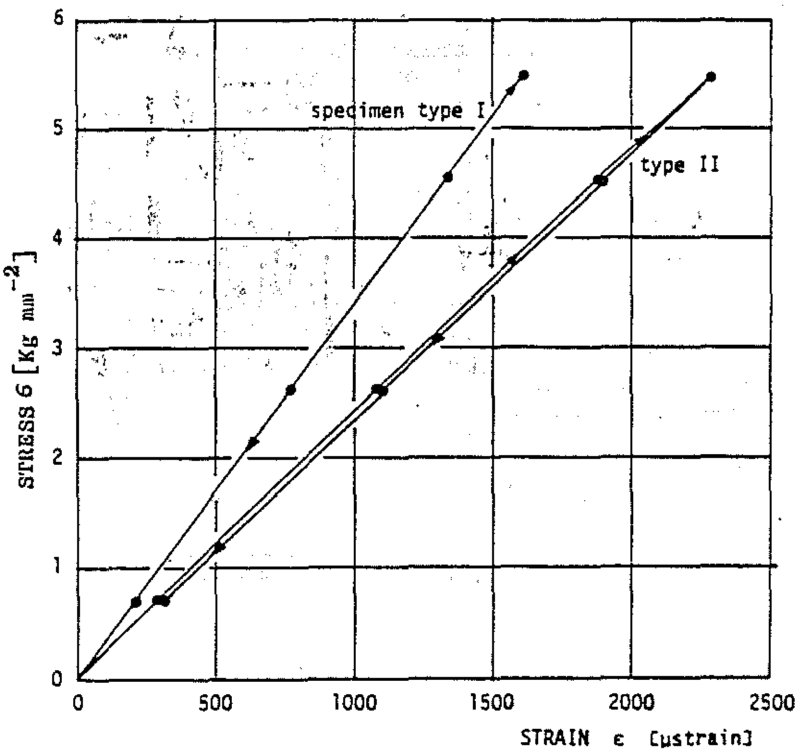


Fig. 13A - TYPICAL STRESS-STRAIN CURVES
FOR THE THREE TYPES OF SPECIMEN.

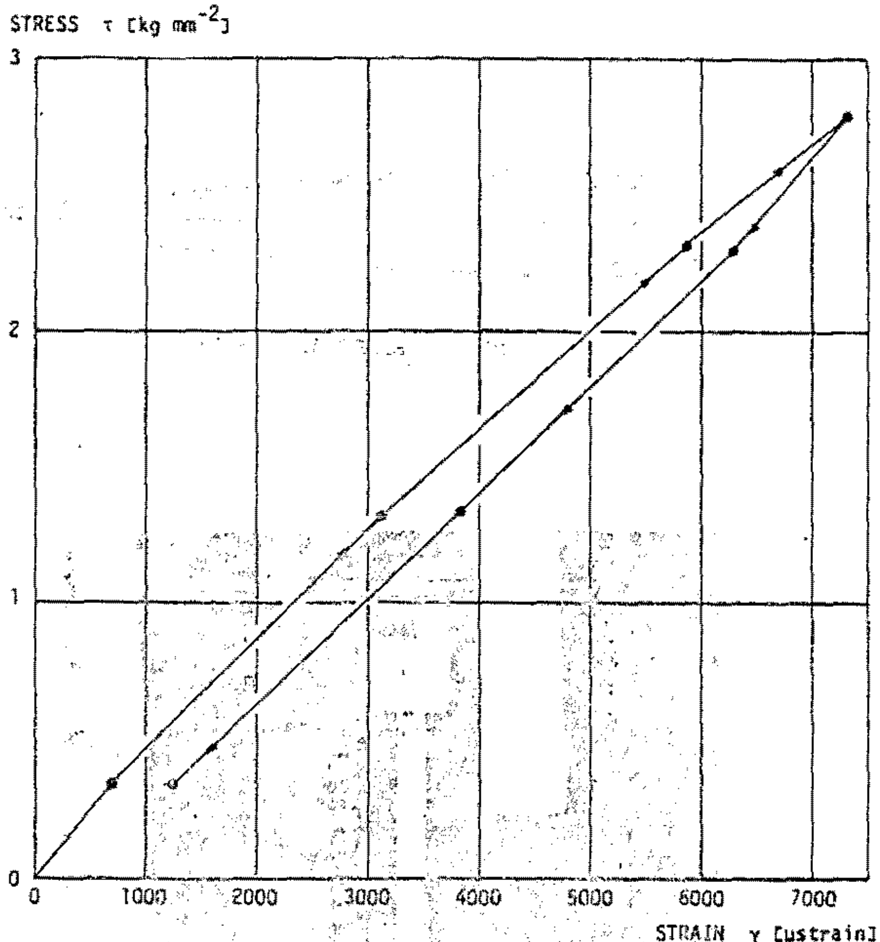


Fig. 13 B - TYPICAL STRESS-STRAIN CURVES FOR THE THREE TYPES OF SPECIMEN

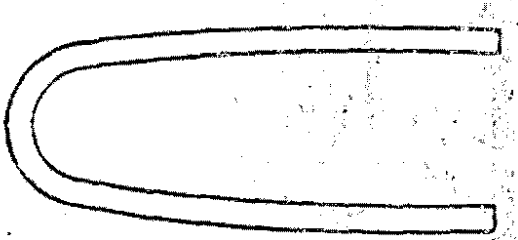


Fig. 14 A - "C" SPAR TEST SECTION

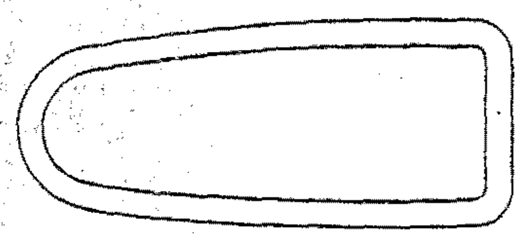


Fig. 14 B - "D" SPAR TEST SECTION

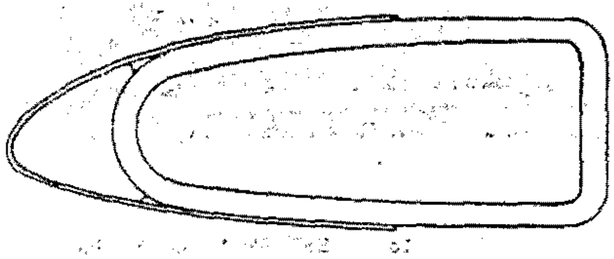


Fig. 14 C - COMPLETE SPAR TEST SECTION

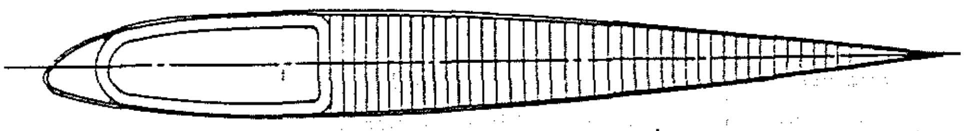


Fig. 14D- COMPLETE BLADE TEST SECTION

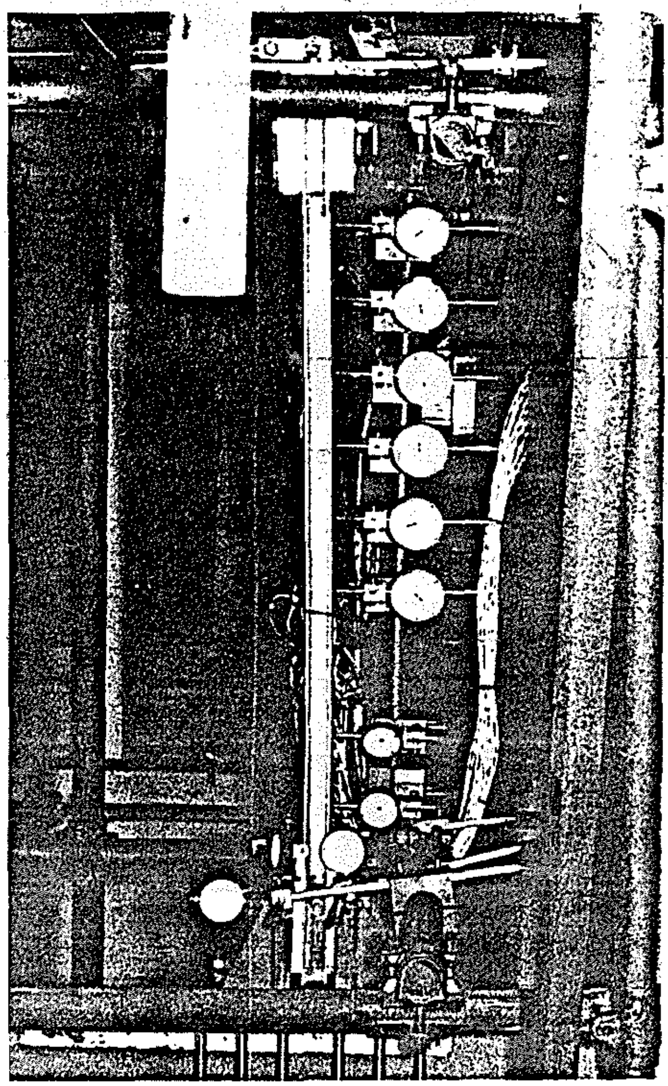


Fig. 15 - TEST ON A BLADE SPAR

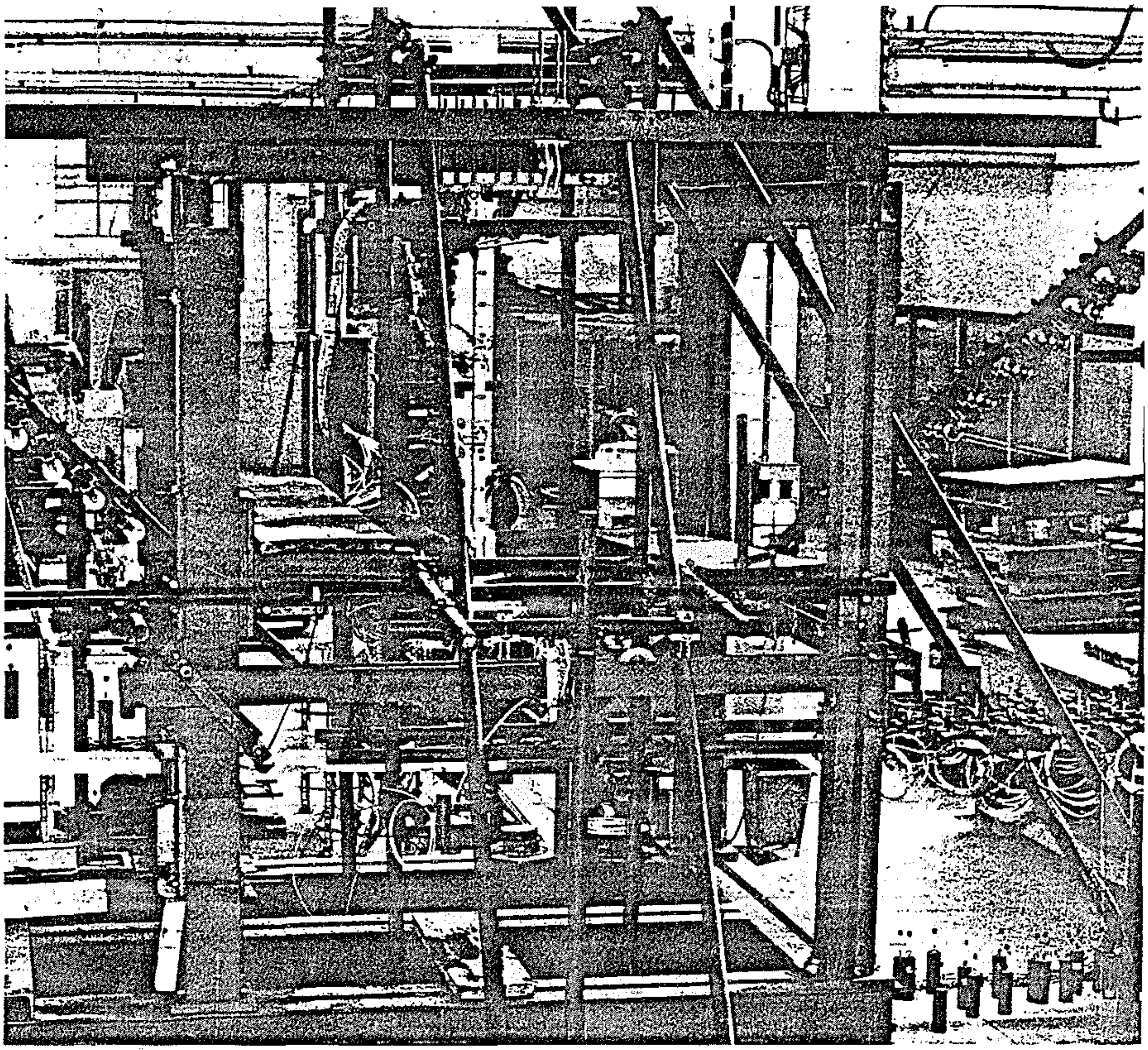


Fig. 16 - TEST ON BLADE SPAR - MEASUREMENTS
WITH LVDT TRANSDUCERS.

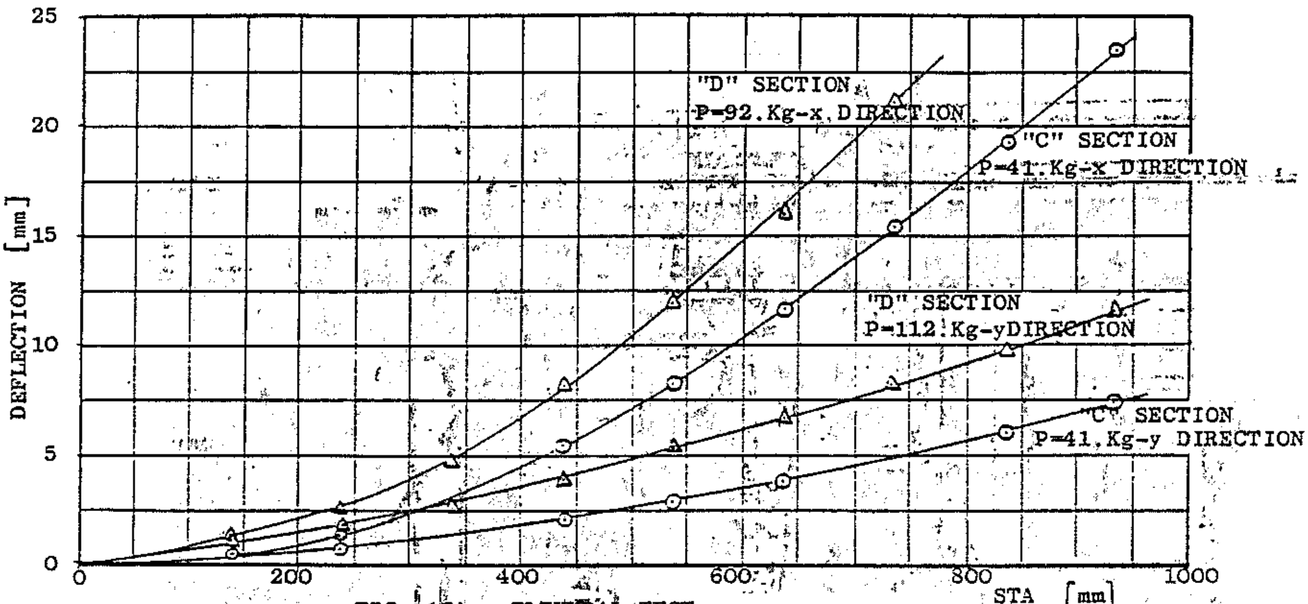


FIG. 17A - FLEXURAL TEST

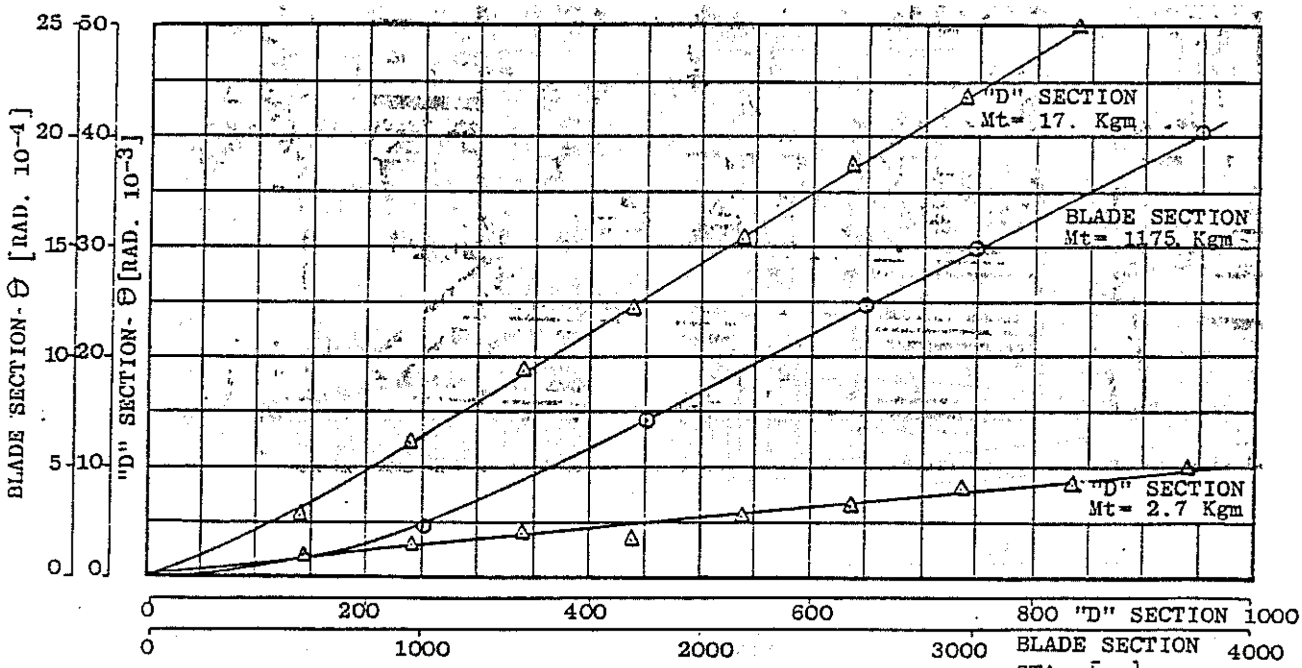


Fig. 17 B - TORSIONAL TEST

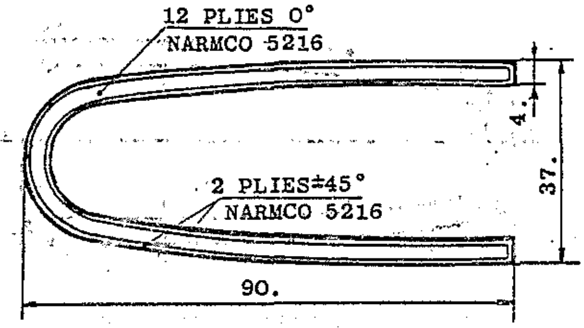


Fig. 18 A - "C" SPAR TESTED

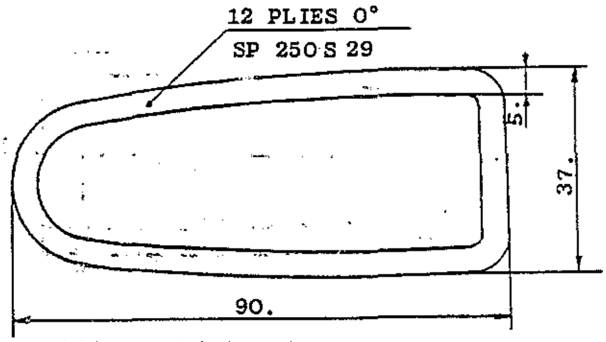


Fig. 18 B - "D" SPAR TESTED

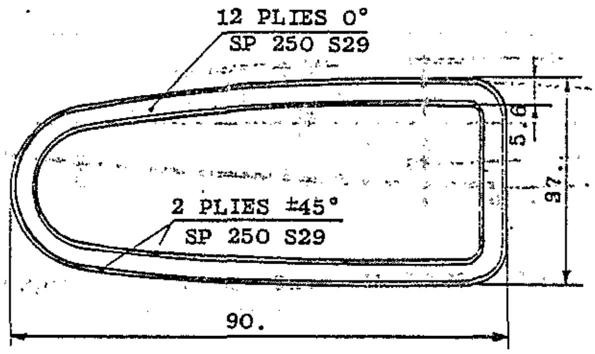


Fig. 18 C -"D" SPAR TESTED

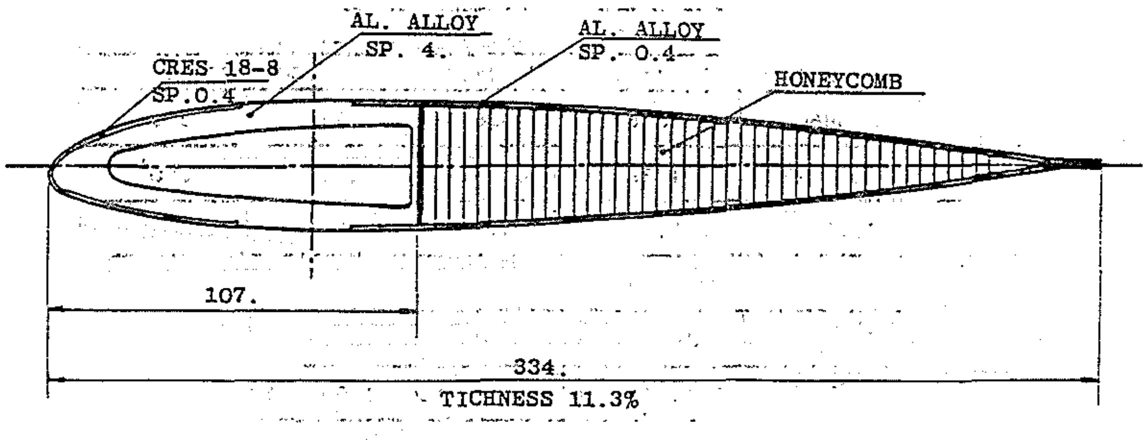


Fig. 18 - BLADE TESTED

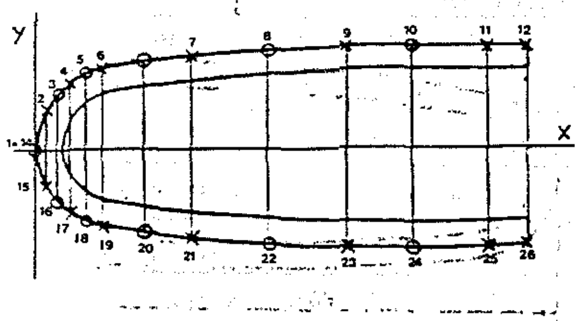


Fig. 19 A- "C" SECTION GRID POINTS.

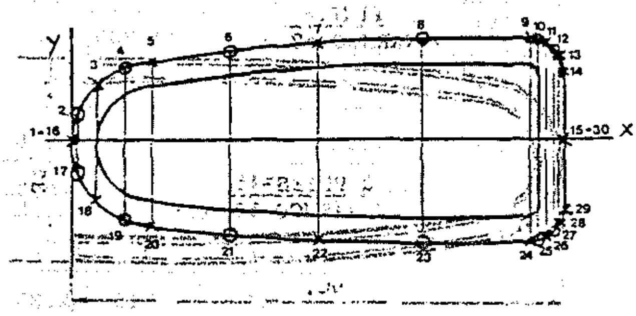


Fig. 19 B-C-"D" SECTION GRID POINTS.

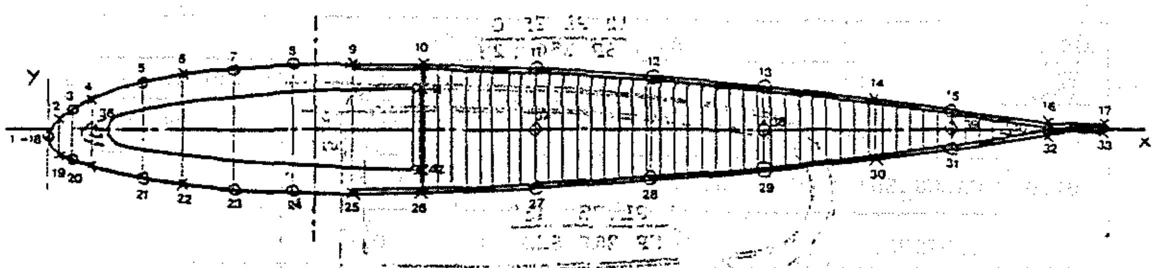


Fig. 19 D -COMPLETE-BLADE SECTION GRID POINTS.

Fig. 20 A TORSIONAL TEST N° 1 -BLADE SECTION Fig. 18D

APPLIED TORQUE [Kgm]	BEAM ROTATION [RAD. 10^{-3}]				
	STA 1000	STA 1800	STA 2600	STA 3000	STA 3400
391.5	0.0666	0.2318	0.3826	0.5217	0.585
783	0.1449	0.4869	0.8111	1.0434	1.200
1174.5	0.2261	0.71	1.231	1.4980	1.794

TORQUE [Kgm]	391.5	783.0	1174.5
EXPERIMENTAL STIFFNESS	0.1813 E 10	0.1781 E 10	0.1798 E 10
% DISPL.	2.7	0.9	1.9

GJ HANBA = 0.1765 E 10

Fig. 20 B BENDING TEST n° 1 - "D" SPAR Fig. 18C.

APPLIED LOAD [Kg]		BEAM DEFLECTION [mm]							
		STA 238	STA 339	STA 439	STA 539	STA 639	STA 739	STA 839	STA 942
112.39	EXPERIMENTAL	1.75	2.6	3.9	5.35	6.75	8.3	9.85	11.65
	CALCULED	1.75	2.729	3.887	5.207	6.667	8.241	9.906	11.69
	% DISPL.	0.	-4.96	-0.33	-2.67	-1.23	-0.71	0.56	0.34
61.6	EXPERIMENTAL	1.2	1.75	2.4	3.1	3.85	4.7	5.5	6.5
	CALCULED	1.2	1.718	2.334	3.039	3.82	4.664	5.558	6.517
	% DISPL.	0.	-1.82	-2.75	-1.96	-0.77	-0.76	1.	0.26

EJ HANBA = 0.433 E 10 EJ BEST FIT = 0.465 E 10

Fig. 20 C BENDING TEST N° 2 - "D" SPAR Fig. 18 C.

APPLIED LOAD [Kg]		BEAM DEFLECTION [mm]							
		STA 238	STA 339	STA 439	STA 539	STA 639	STA 739	STA 839	STA 942
91.99	EXPERIMENTAL	2.625	5.	8.187	12.	16.25	21.187	26.375	32.25
	CALCULED	2.625	5.037	8.185	11.989	16.354	21.181	26.372	31.998
	% DISPL.	0.	0.74	0.	0.	0.64	0.	0.	0.78
51.14	EXPERIMENTAL	1.25	2.625	4.5	6.75	9.187	11.812	14.812	18.25
	CALCULED	1.25	2.661	4.481	6.665	9.161	11.914	14.87	18.069
	% DISPL.	0.	1.37	-0.42	-1.26	-0.28	0.86	0.39	-0.99

EJ HANBA= 0.9256 E9 EJ BEST FIT= 0.943 E9

Fig. 20 D BENDING TEST n° 3 - "D" SPAR Fig. 18C.

APPLIED LOAD [Kg]		BEAM DEFLECTION [mm]							
		STA 238	STA 339	STA 439	STA 539	STA 639	STA 739	STA 839	STA 942
82.15	EXPRIMENTAL	1.3	2.05	2.9	3.8	4.85	6.05	7.35	8.65
	CALCULED	1.3	2.00	2.846	3.817	4.898	6.068	7.309	8.641
	% DISPL.	0.	-2.5	-1.8	0.44	0.98	0.29	0.55	0.1
41.15	EXPRIMENTAL	0.65	1.	1.4	1.9	2.45	3.1	3.8	4.55
	CALCULED	0.65	1.02	1.461	1.866	2.525	3.129	3.769	4.455
	% DISPL.	0.	2.	4.3	-1.78	3.	0.9	-0.8	-2.

EJ HANBA = 0.433 E 10 EJ BEST FIT = 0.433 E 10

Fig. 20 E BENDING TEST n° 1 - "C" SPAR Fig. 18 A.

APPLIED LOAD (Kg)		BEAM DEFLECTION (mm)						
		STA 238	STA 339	STA 439	STA 539	STA 639	STA 739	STA 839
41.15	EXPERIM.	.725	1.375	2.15	3.05	4.05	5.1	6.3
	CALC.	.725	1.382	2.169	3.071	4.071	5.15	6.307
	% DISPL.	0.	0.5'	0.88	0.688	0.51	1.	0.1
61.75	EXPERIM.	1.1	2.	3.125	4.5	5.95	7.6	9.35
	CALC.	1.1	2.06	3.216	4.544	6.021	7.62	9.325
	% DISPL.	0.	3.	2.91	0.977	1.2	0.29	-0.27

EJ HANBA = 0.2503 E 10 EJ BEST FIT = .263 E 10

Fig. 20 F BENDING TEST n° 3 - " C " SPAR Fig. 18 A

APPLIED LOAD (Kg)		BEAM DEFLECTION (mm)						
		STA 238	STA 339	STA 439	STA 539	STA 639	STA 739	STA 839
41.15	EXPERIM.	1.375	3.2625	5.6375	8.375	11.6875	15.375	19.3125
	CALC.	1.375	3.344	5.792	8.66	11.895	15.434	19.222
	% DISPL.	0.	2.5	2.74	3.4	1.77	0.38	-0.46
51.3	EXPERIM.	1.6875	4.05	6.95	10.3125	14.5625	19.25	24.375
	CALC.	1.688	4.167	7.243	10.845	14.9	19.337	24.084
	% DISPL.	0.	2.88	4.2	5.16	2.31	0.45	-1.2

EJ HANBA = .6982 E 09 EJ . BEST FIT = .715 E 09

Fig. 20 G TORSIONAL TEST n°1 - " D " SPAR Fig. 18 B

APPLIED TORQUE (Kgm)	BEAM ROTATION (RAD. 10^{-1})				
	STA 438	STA 538	STA 638	STA 738	STA 838
2.720	.032	.048	.064	.08	.084
8.160	0.114	0.148	0.184	0.214	0.244
13.600	0.20	0.25	0.308	0.356	0.414

TORQUE (Kgm)	2.72	8.160	13.600
EXPERIMENTAL STIFFNESS	.3 10 E 09	.27 E 09	.26 E 09
% DISPL.	6.	----	----

GJ HANBA = 0.3285 E 09