THIRTEEN EUROPEAN ROTORCRAFT FORUM

3.11

Paper No. 21

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C.A.G.AGUSTA

September 8 - 11, 1987

ARLES, FRANCE

ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE DE FRANCE

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# STRUCTURAL AND MATERIAL DEVELOPMENTS

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## ABSTRACT

The aim of this paper is to present design development and structural characteristics of some of the major components of EH 101 helicopter main rotor head.

At first we are going to describe the analysis and testing philosophies followed in the design evolution of complex elements made of composite and metallic materials.

Afterwards we'll give a look to the application of these concepts in the design of ones of the most significant parts of the EH 101 *main rotor : Hub and Inboard Tension Link.*

The hub is formed by composite and metallic sub-structures bonded and fitted together.

Its architecture was designed to provide strenght for flight and ground loads through structural elements supporting particular loading components (e.g. composite loop windings for centrifugal load, metallic support cone for shear loads).

The Inboard Tension Link consists of a top and bottom composite laminate plates and a titanium alloy forging frame bonded and cured together. This kind of structure needed to carry out some lead-in tests in order to investigate the strenght capability of joints with laminate lugs.

Hub and Tension Link structural analysis were performed by *finite elements technique* using particular calculation methods in order to obtain detailed investigation of the most significant parts avoiding the complete 3D modeling.

Several usage optimization of the materials was also performed following structural and manufacturing requirements.

According to these mainlines the report summarizes the development of EH 101 main rotor head design in all its major features.

Structural architecture
(Composite and metallic sub-structures fitted together)

Analysis
(Calculation methods, grafical visualisation, CAD modeling)

Tests
(Lead-in tests achievements, photoelastic investigation)

Materials
(Optimization of C.R.F.P. and G.R.P. characteristics and lay-up, manufacturing considerations).

## 1. DESIGN CRITERIA

We considered many different aspects in order to evaluate the most suitable solution for the EH 101 main rotor head. Mass, cost, stiffness and fail-safe design were the major parameters considered.

An overriding consideration was that the rotor system had to meet the extreme design requirements due to wind speeds up to 60 knots from any horizontal direction, and the inertia loads arising as a consequence of ship deck motion in rough sea.

The flapping hinge offset of 5% rotor radius was meant to provide sufficient control power taking into account the mission profile of this aircraft.

An elastomeric articulated rotor system solution has been chosen to minimize mass and cost.

A composite solution appeared to offer improvements in the following characteristics in comparison to conventional metallic rotor head: cost, weight, damage tolerance and maintenability.

The trend in rotor metallic materials has been toward titanium alloys, which provide high strenght - to - weight ratio and good corrosion resistance.

Although lighter than steel alloys, titanium alloys are more costly.

Conventional metal hubs are machined from large forgings, and they are obtained by high machining waste.
Composite materials offered the opportunity to avoid such losses.

The major problems to overcome in a composite solution were the connections between the splined drive shaft and the hub body and between hub and blades with a tension-link incorporating a blade folding mechanism.

These aspects called for hybrid structures having metal parts in the above mentioned critical areas (fig.1).
For this reasons the EH 101 composite hub has a metal core that provides torque transfer by splines.

The elastomeric bearings hinges of the main rotor head are of two types : spherical elastomeric bearing and a centering elastomeric bearing (fig.2).

In flight the centering bearing transfers the vertical shear component of blade loading which is reacted directly to the hub centre through the support cone.
The axial blade loads due to centrifugal force are reacted by a compressive load in the spherical elastomeric bearing which is in turn reacted as tension in the composite hub structure.

The main rotor hub of the EH 101 helicopter comprises of a metal hybrid structure and composite material.
The metal portion mainly consists in :

- A steel center core which incorporates composite loop-windings and the splined attachment.

- An upper and lower/alluminium-alloy flanges aiming to hold the composite windings.

- Five metallic diaphragms (steel).

- Five metallic damper attachments (alluminium-alloy).

The composite portion is divided in some sub-components:

- The unidirectional graphite-epoxy loop-windings.

  Five upper internal.

  Five lower internal.

  One upper external.

  One lower external.

- The cross-ply epoxy external casings.

- The cross-ply epoxy internal casings.

- Filler.

The main rotor hub was designed to support the centrifugal load coming from the elastomeric bearing.

The hub basic feature is the separation of load paths. In flight, the majority of the shear loads pass directly into the core from the centering bearing and only a portion enters into the composite structure depending on the ratio of stiffness of the spherical elastomeric bearing against the support cone condensed stiffness.

As far as centrifugal loads they are transferred through the spherical elastomeric bearing to the outboard part of hub.

For the same reasons mentioned above, fatigue loads (except that occuring in starting and stopping condition) concern only the metallic part from the centering bearing to the core whilst composite hub is substantially a static (stiffness) design.

## 2. TESTING PHILOSOPHY

The EH 101 main rotor head comprises of hub and tension links which are hybrid metallic and composite material structures; for this reason, in the EH 101 program, tests of structural elements especially dedicated to the substantiation of some fondamental aspects had been done.

The principal aims of these activities were the following :

- Feasibility of a modular structure made by precured composite and metallic composite and metallic parts.

- Materials choice and manufacturing investigation problems including the possible alternatives to optimize the production process.

- Testing manufacturing technique and theoretical estimates validating of strenght and stiffness properties.

- Investigation of the quality controls in order to choose the best way to control the single part and the final assembly.

Tensile and flexural tests on composite loop-windings have been carried out in order to investigate manufacturing and strength properties of composite loop structures with and without a frame inside.

The first one simulated approximately the application of the centrifugal force and the other simulated the vertical force, typical of ground load case.

Tensile tests have been carried out on a composite four arms hub scaled down from the hub of the EH101 helicopter, to use an existing rig with minor modifications and having the objectives:

- To provide the general load path distribution with flight loads and ground loads applied.

- To correlate the predicted estimates of the stiffness and strains.

- To provide qualitative informations on failure modes in relation to the loading conditions.

The specimens comprised of three hubs, the first one made of glass-epoxy material, the second one made of graphite-epoxy with the same construction procedures as the previous one and the third made of graphite-epoxy too but with a different construction process.

This evolution was suggested because during the manufacturing of the specimens, the ground cases of the EH101 helicopter were evaluated and an additional stiffness for the hub was required.

Tensile and bending tests were done on reduced scale tension link ( inboard part only ). The task was to investigate manufacturing ( particularly cocuring of composite plates with metallic frame ) and to correlate the analytical models with the experimental results.

The above mentioned lead-in test activity allowed the viability of the design for all the involved aspects:

- Production

- Choice of the materials

- Quality control by N. D. I. technique

- Substantiation of analytical tools

## 3. ANALYTICAL APPROACH

This section aims to present an approach to structural analysis of complex structures, with special regards to helicopter rotors, and the correlation with experimental data. Analysis were performed with classical linear finite element method using mainly MSC/Nastran program.

Besides some properties of anisotropic elements were provided separately by two programs developed by Politecnico di Milano University in accordance with Agusta, named Hanba and Anba 2.

Hanba means Hollow Anisotropic Beam Analysis and is a f.e.m. program developed expecially to study the problems of blade sections (see reference 1).

Anba 2 , which means Anisotropic Beam Analysis, is an improvement of Hanba for every kind of anisotropic sections (see reference 2).

All the interface programs and automatic procedures (hanna, stress, inthana, ms, outin) were developed by Agusta.

The 3-D models were created using cadam mesh function starting from cadam drawings while for the output of the analytical models the caeds system was used.

### 3.1 NORMAL PROCEDURE OF ANALYSIS

In order to explain this approach we need to give a brief description of normal method for the analysis of complex tridimensional structures in composite materials (the flow chart is shown in fig. 3.

In design preliminary stage it has been necessary to use a very quick and flexible method, since the drawings are not frozen and several different solutions must be evaluated, so a simple model, typically a monodimensional one is created.

In a later stage we need a tridimensional model to take into account the effect of thickness and to perform a more accurate investigation of the strenght capability of the structure.

The first model is constituted by MSC/Nastran cbeam elements but since sections are made of different materials and sub-structures (fig. 1 ), the properties of these elements must be supplied externally. They are calculated by Hanba or Anba 2 programs which are finite elements methods studied to obtain mass and stiffness characteristics of an anisotropic beam.

These programs analyze and store into permanent files the strains, the fluxes and the stresses of the finite elements caused by unitarial loads.

Using the properties stored in files through an interface program (Hanna) we generate automatically the MSC/Nastran beam bulk data from which we obtain information about :

- displacements

- internal forces

Afterwards we evaluate the strength of the sections using stresses and materials allowable values with external post processors (stress and ms) which calculated the margin of safety according to Tsai-Wu theory (see reference 3 and 4).

In the second stage a complete 3-D model of the structure is built using pre-processor mesh generators (normally cadam system but also catia or caeds are available). A 3-D model is necessary because of the geometry of rotor component and of the kind of loads and constraints.

This model must take into account several aspects correlated to rotors and complex modelling which make difficult to obtain results in a reasonable time :

- composite materials
- different loading conditions
- different conditions of constraints
- components divided into vital substructures
- need for special features (cyclic symmetry or superelement)
- huge input data
- cost of computation
- difficult output check
- huge output data to analyze

## 3.2 COMPLETE MODELS OF COMPLEX STRUCTURES

The problems of rotor models in our normal procedure may be divided into three main aspects :

A) - Mesh generation

B) - Execution time

C) - Output analysis

The main problem is the execution time of this kind of model because first of all it was needed the use of MSC/Nastran special techniques (cyclic symmetry, and superelement).
In order to obtain the solution in a reasonable time supercomputer has been used.

Besides we have several loading conditions to examine and at least two different constraining situations (flight and ground).

Other sources of problems are input data preparation and output interpretation of the models with high number of elements applicated to a composite structures.

Take for example the amount of data required to calculate the reserve factors with composite materials failure criteria and how long it takes the analysis of the results.

Because of these problems it was found it is not possible to follow , with a complete model, the advancement of drawings expecially in prototypical production when may be necessary to change some parts or to analyze defects of differences between drawings and components to give a fast answer to manufacturing problems and even flight authorization.

### 3.3 PARTIAL MODEL APPROACH

Even if the complete 3-D model is the best method to perform a detailed analysis we started to look for another approach to solve the problems.

We didn't try to create a procedure completely different from the first one but to utilize what we had in a new way.

At first we analyzed only the most critical part of our structure with a tridimensional model a using the monodimensional model for the complete analysis.

To perform a partial 3-D analysis we needed a program to apply, to our models, the set of forces which are congruent with the total deformation of the structure (ref. 7).

So the data recovered by the monodimensional model were used and the model was cut in a section where De Saint Venant hypothesis are likely to work in satisfactory manner.

The finite element model of this section was created before in the first part of our normal procedure, while the loads to apply were recovered by MSC/Nastran linear statical analysis of the monodimensional model.

The first step was to create an interface program named inthana (*) which could generate, from hanba model and nastran beam forces, a load set for the 3-D partial model (fig. 3).
The checking of the program is quite simple because the load set cards must give, as resultant, the same value of the forces previously applied to the section .

According to the best fit technique these resultant has some differences which depended on the accurancy of the models but normally these values were under 10% for torsional and shear loads and less than 5% for assial loads and bending moments and may be improved with refinements of the meshes.

remark : (*) for more details about inthana see ref. 8

## 3.4 CORRELATION WITH EXPERIMENTAL DATA

The comparison between the analytical results and the experimental data was performed in terms of stresses or strains and displacements.

The displacements were used to check the monodimensional model so they are not presented herein (see reference 5) while strains and stresses were used to correlate the 3-D partial model.

The strains and stresses data were recovered by the application of photoelastic coatings.

The main problems of this application concern the structural reinforcement, strain variation through the coating thickness and mismatch of Poisson's ratio (see ref.6).
So notwithstanding the cited limitations biriefringent coatings provided a valuable method of analysing many problems, expecially geometrical discontinuities, involving composite materials.

The comparison between the models and the tests was reported in terms of the number of fringes for two components of EH 101 : Main Rotor Hub for Test Proposal and EH 101 Inboard Tension Link (fig. 4).
The test proposal component is a scaled structure of the real one built to provide feasibility and strength features according to analytical model.

Besides this quantitative analysis even a more qualitative was performed with caeds visualization which might very well be compared with the imagines of photoelastic coatings.

## 4. CRITERIA OF CHOICE OF MATERIALS

The use of composite materials in EH 101 main rotor head was one of the first choice in the preliminary study of the helicopter not only for the significant weight savings but also for the real structural advantages available tailoring this materials to suit environmental conditions and to withstand, with adeguate reinforcement, to the high static and fatigue applied loads.

The possibility to use composite materials and the choice of the more suitable materials for EH 101 main rotor head needed several tests to prove the real capability of these vital composite structures to match the requirements of the project so, in addition to the tests on scaled or real components reported in section two, several other tests were carried out by Agusta laboratories.

In fact for every material used, chemical and mechanical (static and fatigue) charachteristics were determinated by tests on coupons in different environmental conditions (room temperature dry, elevated temperature dry,elevated temperature wet). Besides tests on elementary structures were carried out to investigated several aspects.

Tests were performed on loop windings to solve the manufacturing problems of the different types of materials and to evaluate the capability of the non-destructive tests to determine the detectability of the defects.

Two different structures of composite lugs (a laminated and a winded one see fig. 5 ) were built in order to analize the strenght of bolted joints, to find a rule for the notched sensitivity and to use these kind of structures in the construction of the tension link (see ref. 3,4).

Of course, during the development of these tests several changes in the choice of materials took place according to a deeper knowledge of the problems concerning manufacturing, optimization of material and quality assurance performed by non destructive tests. An explanation of these development is briefly summarized in this section.

The composite structures in EH 101 main rotor head are :

- The hub

- The inboard tension link

- The outboard tension link

The used composite materials are termosetting epoxy resins reinforced with :

- "S2" fiber glass

- Hight modulus carbon fiber

- Intermediate modulus carbon fiber

The hub, previously described in section 1, is a structure resulting from several developments in material manufacturing and N.D.T. technology. As an assembly, the hub is made of different component which are bonded and assembled together with a curing cycle in order to optimize the quality.

The main subcomponent of the assy are the loop windings which are closed structures and are generally flat while in some section they have complex forms with double contour on the shapes.

To build these components different materials (S2 glass, high and intermediate modulus graphite) and different way of lay-out (roving or tapes) were evaluated.

In the first stage the hub was enterely made of S2 glass (the strenght requirement didn't allow the use of E-glass) but in the development the increase of stiffness requirements in ground condition, especially during the folding of the blades, the improvement in manufacturing technology for carbon fiber reinforced materials and the advance in controlling with N.D.T. these components, permitted to build the loop windings in C.R.F.P. with U/D tape and to test them (see ref. 9).

The choice of the kind of C.R.F.P. was determined by the strength to stiffness ratio so that we preferred intermediate modulus graphite epoxy material at a volume fraction of 50% to an high modulus graphite considering also the better iterlaminar properties of the intermediate modulus.

Nowadays the loop windings are cured separately and checked with N.D.T. then they were bonded with the boxes and the central core in three steps and it was possible at each step to control with ultrasonic technics the quality of the bonding and with x-rays the possible delamination created by the cycle.

The other two composite structures in the main rotor head are the plates of inboard and outboard tension link.

As previously reported is section 1 and 2 lead-in tests on a scaled inboard tension link structure were performed by Agusta laboratories. The main aspect involved in these tests was the different types of construction of the composite plates.

Four different kind of plates were built and bonded with the metallic frame (fig.5):

- A laminate glass structure

- A laminate glass structure reinforced with 4 carbon high modulus loop windings around the holes

- A laminate glass structure reinforced with metallic lamines in the areas of the holes

- A laminate hybrid structure with glass and high modulus graphite

All these structures were winded with a glass box to avoid interlaminar delamination at the free edges.

During the tests all the solutions provided sufficient strenght to withstand the loads but other aspects might be consider to find the best solution.

In fact the second and third type of construction rised complex manufacturing problems because of the difficulty in the realization of carbon loop windings with complex inclination and curvature and of the possibility of delamination in the area where the metallic lamina ended.

The first solution was the best for manufacturing and for non-destructive inspection beacause of the omogenity of the materials but didn't provide necessary stiffness without thickness increases.

In the fourth type the carbon fiber reinforcement provided the stiffness and an optimization of the stacking sequence of the laminate was performed to obtain the best results according to both the manufacturing (mismacth between carbon and glass coefficient of the thermal expansion) and the project requirements.

Of course this solution involded some problems: non-destructive inspection (tuning parameters needed more accurancy) and a different manufacturing procedure for the laminate with the introduction of some pre-cured plies.

At the present situation the EH 101 inboard tension link composite plates were built with an hybrid laminate solution while in the outboard tension link we adopted a glass laminate solution because in the component the plates are completely supported by the metallic frame which provide the necessary stiffness in flexural bending.

## 5. CONCLUSION

The design criteria and the shown analytical approach involved manufacturing and structural tests. Testing philosophy was ideated to lead the test performance and allowed the program improvement.

The flexibility of the analytical approach permitted to reach satisfactory results in a relatively short time. The more satisfactory aspect of this method is the chance of paying attention to local problems and very detailed analysis which provide good results and meanwhile save time an money with reguard to the procedures used before.

The choice of materials with the charachteristics most compatible at the applications led to develop a simpler, lighter, longer lasting and lower cost rotor compared to a standard rotor system.

In conclusion EH 101 main rotor head is the result of an hard work to find an adequate solution, with composite materials, to all the problems involved in the realization of a modern rotor.

## 6. REFERENCES


1. V.GIAVOTTO : "Evaluation of section properties for hollow composite beams" Vth Eur. Rotorcraft and P.L.A. Forum .
2. V.GIAVOTTO : "Anisotropic beam theory and application" Comp. & Struc. Vol. 16 1983.
3. R.JONES : "Mechanics of composite materials".
4. S.W.TSAI : "Composite design - 1986".
5. F.BARANI - E.ANAMATEROS : "Analytical evaluation of a composite loop winding by the use of mono-tridimensional element models". XIIth European Users' Conference of MSC-NASTRAN.
6. R.E.ROWLANDS : "Application of photoelastic coatings to composites". Dev. Composite mat./2 Ed. Holister.
7. C.DESAI-J. ABEL :"Introduction to the finite element method".
8. E.COLOMBO - F.SCAPINELLO :"An approach for detailed analysis avoiding complete models". XIVth European Users' Conference of MSC/NASTRAN.
9. L.CARONI-M.FARIOLI-C.ROTONDI-E.ANAMATEROS :"Composite vital parts optimization for EH 101". XIIth European Rotorcraft Forum.


## 7. AKNOWLEDGEMENTS


The authors greatly appreciated the kind permission of Costruzioni Aeronautiche Giovanni Agusta to report on this subject.

A kind thanks also to Rotor Design and Development Department and to Structural Test Laboratory for their technical support.

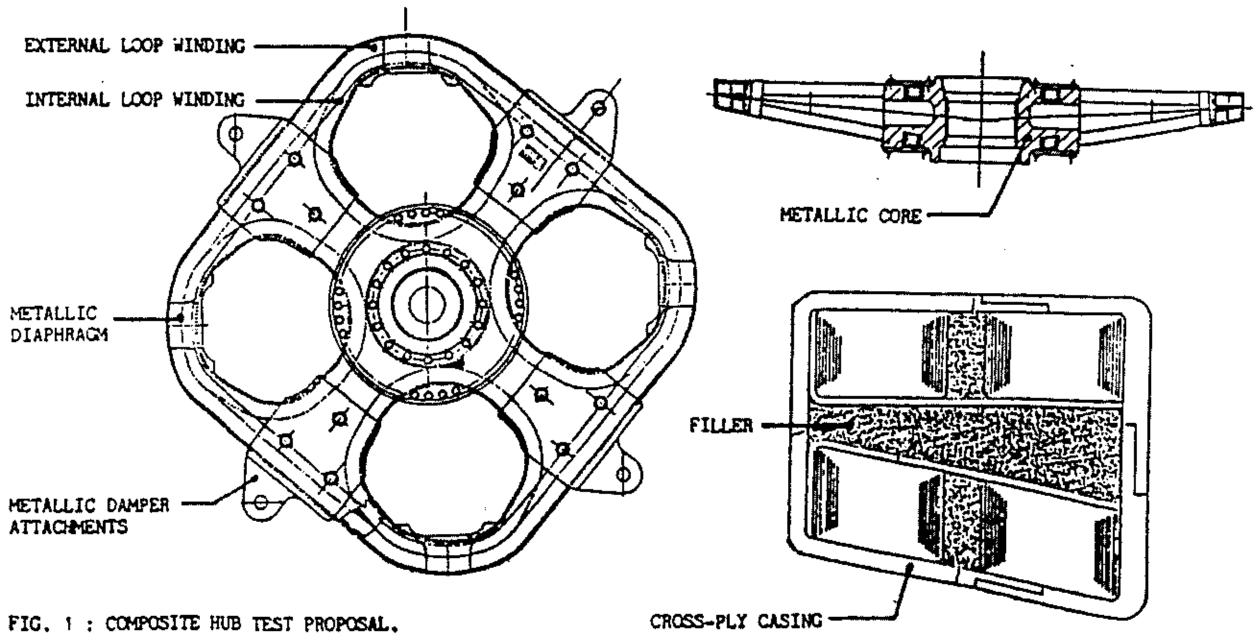




FIG. 1 : COMPOSITE HUB TEST PROPOSAL.

FIG. 2 EH 101 MAIN ROTOR HEAD

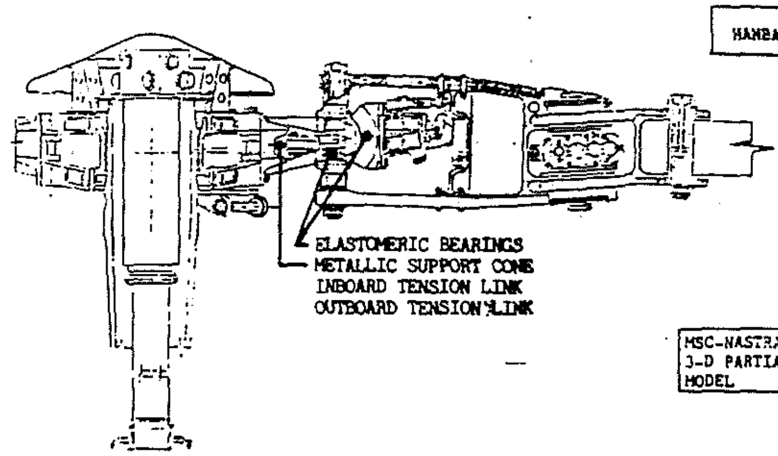
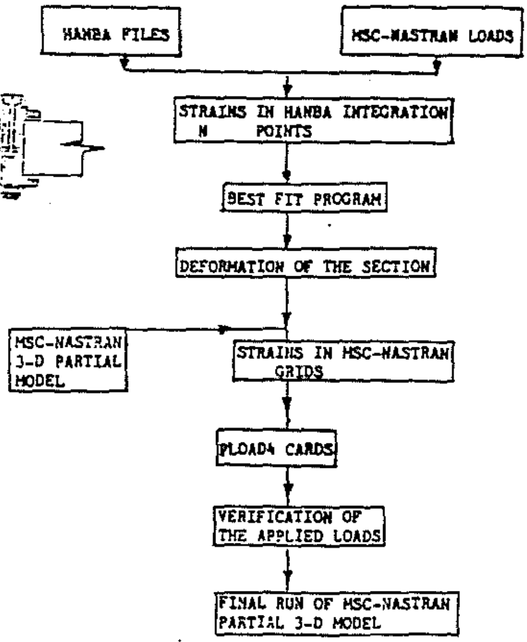



Fig. 3 FLOW CHART PROGRAM INTHAMA



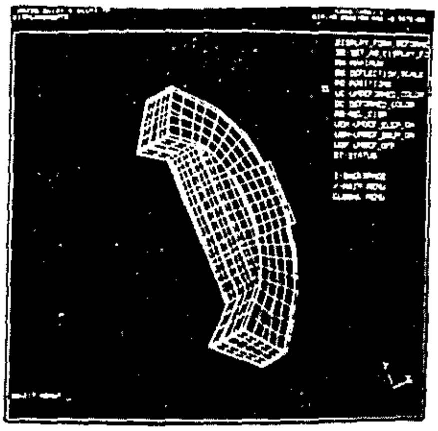
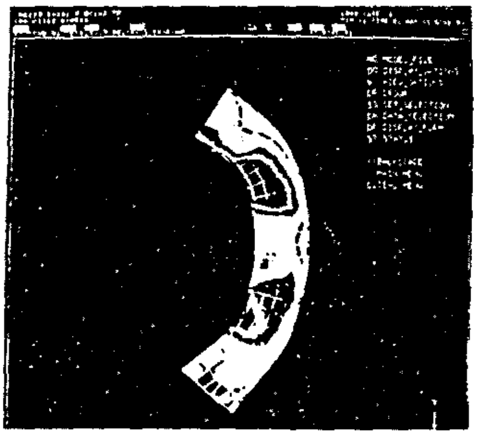



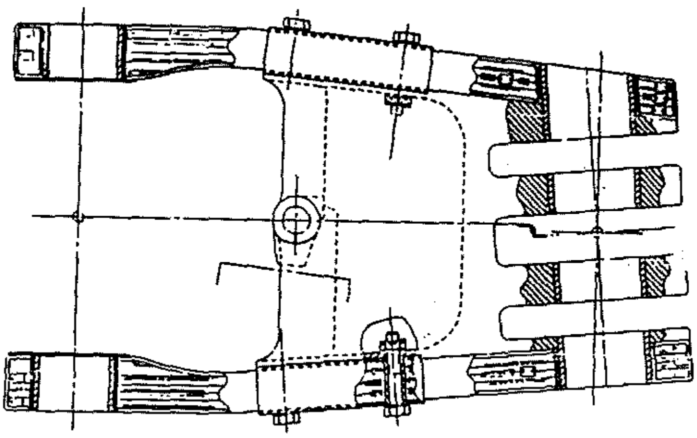
FIG. 4 Results of partial 3-D model of Main Rotor Hub T. P.



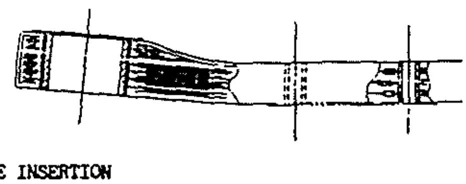
EH-101 MAIN ROTOR HUB T. P.

| N=NUMBER OF FRANGES | | ALFA=ANGLE OF PRINC. DIRECTION | |
|---|---|---|---|
| EXPER. | THEOR. | EXPER. | THEOR. |
| 4.09 (ARM3) | 4.67 | 54° | 63° |
| 4.23 (ARM1) | 4.67 | 64° | 63° |
| 3.00 (ARM3) | 3.40 | 50° | 55.65° |
| 3.14 (ARM1) | 3.40 | 53° | 55.65° |

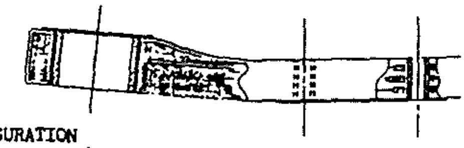
FIG. 5 INBOARD TENSION LINK TEST PROPOSAL



GRAPHITE EPOXY, LOOP WINDING CONFIGURATION



METALLIC LAMINAE INSERTION



LAMINATE CONFIGURATION