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DESIGN AND MANUFACTURING  
OF COMPOSITE MATERIALS BLADES MODELS

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## 1. INTRODUCTION

Actually a great part of the research in aeronautic fields is dealing with the conception of helicopter rotors "globally optimized". Within this research, experimental tests in wind tunnel are performed. The models used should follow specifications for which coupling between aerodynamics and structural behaviour took place. Therefore the design methods used for the model and for the real blades should be similar. So, it is necessary to study the dynamic behaviour of the blades in rotation, their stability and their fatigue life. In the general case, the use of composite materials is required.

To solve these problems, a specific group has been created inside the Institute of Fluid Mechanics in Lille to conceive and to realize blade models. An iterative scheme (figure 1) is proposed for blade models design and the ways of manufacturing and testing them.

The paper is consisting of four parts :

- the design methods
- the tools used by the design office and the workshops
- the instrumentation
- the quality control.

Some comparisons between calculation and testing results are presented concerning composite material blade models.

## 2. THE DESIGN METHODS

### 2.1. Structural study

#### 2.1.1. Finite beam element

In our general design scheme and for a preliminary approach, a finite beam element is used to represent the mechanical behaviour of blade models.

For a quick calculation, a simple finite beam element with two nodes per element and six degrees of freedom by node is used. This type of element gives an adequate accuracy between experimental and calculated static and dynamic values if the length of the blade is about ten times greater than its chord. The mechanical characteristics of this element are introduced by the equivalent stiffnesses  $EI$  and  $GJ$  resulting from an analytical formulation. The first eigenvalues and mode shapes are determined by a subspace iteration method. The table 1 presents the comparison between calculated and experimental values of the eigenfrequencies for a straight rigid graphite-epoxy blade, of five centimeters chord and fifty eight centimeters of length, constructed with carbon fibers. By this analytical formulation, the torsion eigenfrequency is underestimated and so we propose to introduce, as shown in figure 2, a two dimensional finite element program which is actually developed in order to calculate equivalent  $EI$ ,  $GJ$  and the transverse shear inside the section (this type of section is composed of cross-ply laminate and medium density foam for the skin and the central part respectively).

By introducing the aerodynamic loads during the rotation, the deflection and the torsion of the blade can be evaluated. From the local curvatures and the torsion deformation, the induced stresses in each cross section can be determined for the structural design.

### 2.1.2. Structural design with a shell element

#### Description of the element

In order to refine the knowledge of the structural design with respect to stresses, vibratory design, ... of our composite blade models, we use the finite element method. The finite element software used is the ONERA's ASTRONEF linear code {1} with a particular degenerate three-dimensional composite shell element. It was particularly developed at ONERA for static and dynamic analysis of helicopter and aircraft blades {2}, {3}, {4}.

This multilayer finite element is quadrilateral and isoparametric with the hypothesis of mean transverse shear. It has eight nodes and five degrees of freedom per node, i.e. the three components  $u$ ,  $v$  and  $w$  of the displacement vector and the two rotations  $\alpha$  and  $\beta$  of the unit vector  $\bar{V}_3$  around the unit vectors  $\bar{V}_1$  and  $\bar{V}_2$  respectively (figure 4).

The formulation of the element, not presented here, is based on the formulation of the twenty node isoparametric finite element with the following hypotheses :

- linear thickness-wise variation of the displacements,
- stress  $\sigma_{zz}$  is supposed negligible in the expression for the internal strain energy and consequently the  $\epsilon_{zz}$  strain is eliminated.

Moreover the formulation was also developed to take into account the evolution of the thickness of the layers in the composite blade models and in particular in the leading edge areas. So, the relative thickness of each ply (layer thickness/total thickness) is considered varying linearly in the direction  $\zeta$  and constant in the other direction  $\eta$  (figure 5).

In order to modelize the most current encountered materials in the composite blade models (unidirectional carbon-epoxy layers, glass fiber-reinforced epoxy, titanium, foam, ...), each ply of the laminate structure is considered in the form of an equivalent linear elastic homogeneous material. For each of them, the constitutive equation law will be taken as that of either an isotropic, NIDA or transverse isotropic material. For instance, five mechanical properties are necessary to characterize a transverse isotropic material for the calculation.

In addition, the fiber lay angle must be provided as input to laminate shell element.

All mechanical properties of isotropic or composite materials came from a material data base developed at I.M.F.L. and based on static and dynamic tests.

### Some structure applications

A recent example of application of this thick degenerate shell element to structural design, corresponds to the analysis of the vibratory behaviour of a composite blade of a high speed propeller (figure 6). A static analysis of this structure under aerodynamic and centrifugal forces has been also undertaken.

The external geometric shape of the model, is generated using a set of basic airfoil sections and the CATIA Design Software implanted at the I.M.F.L.. Let us also add that this software was used to define the complex connection area between the blade and the root (figure 8).

The internal structure of the composite blade is made up of :

- a skin of cross-plyies of unidirectional carbon fibers-epoxy,
- reinforcements constituted of layers of high-strength carbon fibers-epoxy,
- a set of layers of carbon fibers-epoxy for the wingtip and the front spar,
- rigid foam filler and a titanium blade root fitting.

Figure 7 shows a internal view of the layers setting for the leading edge, the front spar and the rear-spar.

For the different free-vibration analyses of the composite blade at rest and in rotation, several meshes have been defined. Following a convergence study, the retained grid is a mesh with fifteen divisions in the X direction, five in the Y direction for the blade root area and seven divisions for the rest of the blade. This mesh allows 330 nodes, 190 multilayer shell elements and 1,650 degrees of freedom.

The mesh and the half-mesh of the mean and lower surfaces respectively are presented in figure 8.

During this study of mechanical behaviour of the blade, the boundary conditions correspond to a clamped root.

The first six calculated eigenvalues of the high speed propeller blade at rest, are given in table 2. The experimental values are included in the same table for the blade eigenfrequencies as determined from a pulsed excitation method. The computed and measured nodal lines corresponding to the first three modes are plotted in figure 9.

To determine the dynamic characteristics of the composite blade in rotation, the analysis is more complex because of the problem of small vibrations of a structure in rotation which must be solved around the quasi-static equilibrium position due to centrifugal forces. In addition under the action of these forces which may be very important, a nonlinear analysis must be made up to evaluate the quasi-static position. In order to solve this problem, the Newton-Raphson iterative method was developed and used. More details about the formulation of the determination of frequencies of a composite structure in rotation are described elsewhere {2}, {5}, {6}.

Figure 10 shows the evolution of the first two numerical frequencies of the composite blade, as in function of the rotation speed. Experimental results obtained at the S1 wind tunnel in Modane, are also given in figure 10. The numerical and experimental results were obtained for a setting angle of -2 degrees.

Considering the results obtained for the composite blade at rest and in rotation, we note :

- at rest, the multilayer thick three-degenerate shell element predicts the eigenfrequencies and the nodal lines accurately. The calculated eigenfrequencies are very close to those measured.
- in rotation, an excellent agreement between the measured and numerical frequencies. It was observed that the rotational speed increases the first two frequencies corresponding to flexural modes. The composite blade has a stiffening behaviour.

In conclusion of this application, the multilayer quadrilateral shell element with 40 degrees of freedom has been found reliable and effective and it is used satisfactorily to other structural analysis for composite blade models.

## 2.2. Aerodynamic methods

In order to answer to the particular specifications concerning the dynamical behaviour of rigid or flexible blade models for helicopter rotors, the knowledge of aerodynamic loads is very important during the conception design.

In hovering flight, we use a full potential code coming from the ONERA Aerodynamic Department. This full potential code has been adapted by A. DESOPPER and T.H. LE to the case of an isolated helicopter blade and was performed to a quasi-steady blade computation of the rotor in hover.

Actually, this programm is used to evaluate the aerodynamic loads of an flexible torsion blade rotor in hover.

In forward flight, an unsteady full potential code, called FP3D {7}, is used.

## 2.3. Dynamic methods

In order to predict the instabilities and forced vibration of the blade models, we use two codes developed by the ONERA Structures Department.

The first code, called TF, permits to determine Floquet's modes characterizing the stability of the blade and it permits also to evaluate the responses to external dynamic loads. This program is based on a modal representation with a quasi-steady aerodynamic 2-D model or a unsteady aerodynamic semi-empirical model for the dynamic stall {8}.

The second program, called PAP, has been developed to simulate the dynamic behaviour and particularly the forced response and the dynamic loads in space time. Its formulation is based also on a modal approach and takes into account the unsteady aerodynamic semi-empirical model for the dynamic stall {9}. The set of differential equations is solved by the use of an explicit time integration method.

These two programs, implanted at I.M.F.L., are actually used for the studies of flexible blade models.

#### 2.4. Material data base

For the design of blade models with particular structural behaviour, in a research field, a large choice of composite materials is required in function of their mechanical properties and their layer thicknesses. So a specific material data base is built in accordance to the general scheme as shown on figure 11.

The static mechanical properties of composites considered as transverse isotropic materials,  $E_L$ ,  $E_T$ ,  $\nu_{LT}$ ,  $G_L$  and  $G_T$  are obtained by classic tensile tests. The failure criteria are also given by these tests.

The dynamic mechanical properties are obtained by identification technics from the knowledge of the eigenfrequencies of a vibrating rectangular plate clamped on one side. The comparison between static and dynamic values can be made and some adjustments are realized before the application for a blade calculation.

Fatigue machine testing is used to establish fatigue degradation models.

In an other way the gel times of composite materials are determined in order to control the curing cycle of the blade models.

Among the composite materials, the carbon and glass unidirectional laminates and woven satins are specially studied.

### 3. DESIGN OFFICE AND WORKSHOPS TOOLS

The principal tools, encountered in the design office, concern a group of softwares specialized in the creation and handling of complex surfaces for the conception or for the numerical machining program. The main softwares, CATIA, CADAM, APT and CADSAP are located on an I.B.M. 9377 computer. Four graphic terminals are used simultaneously.

A microcomputer is used as an interface between the host computer and the computer numerical controls associated to the numerically controlled machines (5 axes milling machine  $X = 1600$  mm,  $Y = 800$  mm,  $Z = 500$  mm,  $A = B = 22^\circ 5$  ; 3 axes turning lathe with milling possibility,  $\phi = 400$  mm,  $X = 200$  mm,  $Z = 1000$  mm).

A synopsis, figure 12, shows the different interactions and possibilities of the design office tools.

For plastic and thermoplastic manufacturing the main tools are :

- autoclave of 1,15 m diameter and 2,3 m of length, range of temperature from ambient to 250°C, curing pressure lower than 10 bars, control of the temperature inside the mould,

- heating room with an internal volume of 2,35 x 1,5 x 1,25 m<sup>3</sup>, regulated temperature in the range of ambient to 300°C,

- with an internal oven of 0,6 x 0,6 x 0,6 m<sup>3</sup>, regulated temperature lower than 600°C,

- hydraulic press with heating plates with an area of 0,65 x 0,65 m<sup>2</sup>, regulated temperature lower than 300°C, water cooling, maximal closed force of 50 tons,

- thermoplastic machine, injection plastic machine, etc ...

#### 4. BLADE MODEL INSTRUMENTATION

The blade model instrumentation is mainly constituted of pressure transducers and strain gauges to measure, during the rotation, the evolution of the pressure field and associated stress field on the blade and its deflection. In order to have a smooth surface, pressure transducers and strain gauges are setted inside the blade models before the curing process.

To dissociate the implementation of the instrumentation from the other phases of manufacturing, the internal light foam part of the blade, which receives the instrumentation, is coated with a thin layer of satin glass prepreg in order to be easily handled. It is also the best way to set the instrumentation more precisely and to introduce the wire layers.

Strain gauges are correctly positioned on their opposite sides on the foam - figure 13.

Pressure transducers are lodged into small injected glass reinforced plastic pipes - figure 14 - and the pipe caps are drilled precisely, after the curing process, on a numeric machine.

Tests have been performed to evaluate the transducers linearity response before and after curing. Figures 13 and 14 show that pressure transducers and strain gauges responses are not affected by curing process.

#### 5. QUALITY CONTROL

The geometric control is performed by a tridimensional S.E.I.V. measurement machine with the capability of a volume work of 1,600 x 0,8 x 0,6 m<sup>3</sup> with a precision of about 6 microns.

This machine is driven by a local microcomputer and the I.M.F.L. software is able to communicate between the host computer and the local microcomputer the point coordinates. So it is possible, by using the CATIA numeric command modulus, to program the measurement machine as a conventional numeric controlled one.

The measurement machine is integrated in an interactive tridimensional control system inside the machining process. During the intermediary machining states, controls can be made and, after point coordinates transfert to the host CATIA system, new orders can be generated to have the best accuracy as possible. This point is important for the quality of the blade moulds. Figure 15 gives a synopsis of the control process and figure 16 shows the measurement machine during a test.

The composite control quality is realized by an ultrasound technic. The porosity ratio and the porosity localization are measured in order to have an idea of the encountered risks on the mechanical behaviour, specially for the fatigue life.

The stiffnesses are experimentally determined by a classic static momentum method and compared with the previous ones.

A complete test of vibration - figure 17 - is also made by a shock method or harmonic excitation. The eigenmodes are compared to those calculated. The rigidity and mass matrix calculation can be evaluated by comparison with static and dynamic tests. If a agreement is found, the structural model is considered as valid and can be used to build the eigenvector base for the aeroelasticity problem.

At last fatigue tests with representation of the centrifugal forces, flexural and torsional momentum - figure 18 - are applied to the prototype blade.

## 6. CONCLUSION

This scheme is actually developed and the different calculation tools (structural methods, aerodynamic methods, aeroelasticity) are implemented but not totally validated.

This blade model design method is now used to the concept of flexible blades in torsion.

In a near future, these technics will be applied to research and development of a new design of blades specially adapted in order to obtain a globally optimized rotor.

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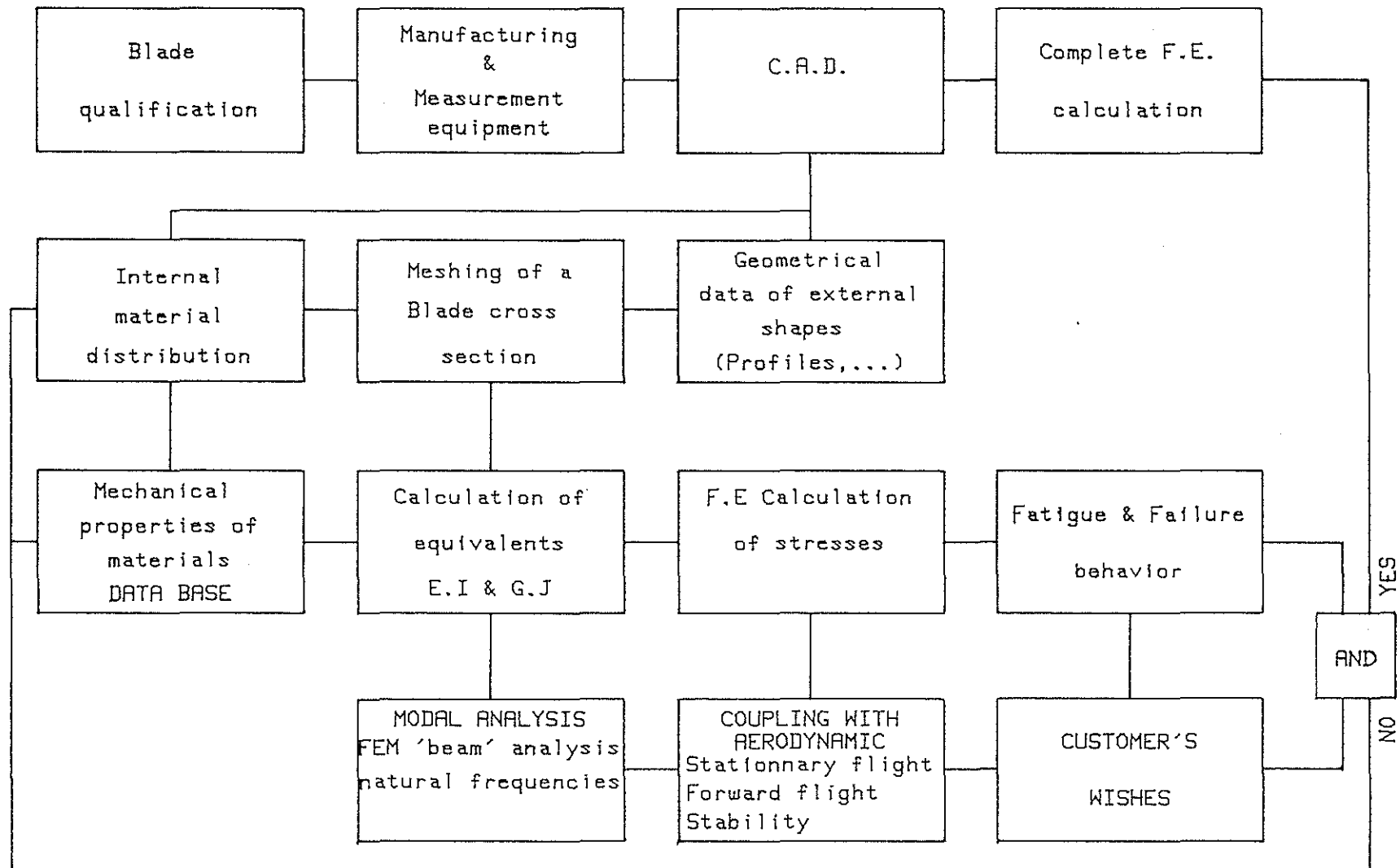
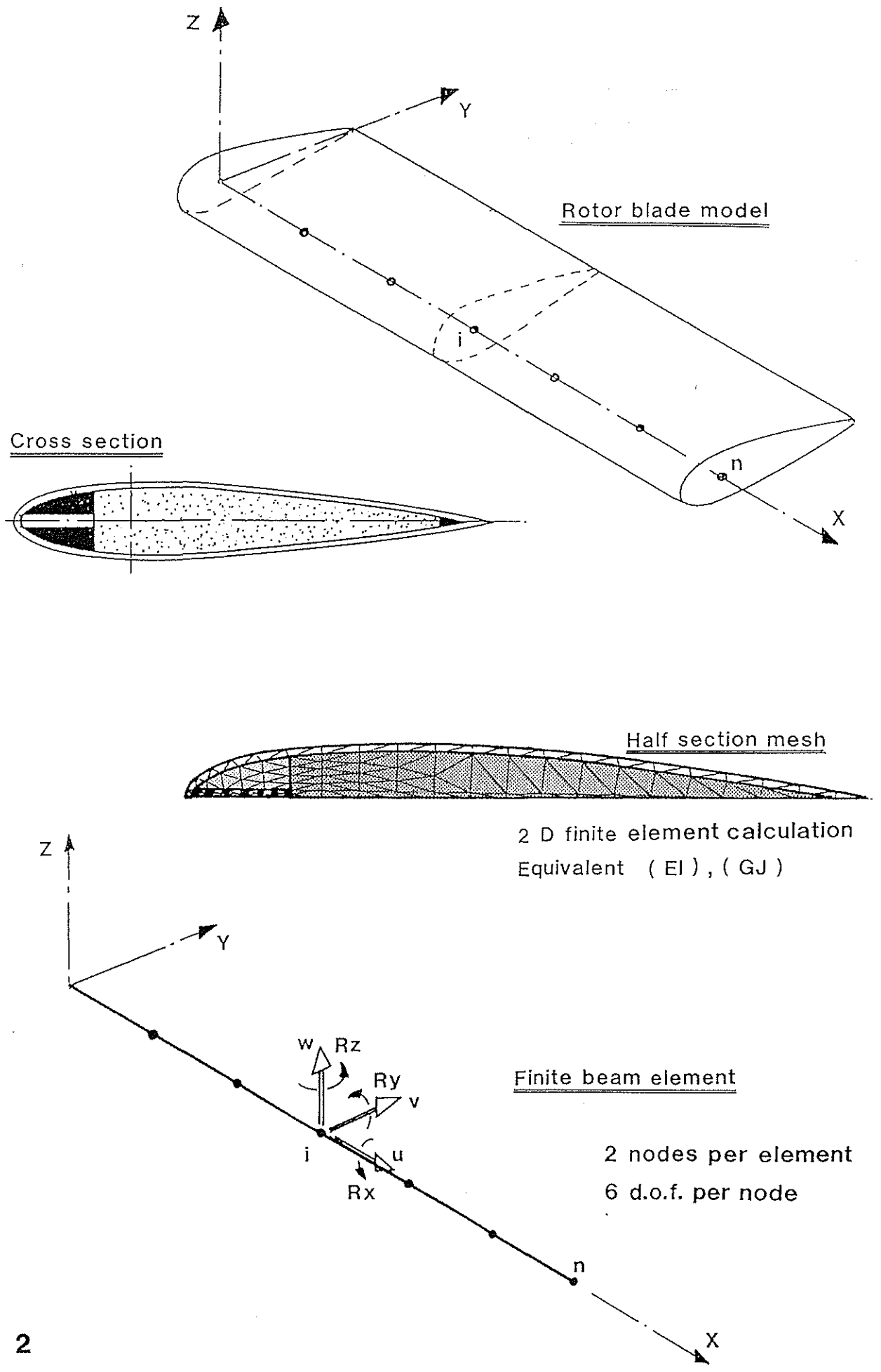
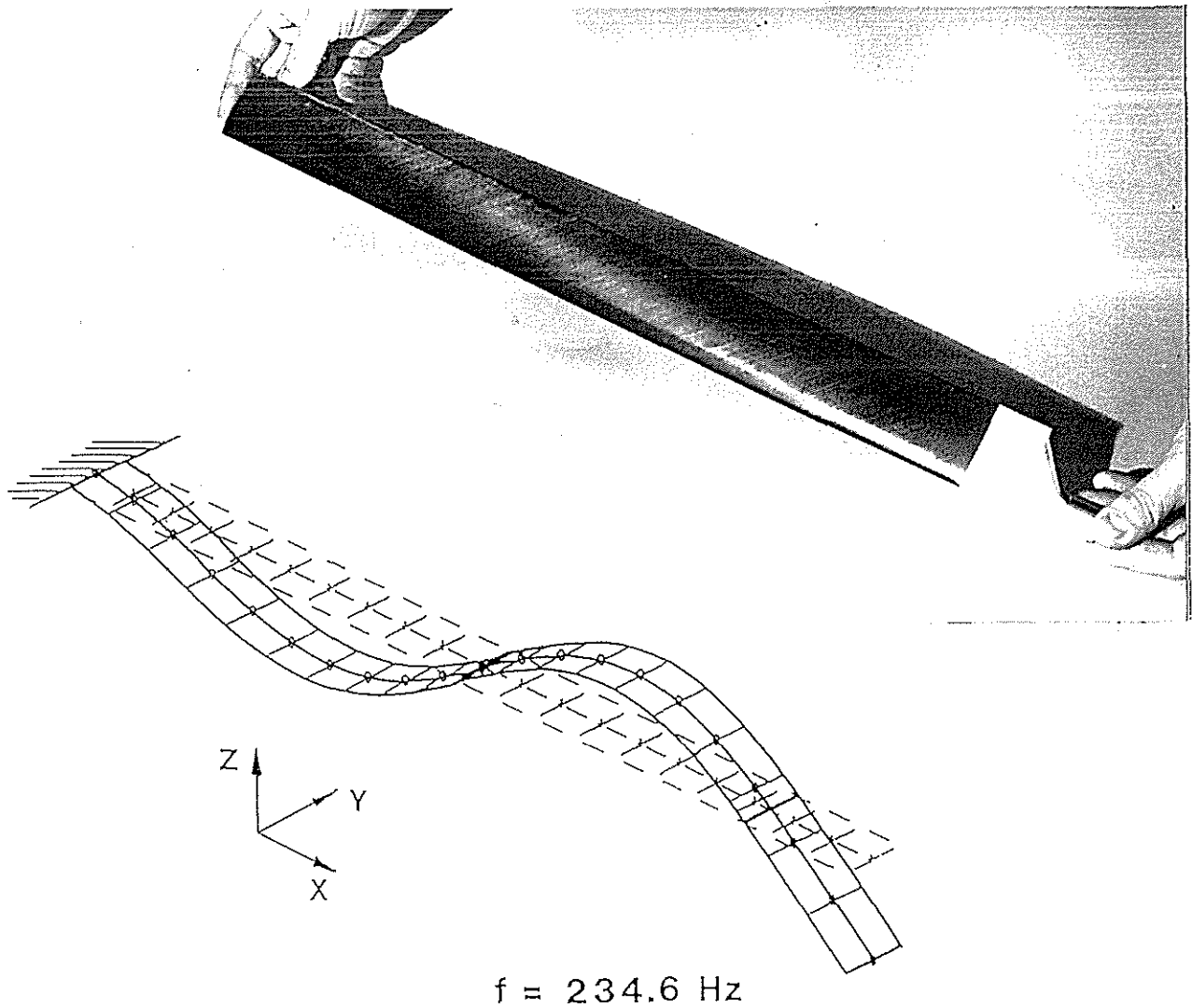


Fig. 1 Conception of blade models . General scheme



**Fig. 2**

**Modelisation steps for finite element calculation of Eigenfrequencies and Mode shapes of Rotor Blades**



**Fig. 3**  
50mm Chord straight rigid blade model - 4<sup>th</sup> mode shape -

Mode N°	Mode Shape	Eigenfrequencies (Hz)	
		Experimental	Calculated
1	Lift 0	14.1	13.4
2	Drag 0	67.3	64.0
3	Lift 1	86.1	83.7
4	Lift 2	234.6	234.6
5	Drag 1	388.0	396.5
6	Lift 3	444.6	462.0
7	Torsion	460.0	325.5

**Table 1**

Comparison between experimental and calculated Eigenfrequencies

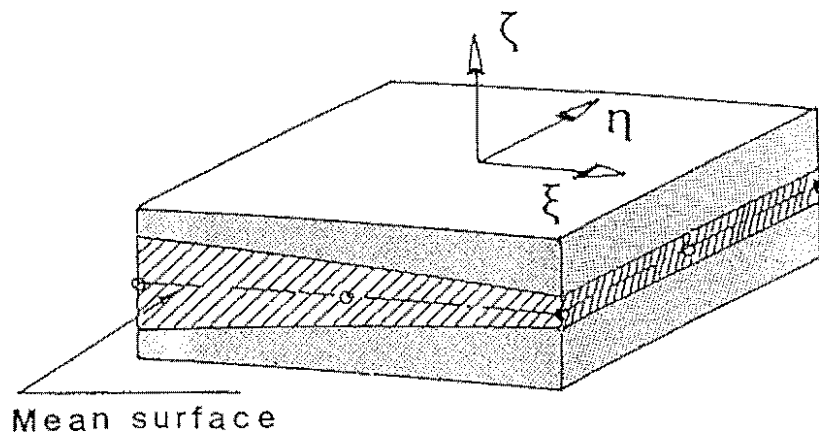
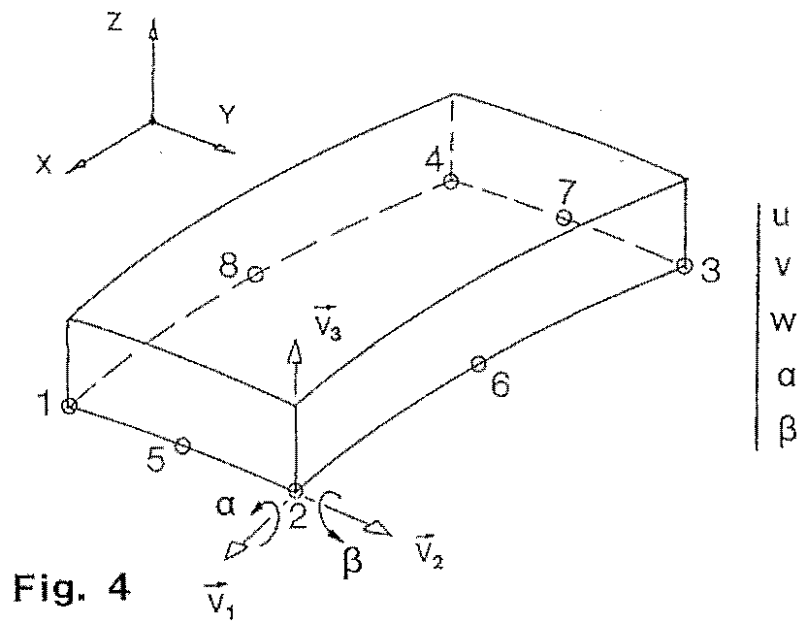


Fig. 5 Linear variation of the thickness

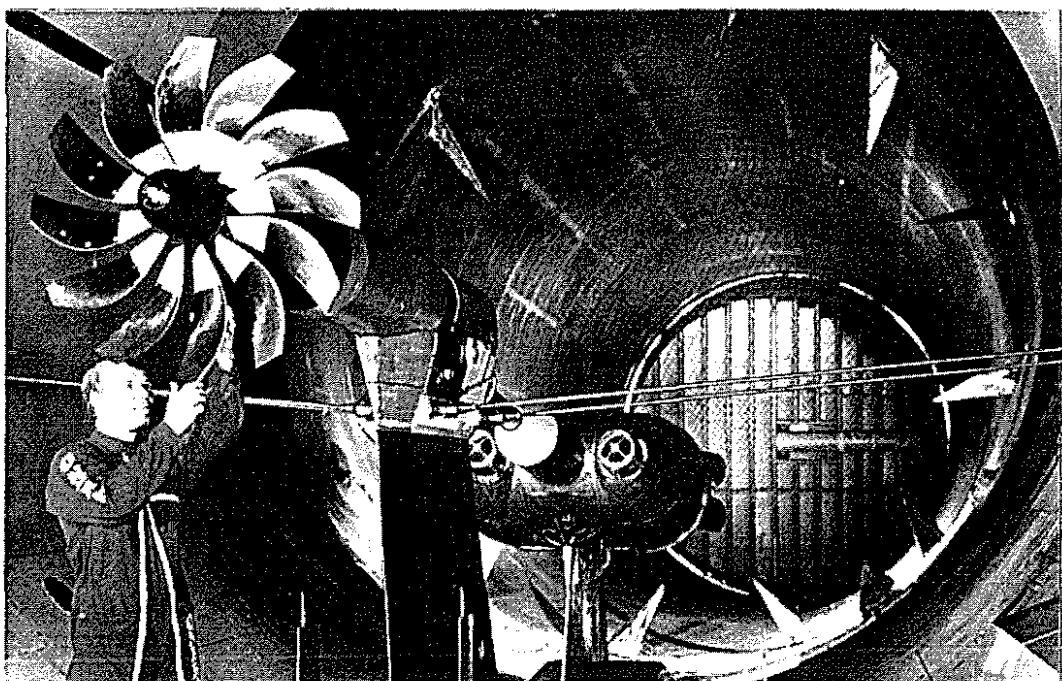
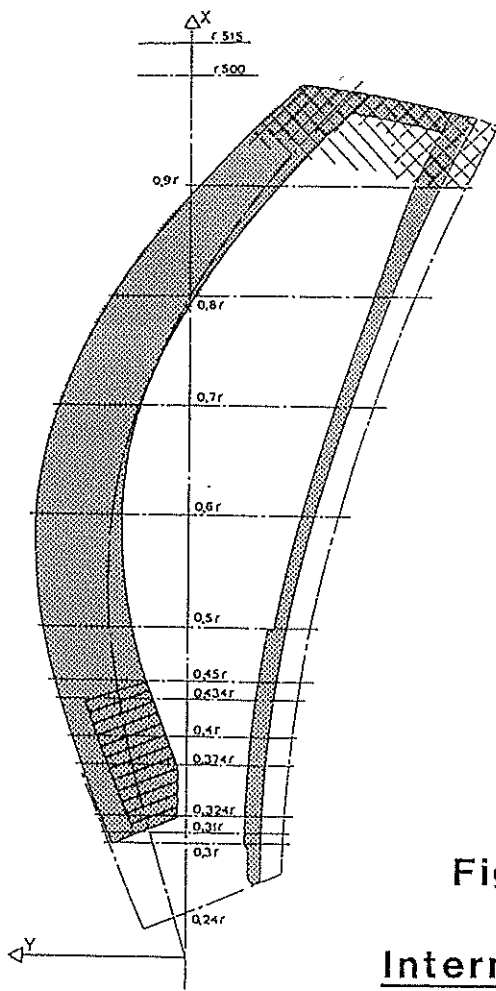
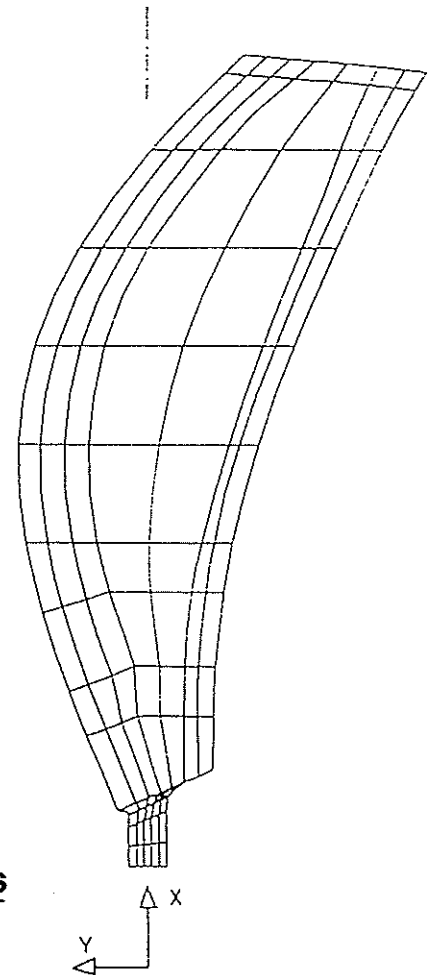


Fig. 6 Facilities high speed blade at S1 Ma

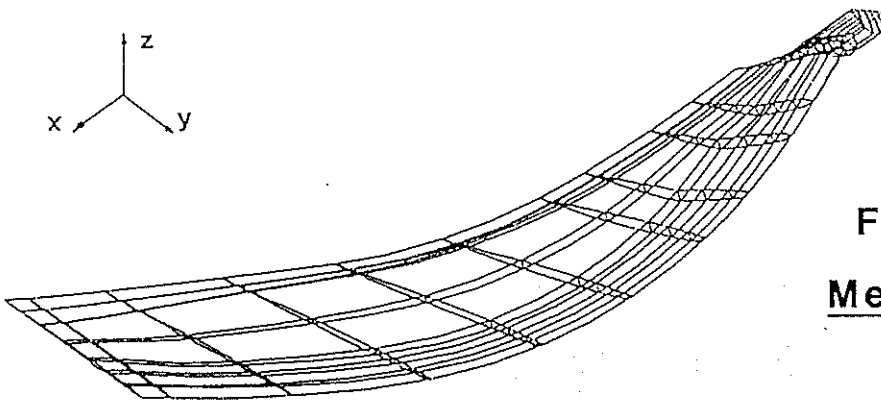


**Fig. 7**

Internal view  
of the composite structure



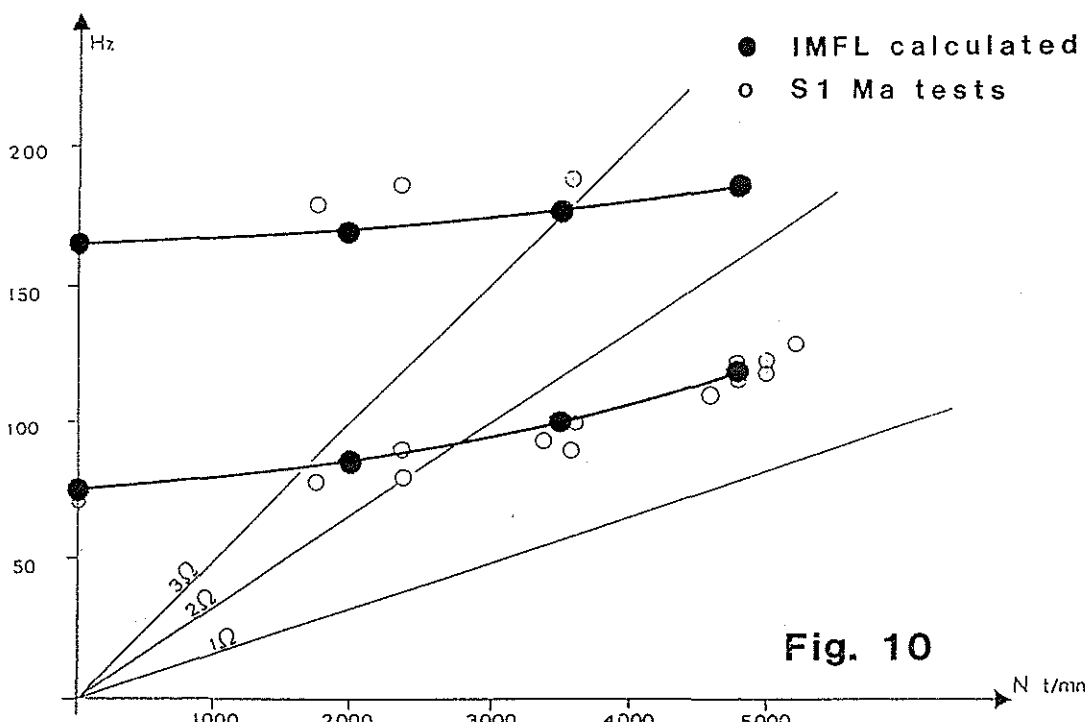
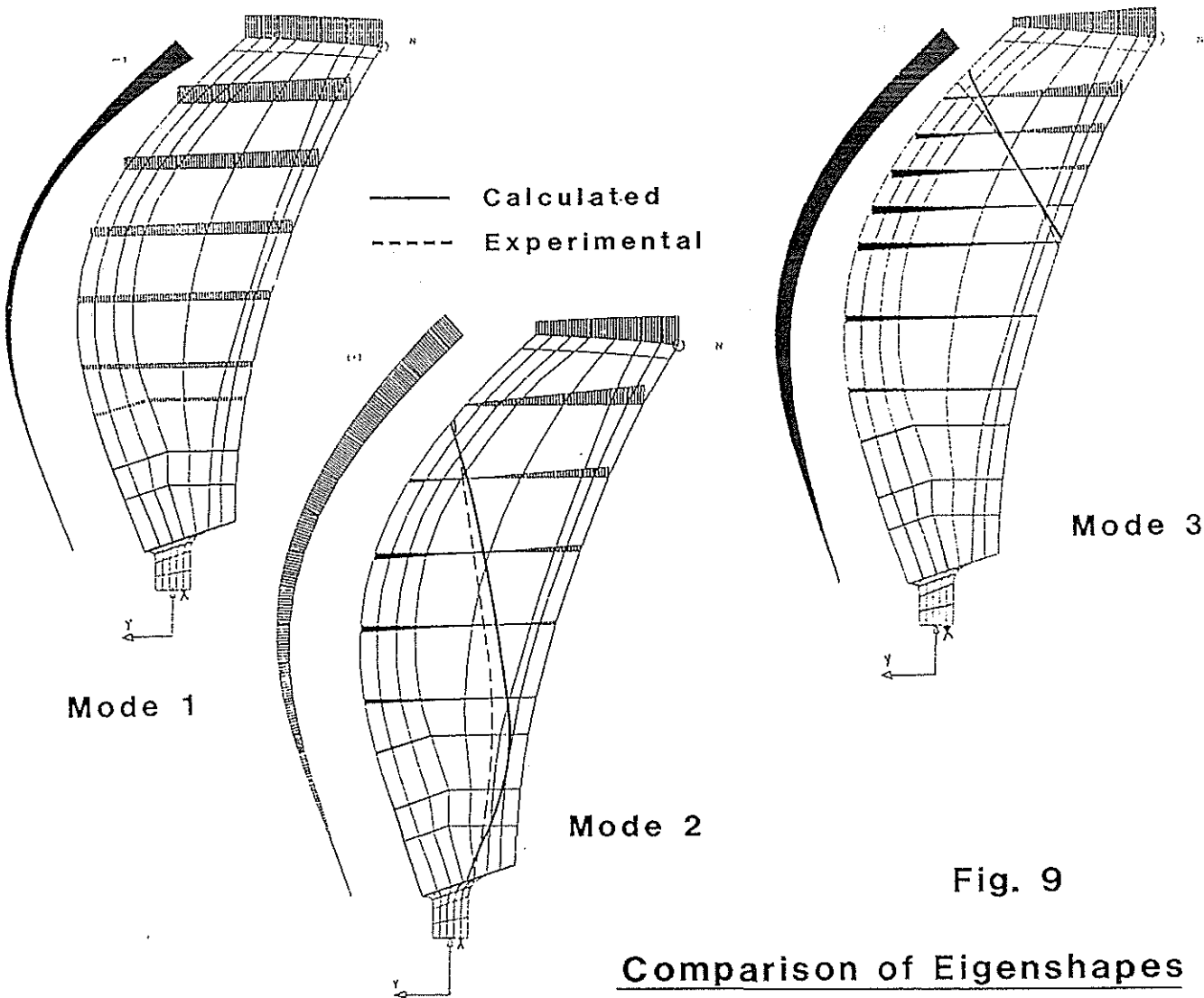
**Fig. 8**  
Meshes



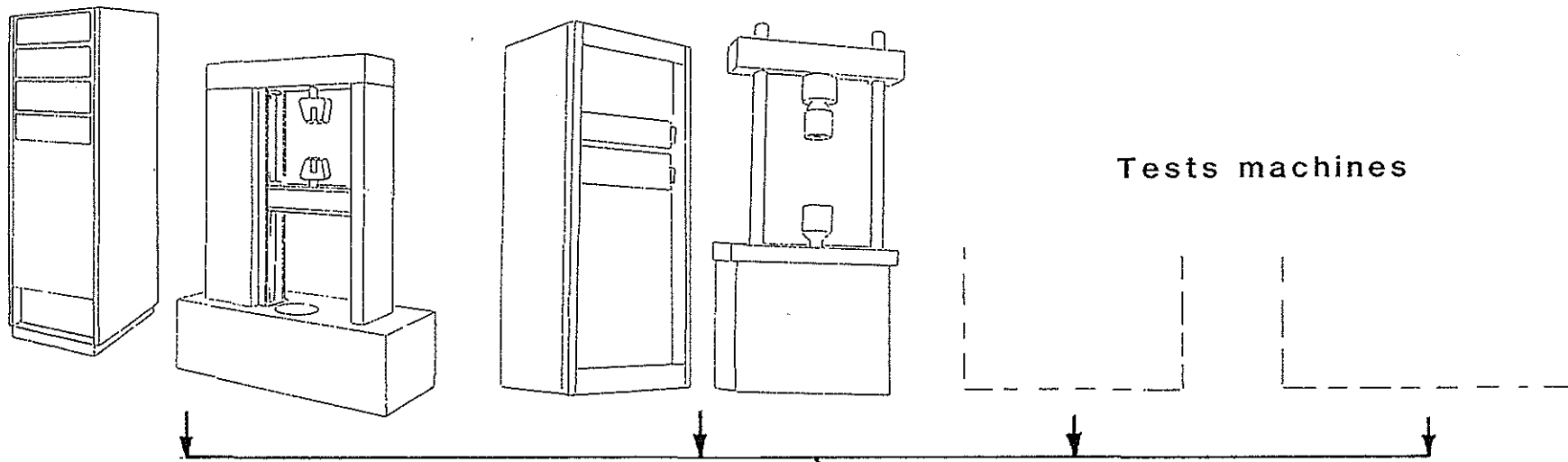
**Table 2**

Frequency (Hz)	Calculated	Tests
1	75.2	75.2
2	164.7	179.7
3	260.4	265
4	413.5	407
5	549	586
6	715	742

Comparison of computed and measured eigenfrequencies



Comparison of Eigenfrequencies as a function of the speed rotation



Tests machines

Computer

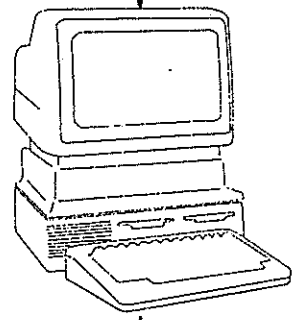
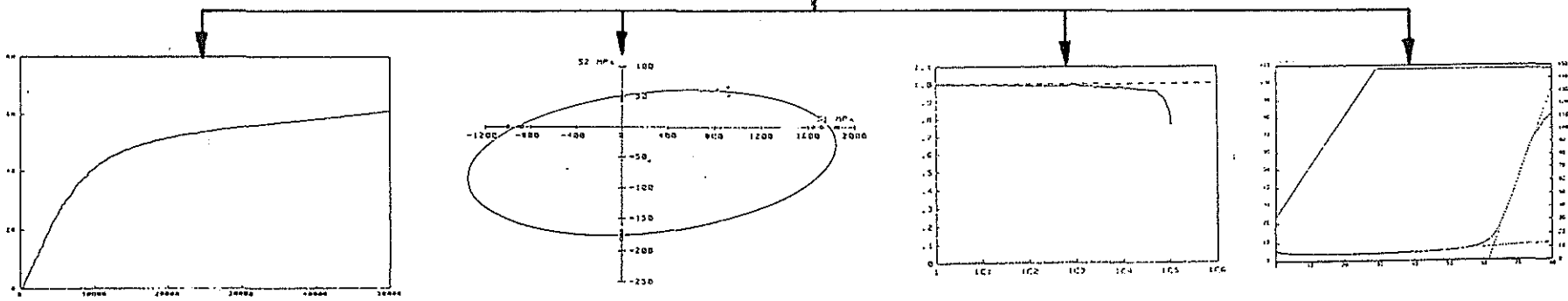


Fig. 11

Generation overview  
of material data base



Mechanical characteristics obtained



DESIGN WORKSHOP

CONTROL

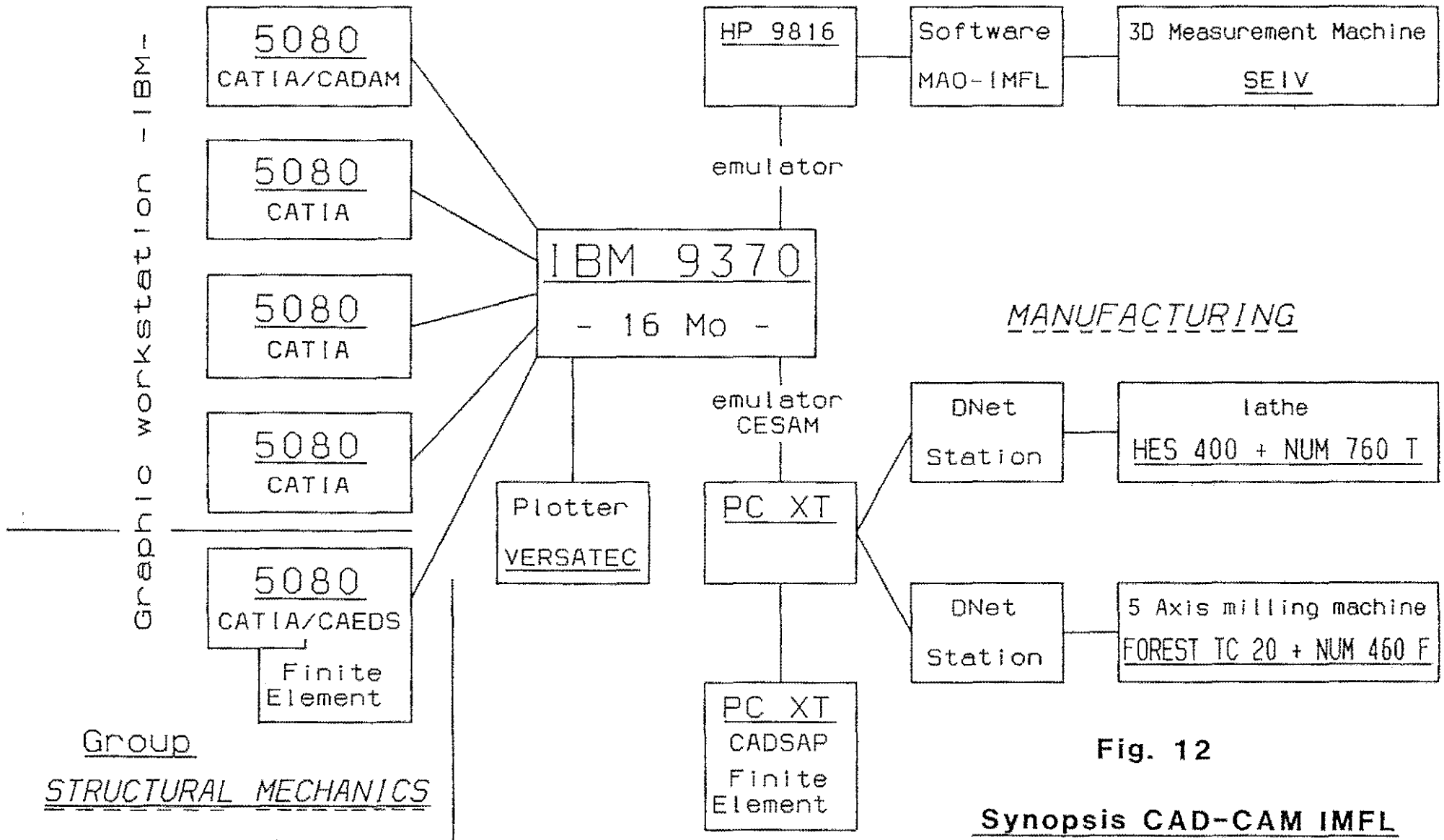
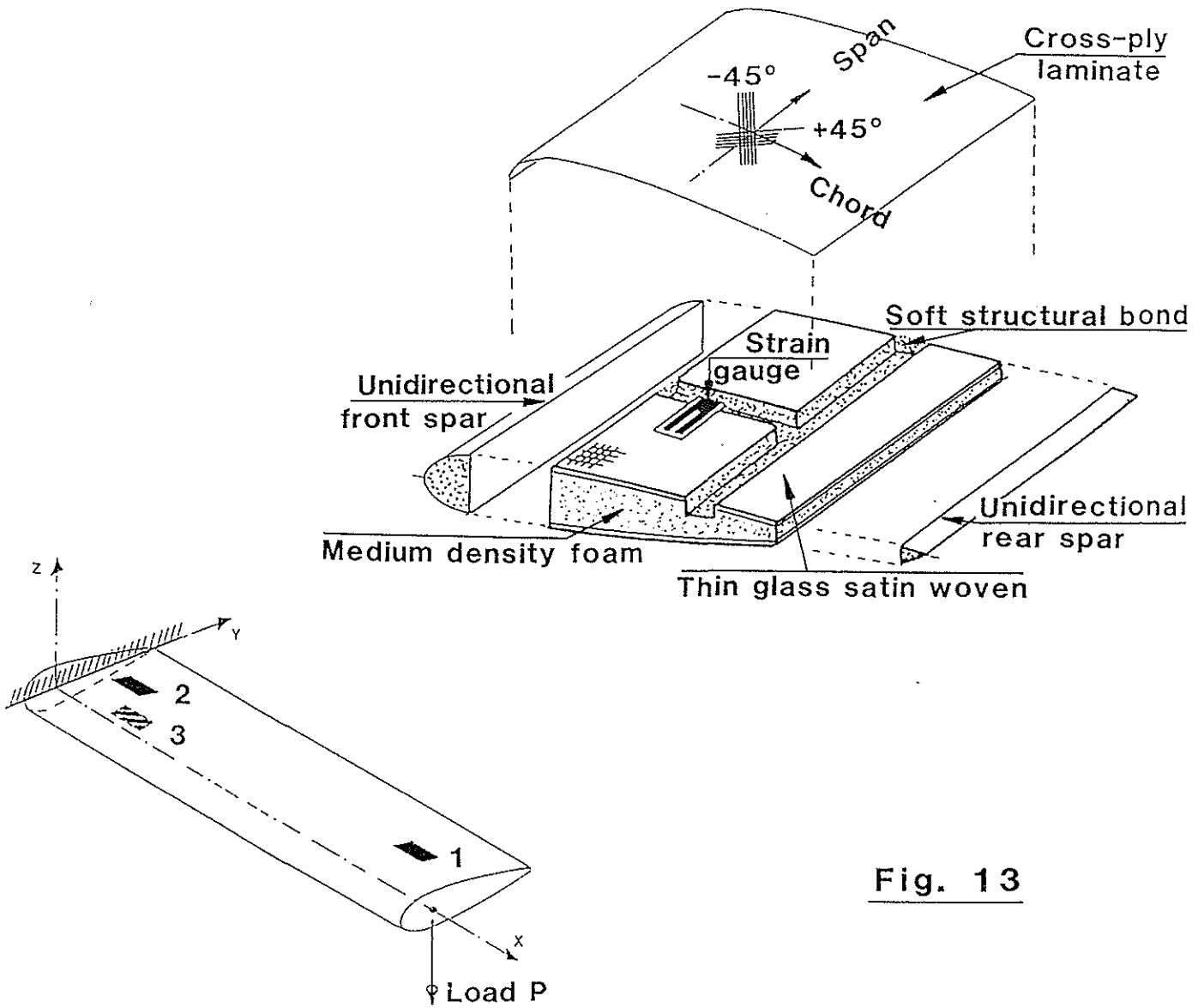
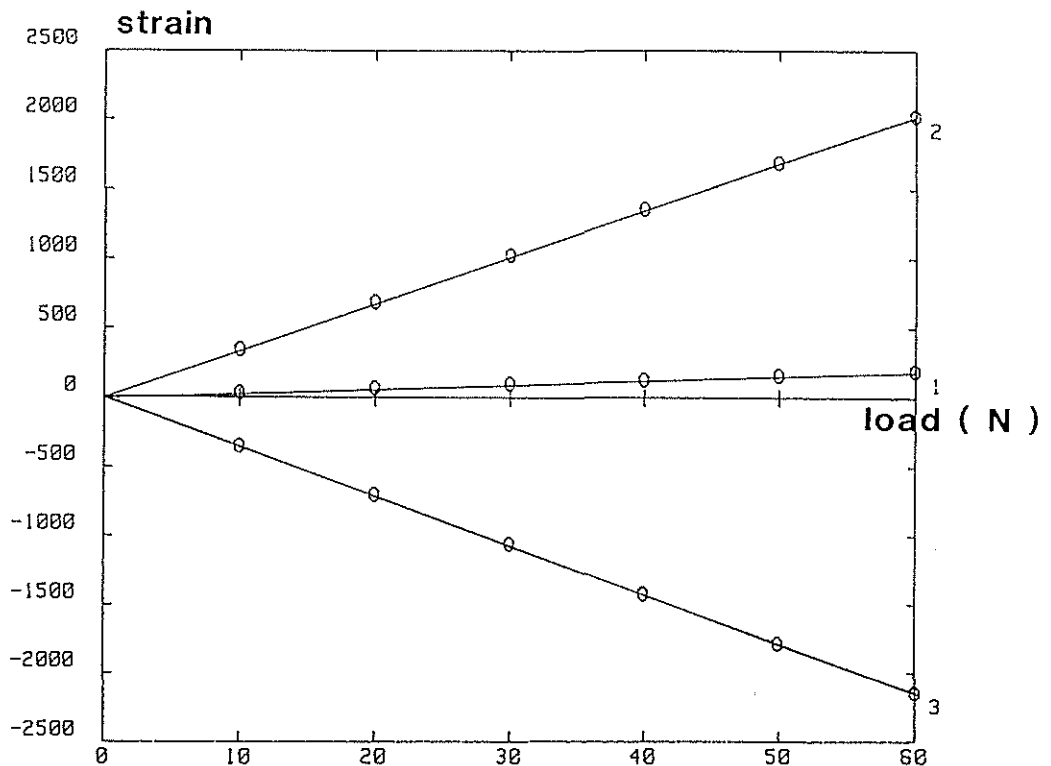


Fig. 12

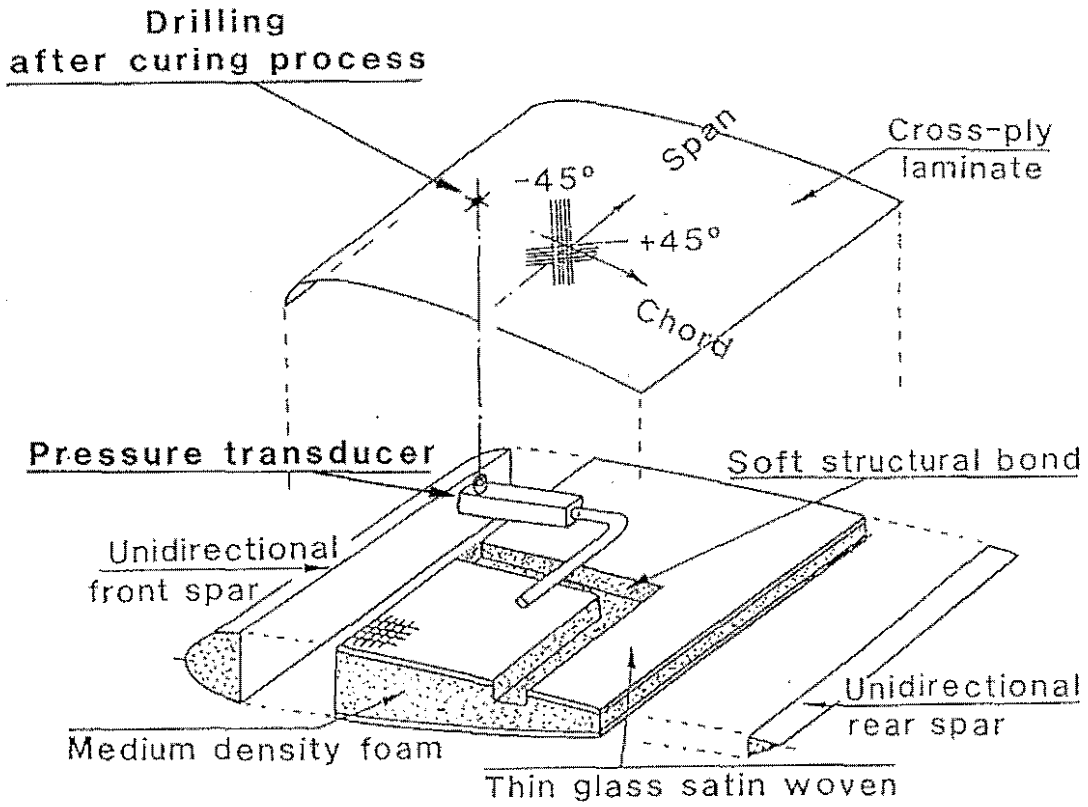
Synopsis CAD-CAM IMFL



**Fig. 13**

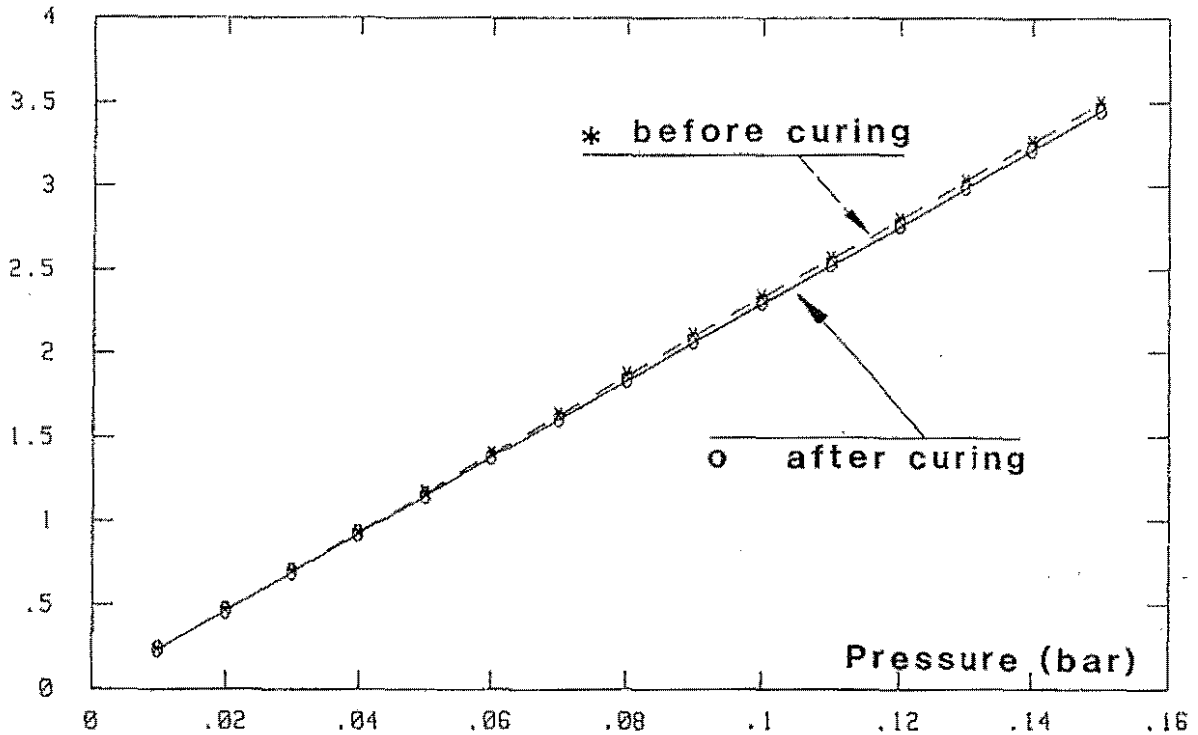


**Blade instrumentation with strain gauges**

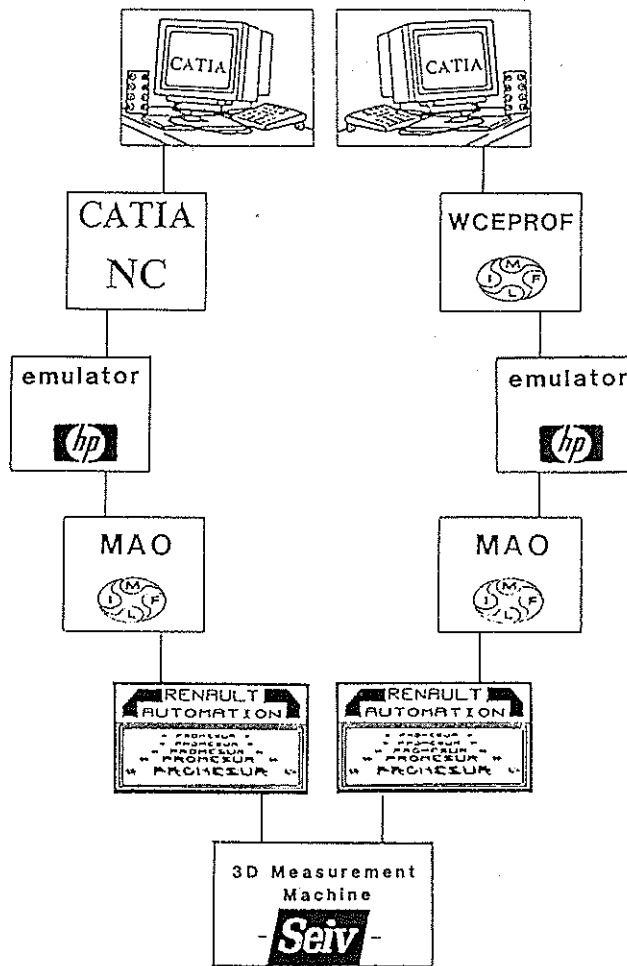


**Fig. 14**

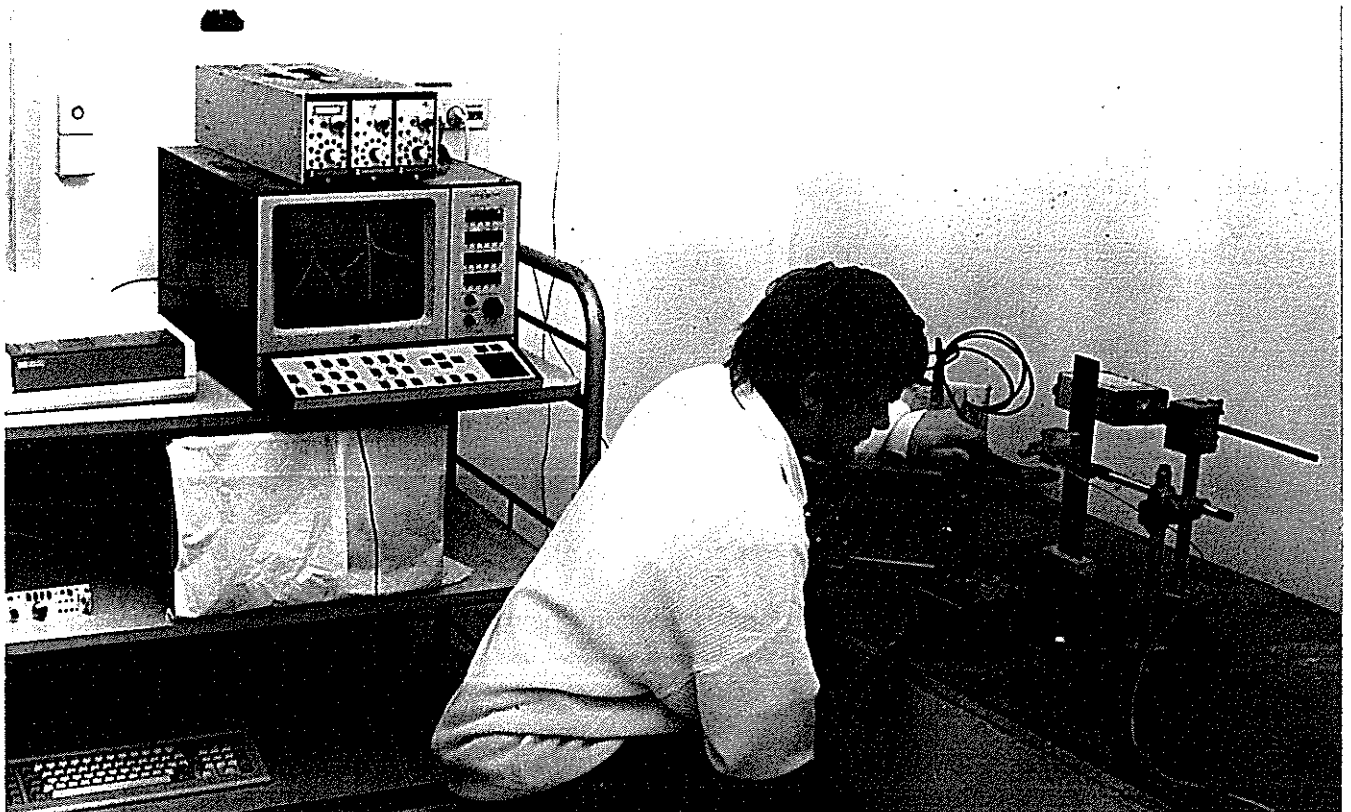
**Pressure transducer response (V)**



**Blade instrumentation with pressure transducer**



**Fig. 15 Synopsis of the control process**



**Fig. 16 3D measurement machine**

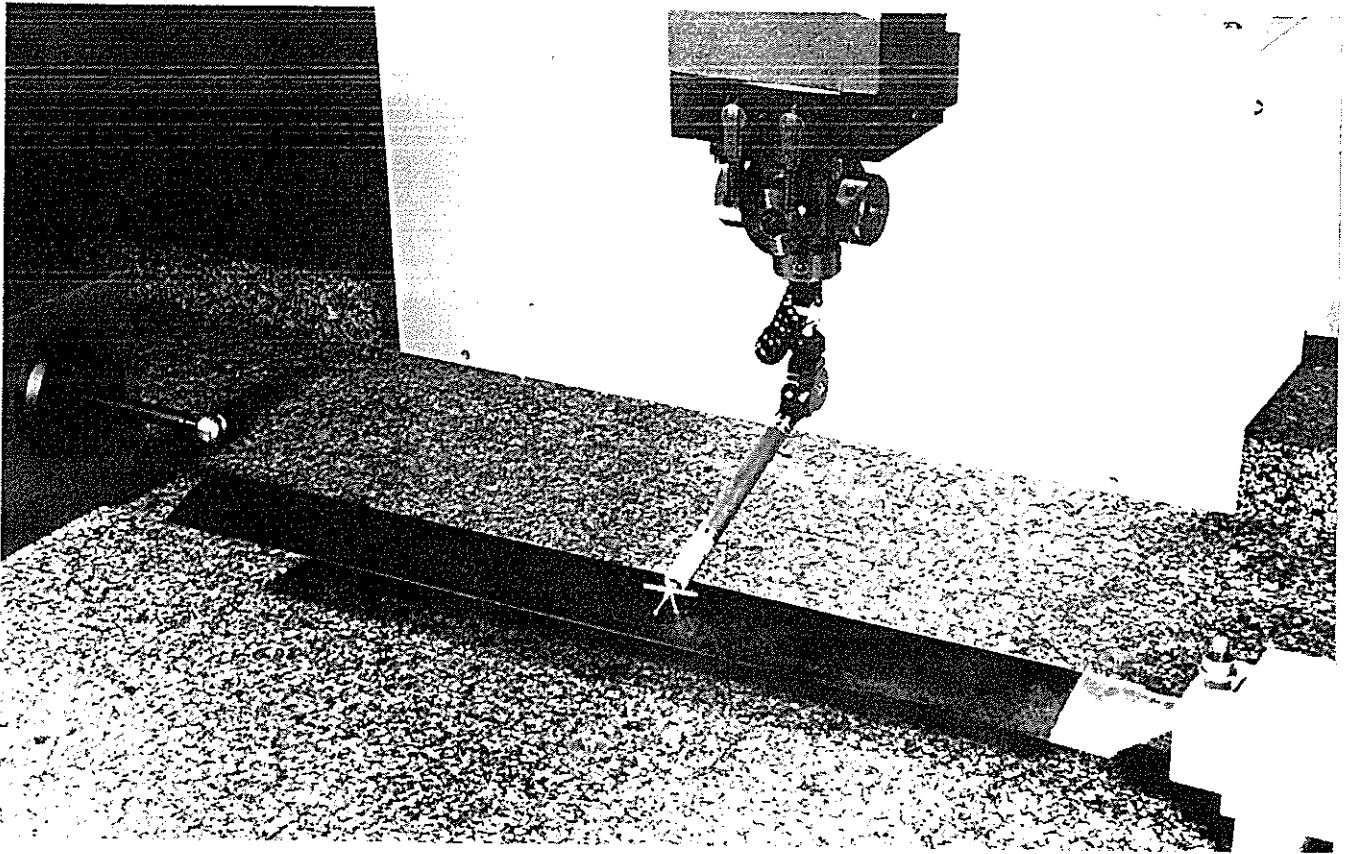


Fig. 17 Vibration test system

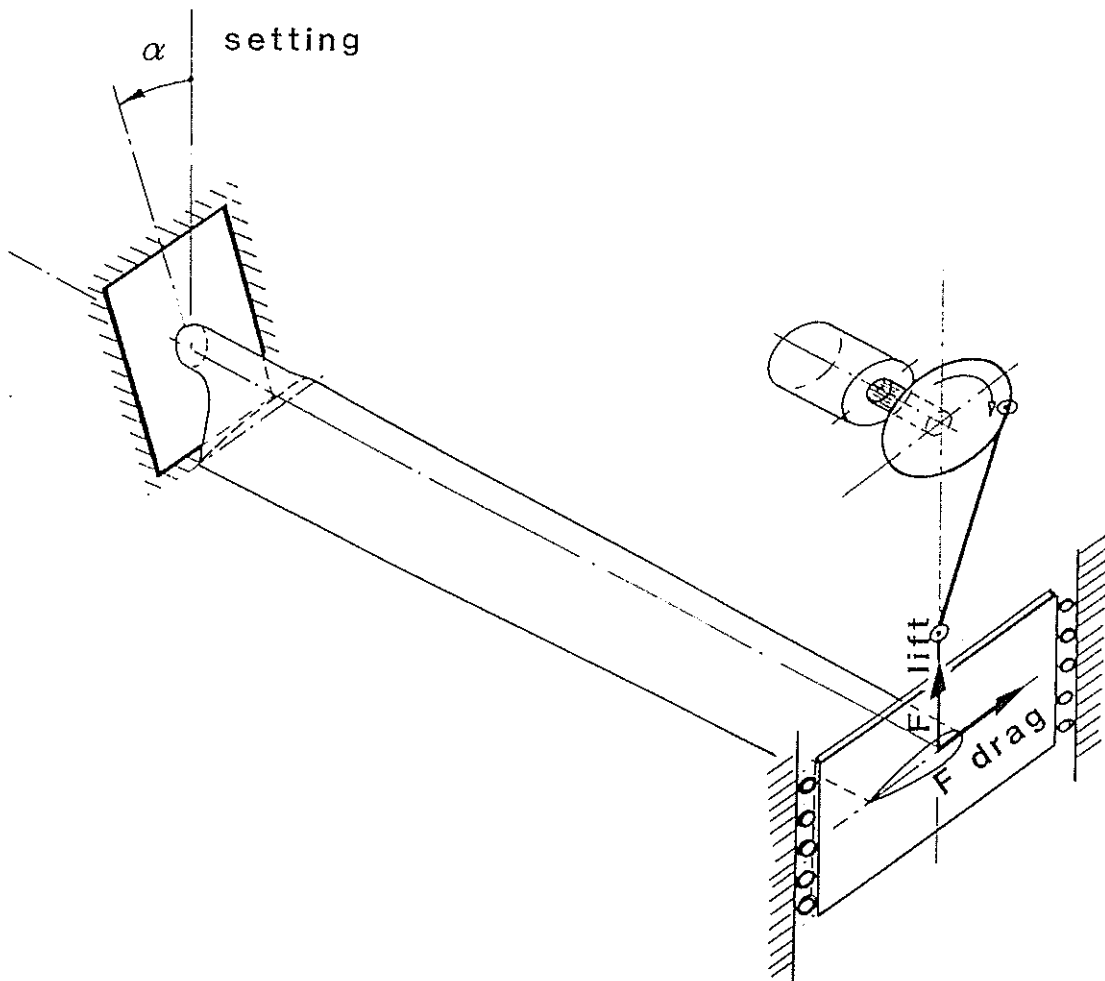


Fig. 18 Fatigue test scheme