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Shells, Membranes and Space Frames

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RECENT DEVELOPMENTS OF DESIGN AND CONSTRUCTION OF MEMBRANE STRUCTURES IN ITALY

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INTRODUCTION

During the initial 60's several smaller pneumatic structures were constructed in Italy based up on empirical methods of design and fabrication. Since the late 60's and early 70's the applied research made in the universities originated a homogeneous scientific and related technology development.

Now, with the experience and feedback obtained from the observation of membrane structural time-behaviour on several different typologies, we may assume that the pioneer period of theoretical and technical development of membrane structures is coming to an end. Today we can elaborate a balanced-synthesis concerning the validity spectrum obtained from the membrane structural systems, as tensile plane and spatial cable structures, and pre-stressed or pneumatically loaded membranes, due to their technical-economical characteristics.

DESIGN METHODOLOGY

In the last ten years, a wide-spread diffusion in the application of membrane structures as a covering for sports and industrial complexes has been noted in Italy. This considerable commercial assertion has not always been accompanied by a homogeneous development in related technology which presents delicate, design and construction problems. In the field of design, for example, the geometric forms adopeted for the roof surface are frequently not the most suitable from a structural point of view.

The geometric forms used most by constructors of pneumatic structures were obtained mainly by empirical method, starting from cylinders, spheres and their possible combinations (1). In this way one arrives at surfaces which, under application of internal pressure, manifest concentrated stress and folded zones of the material which does not have the possibility to allow compression forces. In the latter zones, local curvatures of the geometric surface, empirically defined, preclude satisfaction of condition:

$$n_{min} = \frac{1}{2} (n_x + n_y \pm \sqrt{(n_x - n_y)^2 + 4t^2}) \geq 0 ,$$

which guarantees a distribution of positive forces over the whole of the pneumatic structure surface (2).

Empirical design process to obtain the geometry of the structure typical of the 60's was one of the manufacture of models. But it is obvious that, as the attempts of design must be numerous, the manufacture of models would bring with it remarkable and sometimes not acceptable times and costs. Further, this type of model can give a visual indication without giving any assurance of geometric suitability to assure its static operation both in the condition of pre-stress and in the various loading combinations. The only actual convenient method for the design, both architectonic and structural, of membrane structures, adopted today in Italy, is the interactive graphics or CAD method.

The research concerning an integrated computer aided analysis and design of membrane structures started, in the Department of Structural Engineering of the University of Bologna, in 1968. The first interactive computer aided shape-finding program ran in a IBM mainframe with a video Console 2250, and in a CDC-6600 with a Tektronik 4010 video display. Actually the interactive programmes, available in our centre, run in mini-computers as: VAX 11-780, HP-1000 and ATT-3B2. According to this philosophy the addressed interactive software for analysis and design of membrane structures developed until today, have the following names:

RETE (Net) : addressed to the shape-finding of cable and membrane structures (2);

PNEUS : addressed to the shape-finding of pneumatic structures (2);

TENSO : addressed to the statical non linear analysis of cable/membrane structures (2);

TENSO-TEL : version of TENSO, addressed to the analysis of cable membrane structures which interact with anchorage structural systems (2);

TENSO-DIN : addressed to dynamical non linear analysis of cable and membranes structures (2);

STRIP : interactive cutting pattern on geodetic surface lines (3).

Design software

RETE and PNEUS are two programmes written in interactive graphics language (IG). Data input takes place according to the natural operations mode of the designer by means of geometrical sketches which may be read by the digitizer. Data so introduced may be video controlled. Other data, such as the mechanical characteristics of the structure, may be introduced through the alphanumeric keyboard. Once the calculation has been carried out, immediate visual information on the state of deformation and stress may be obtained graphically on the video or on the plotter.

The interactive graphic system may be used for designing, and verifying constructive details, allowing execution of changes and modifications visually controllable by making the figure under examination rotate and translate and, on obtaining the solution, allowing representation on paper on request.

To interact graphically one must communicate with the programme being executed with suitable hardware-software interface. The hardware interface is obtained with the new generations of extremely powerful mini-computers at ever-increasingly accessible cost permitting the constitution of a man-machine combination according to an interactive configuration as outlined in Fig. 1.

The software interface is obtained with an addressed pre-processor of input data and a post-processor of output results (Fig. 2).

Through this interactive configuration (software-hardware interface), communication between man and computer takes place in human language, intending by this the collection of numerical data, symbols and graphics commonly used by

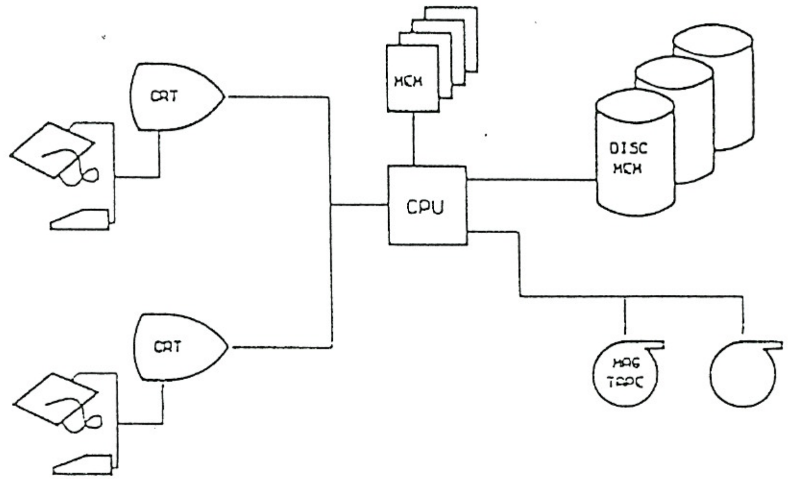

Fig. 1

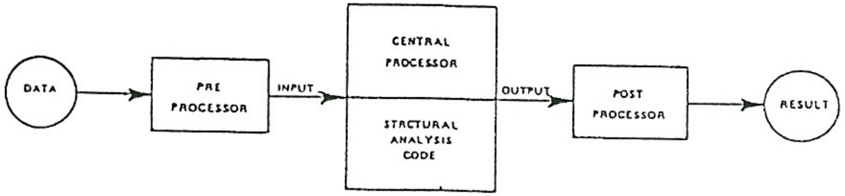

Fig. 2

man in relation to his particular professional technique.

The communication is made through a graphic (main-menu: Fig. 3) resident in a digitizer or in the screen, which executes the commands according to the theory proposed in (2).

The interactive graphic technique assumes particular importance in the design of membrane structures. The particular advantages, mainly in saving of time and design costs, may be listed illustrating the flowchart of the RETE and PNEUS programme in Fig. 4. The core of the interactive structure of the calculation programme lies in the control-block of the interactive commands.

Once the fixed data (e.g. co-ordinates of anchorage points) that may come from an automatic generation programme, from peripheral memories or simply from cards and the parametric data which need to activate a precise calculation sequence have been input, it is possible to obtain an initial result on the video (Block A). An immediate control is possible on the video by ample visual examination of the correctness of data. In this case it is sufficient to halt the calculation on the first runs and; if the result is negative, by means of Block C it is possible to modify erroneous data and re-start the calculation.

Once equilibrium has been achieved with the preliminary data, the pneumatic structure is examined on the video where prospects and axonometries may be visualized. Rotations, translations and changes of scale may be carried out by means of Block B, permitting an initial, precise design evaluation from the geometric point of view. With Block E, it is also possible to obtain on the video information on the precision reached and on the values of force/stresses in the cable/membrane.

After the examination of the first complete result (geometric-state of stress) it is possible to:

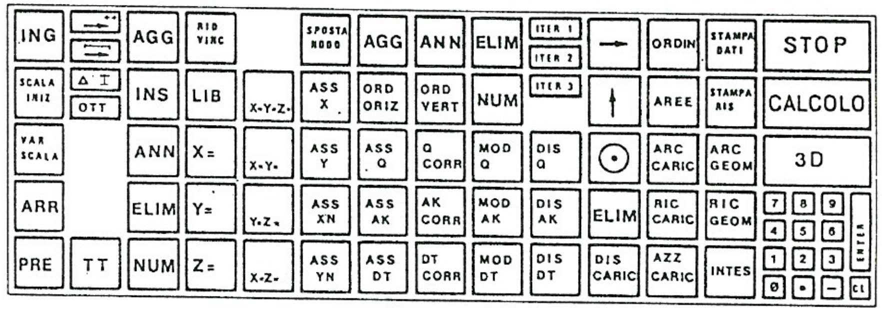

Fig. 3 Graphic menu-control of interactive commands.

ING	- Zoom	NUMN(A)	- Display bar number
OTT	- Optimal scale factor	MOD Q	- Modify Q
SCAL INIZ-	Standard scale factor	MOD AK	- Modify AK
VAR SCALA-	Variable scale factor	MOD DT	- Modify DT
ARR	- Rounding	ITER 1	- L-cost shape-finding
PRE	- Precision	ITER 2	- S-cost shape-finding
TT	- Keyboard input	ITER 3	- Mixed shape-finding
AGG(N)	- Add joint	DIS Q	- Display Q
INS(N)	- Insert joint	DIS AK	- Display AK
ANN(N)	- Cancel joint	DIS DT	- Display DT
ELIM(N)	- Elimin. joint	-->	- Loading in X-direction
NUMN(N)	- Display joint number	^	- Loading in Y-direction
RID VINC	- Define boundary condition	*	- Loading in Z-direction
X;Y;Z	- X;Y;Z boundary condition	ELIM(P)	- Cancel load
XY;YZ;XZ	- XY;YZ;XZ boundary condition	DIS CARIC-	Display loading
X Y Z	- X Y Z boundary condition	ORDIN	- Automatic surface triangularisation
SPOS NODO-	Displace joint	AREE	- Compute surface area
ASSX	- Assign X coordinate	ARC CARIC-	Gen. load file
ASSY	- Assign Y coordinate	RIC CARIC-	Call load file
AGG(A)	- Add bar element	AZZ CARIC-	Cancel load file
ORD ORIZ	- Auto generation X-direction	STAM DATI-	Print data
ASS Q	- Assign Q	STAM RIS	- Print output
ASS AK	- Assign cross section	ARC GEOM	- Gen. file of structural geometry
ASS DT	- Assign DT variation	RIC GEOM	- Call geometry file
ANN(A)	- Cancel bar element	CALCOLO	- Run
ORD VERT	- Auto generation Y-direction	3D	- Graphic menu
QCORR	- Default value of Q	?	- Help
AK CORR	- Default value of AK		
DT CORR	- Default value of DT		
ELIM(A)	- Elimin. bar element		

TABLE 1. Interactive commands

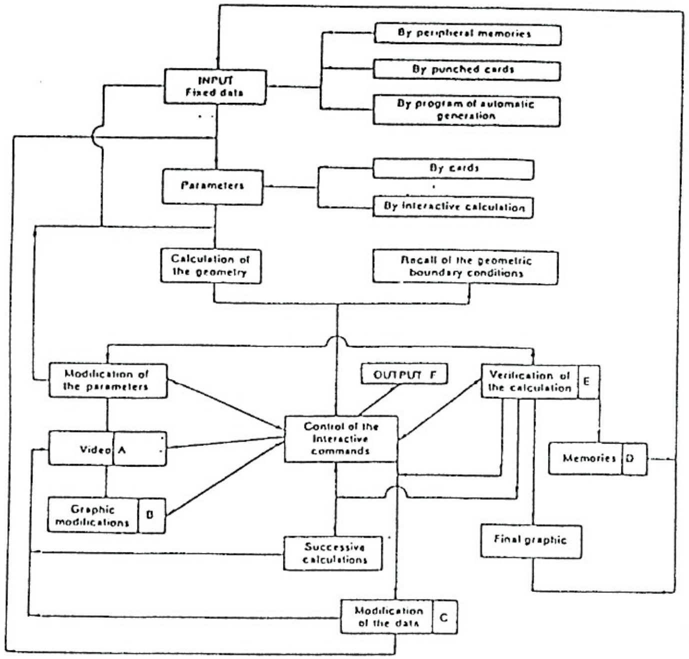

Fig. 4 Interactive flow-chart for shape-finding membranes structures.

- change data such as internal pressure, co-ordinates of points of restraint, initial forces, etc.;
- conserve results obtained on a peripheral, for eventual successive use as a basis for automatic optimisation process (Block D);
- obtain results on the plotter in hard copy and on the printer (Block F).

In the case of an optimisation sequence (iter 1; 2; 3) being required, modifications of the parameters must be carried out followed by an order to proceed with the calculation.

As is clearly evidente from the above, there is considerable economy of the interactive organisation of the design through the help of fast machines which constitute an operative mental extension of the designer, enormously increasing his capacity and the quality of the design.

The typical phase of design and subsequent verification are greatly accelerated even in comparison with the normal use of the computer as an input-output in-

strument. In Fig. 5 is illustrated an interactive design sequence of a prestressed membrane.

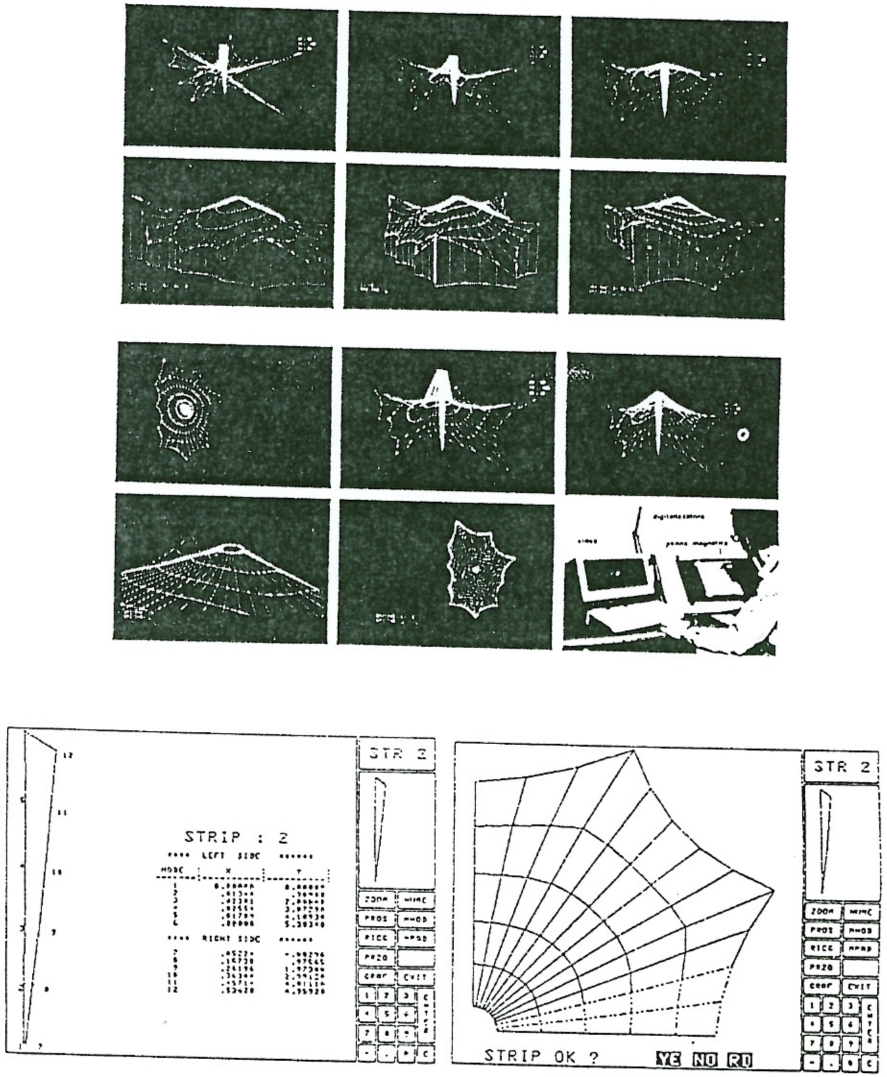

Fig. 5 Interactive design sequence of membrane shape-finding on HP-1000 minicomputer: the interactive hardware; iterative equilibrium steps; plant view; modification of mast hight; perspective views with hidden lines; zoom; level curves; cutting pattern video controlled.

The TENSO, TENSO-TEL and TENSO-DIN are addressed in order to analyze statistically and dynamically membrane structures according to the theory illustrated in (2). A general flow-chart of TENSO-TEL is illustrated in Fig. 6. This program was checked with the global structural analysis of the roof structures of the Sport Hall of Athens (2).

The main features of this program is the possibility to be integrated with other conventional programmes of finite elements analysis (FEA) or space frame analysis (SFA) in order to analyse the rope net-anchorage structural system.

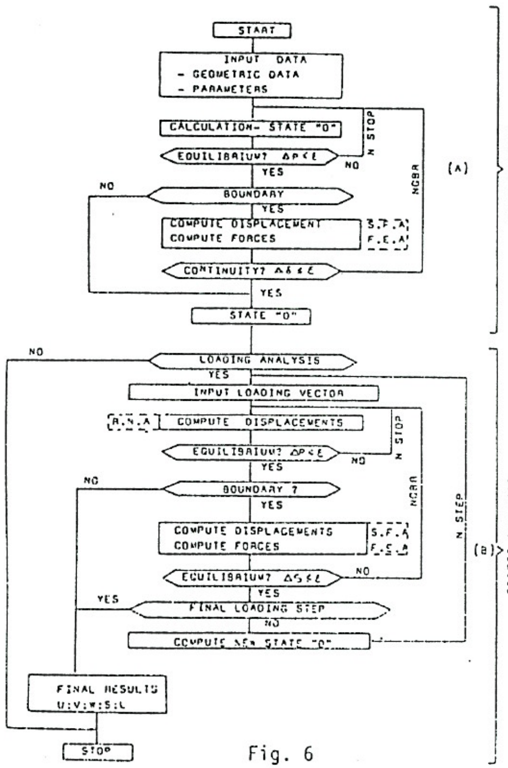

Fig. 6

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DEVELOPMENT OF COMPUTER-AIDED DESIGN OF CABLE-REINFORCED MEMBRANE STRUCTURES IN THE U.S.A.

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INTRODUCTION

Air-supported and prestressed membrane structures continue to evolve and to find a steady market in the U.S.A. Their frequently cited advantages include light weight, applicability to spans of a variety of shapes and sizes, and suitability to prefabrication. Architecturally, they are not only flexible, but also provide opportunities to create aesthetically appealing structures.

Concommitant with these advantages, the special challenges presented to designers working with membrane structures are also well known. First among these is the difficulty of devising, representing, and communicating their typically complex, doubly curved shapes. Because the structures are form active, the designer must identify and work with feasible membrane equilibrium shapes. Moreover, the large-deflection behavior requires the use of geometrically nonlinear analysis. Finally, the stress-strain behavior of the coated woven fabrics is anisotropic and complex.

From the early 1970s, it was recognized that the finite element method was an appropriate tool for design analysis of membrane structures, and geometrically nonlinear analysis programs, first devised to find the "ideal" shapes for shells, were adapted to treat both the shape finding and load analysis of fabric structures. This was the first step toward comprehensive use of digital computers for the design of membranes because finite element analysis cannot be accomplished without computing. However, the adoption of finite elements presented a new set of problems for the membrane-structure designer. Foremost is the very large input datasets needed to describe the geometry, properties, and attributes of the structure; the preparation of these datasets is tedious, time-consuming, error-prone, and generally detracts from the creative aspects of design. In addition, when a finite element analysis is completed, one is faced with the task of interpreting the lengthy lists of displacements and stresses which are produced. The designer not only needs to develop a sense of the overall and local behavior of the structure but also must determine whether serviceability requirements are met.