The Unique Role of Computing in the Design and Construction of Tensile Membrane Structures:

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Abstract

This paper provides background and overview of the methods and utilization of computing in the design and construction of tensile membrane structures. In addition the author outlines the general methodology employed in the use of automated processes in the design, fabrication and construction of these structures.

Introduction

No other class of architectural structural systems is as dependent upon the use of digital computers as are tensile membrane structures. The shape or form and prestress of tensile structures are determined using true "computer aided design". Typical simple structural systems defy classical analysis. Structural behavior is simulated under load using computer modeling techniques. The procedures for prestressing the system are determined in similar analysis. Finally, the drawings or templates used to cut and fabricate the fabric membrane surface are typically computer generated.

The modern use of tensile membrane structures as a means of permanently covering large spaces has been wholly dependent upon the use of digital computing. Many of the developments in membrane structure technology have occurred in the last twenty years precisely because of the accessibility of relatively powerful digital computers. Significant pioneering work of Frei Otto was accomplished using physical models (1), which while they well illustrate the desired form of a membrane are not conducive to the precise communication and/or documentation of the membrane's structural characteristics in a manner necessary for the construction of large and/or complex systems.

Tensile membrane structures have unique difficulties that have made them resistant to classical methods of design and analysis. Generally, they are nonlinear in behavior. Typically structures exhibit both geometric non-linearity due to large deflections in addition to material non-linearity. The nature of tensile membrane structures is such that much of their stiffness is achieved by virtue of initial prestress in the membrane and its supporting components. This prestress is an internal stress condition usually prescribed by the designer to achieve the desired performance of the structure and must be induced into the system in its construction.

The general methodology pursued in the design and construction of a tensile membrane structure is illustrated in the flow chart shown in Figure 1. Processes which are typically automated are highlighted. As with most design methodologies the process is iterative, such that anticipation of the results in the conception of a structure will reduce the general effort involved in the design and engineering of the system. While there are a number of algorithms presently used with success for each of the computer processes, the general methodology illustrated is appropriate for a wide variety of prestressed tensile systems.

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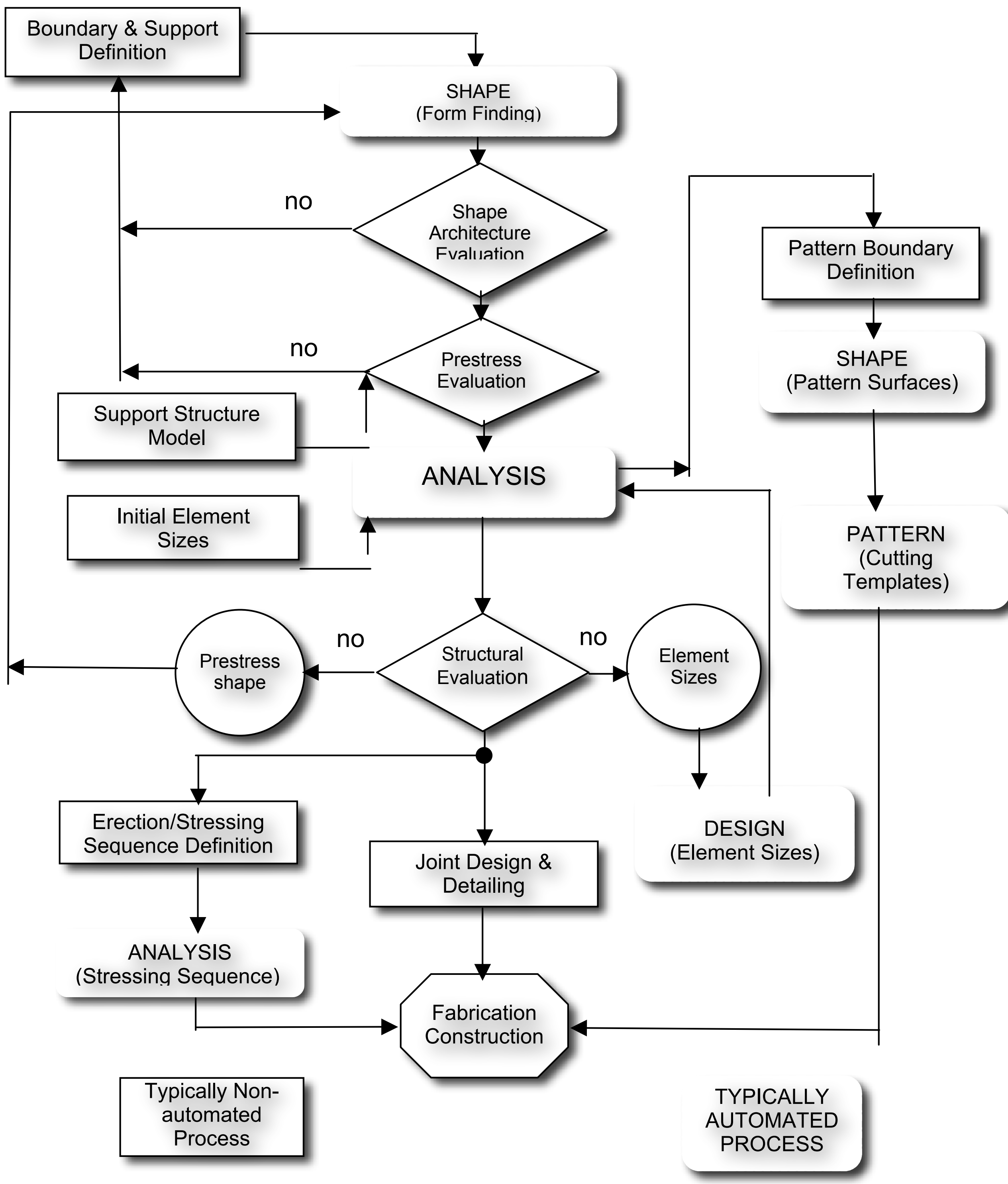

Figure 1. Flowchart Illustrating General Approach to Tensile Membrane Structure Design and Engineering

Form Finding

In the simple case of air- supported structures the membrane prestress is achieved by loading a synclastic shaped membrane with a differential air pressure. The simplest form of air-supported structure for which the prestress can be easily determined is a spherical dome. Assuming that the unit weight of the membrane is small with respect to the internal operating pressure, the membrane stress at a given pressure is proportional to the radius of curvature of the sphere. While analysis of such a structure under real wind loads is non-trivial, both membrane patterning and determination of prestress are easily accomplished without the aid of computing. Consequently, it is not surprising that the first widely used air-supported membrane structures were the spherical air-domes designed and built by Birdair Inc.

The consideration of low profile non-spherical air-supported membrane structures required better analytical tools. Both the geometry or "shape" of the cablenet and the analysis of the air- supported roof of US Pavilion at Expo '70 were accomplished on a digital computer by David Geiger Associates with assistance from Dr. Michael McCormick. This is believed to be the first use of the digital computer in form finding and analysis of a built membrane structure. In this case as with all of the early air-supported structures engineered by Geiger, the fabric surfaces were patterned by "hand" as the surface geometry of the membrane was simple enough that this could be accomplished satisfactorily. The first computer patterned fabric membrane for a low profile cable-restrained air-structure was used in the Minneapolis Metrodome roof, patterned by Birdair.

Prestressed anticlastic tensile structures present a more difficult problem. A wide variety of complex forms can be determined from physical models. As demonstrated by Frei Otto, minimal surfaces can be created using soap films. However, none of these techniques can precisely communicate to the fabricator the prestress and surface geometry information required to fabricate and stress the membrane shape. This became a pressing issue as desirable materials suitable for permanent structures, such as TEFLON™ coated fiberglass fabric became available. Fabrics such TEFLON™coated fiberglass have desirable attributes such as their non-combustibility, however, they are significantly stiffer than other materials commonly used in tensile membrane structures and consequently require greater precision in patterning. The development of algorithms for defining the surface form or shape of a general class of prestressed networks was the key to the general exploitation of tensile membranes in structures of significant scale.

There are a number of form finding algorithms currently in use. Geiger Engineers employ software based upon the force density method (2). This matrix method solves directly for the geometry of a general network of prestressed tensile components. Iterative techniques allow the designer to prescribe desired prestress conditions for cable and membrane elements. Birdair Inc. successfully employs their matrix analysis algorithm for form finding. Basically elements are given very low mechanical stiffness and a prescribed prestress. Equilibrium geometry is determined in an iterative analysis of the structure. Another method of form finding in common use is the method of dynamic relaxation with kinetic damping (3). This method is employed in the form finding software used by FTL Associates.

The ability to generate shapes on a digital computer within a prescribed boundary with a prescribed prestress quickly lead to computer patterning of shapes. The problem is to determine the pattern for flat strips of fabric which when seamed together will approximate the shape's surface. As the shape geometry is determined for a prestressed condition, patterns must be compensated for strain in the fabric. Compensated strip patterns are used for cutting.

While physical models are still utilized to study membrane forms, the geometry and stress conditions of the membrane surface are now almost exclusively determined by designers utilizing computing techniques. Data from form finding, typically comprised of connectivity, nodal geometry and element prestress represents a complete model description of the membrane structure, sans the element properties. Consequently, shape results can be utilized directly for analysis. Often, additional elements, such as struts and or beams, are added to a shape model to create an analysis model of a complete structural system.

Structural Analysis

General analysis of membrane structures requires geometric non-linear techniques. Typical matrix methods employ an iterative procedure using the **Newton-Raphson method** or a variant, often with a damped solution strategy. Many tensile structural systems are strain hardening. A variety of common tensile structural systems are initially strain softening and begin to exhibit strain hardening behavior once sufficient load is applied. Consequently, non-linear solution strategies that anticipate strain hardening have been employed with success and can speed convergence in a wide variety of commonly encountered problems. There are significant exceptions, such as a class of "tensegrity" type structures that become strain softening as load is increased (4). The dynamic relaxation method is also used with success for the general analysis of geometrically non-linear problems.

Most architectural/structural fabric materials exhibit non-linear behavior, as a consequence of being woven composites. Almost all architectural/structural fabrics in use today are coated composites. However, material non-linearity is rarely modeled. Mechanical behavior of textiles is primarily dependent upon the properties of both the yarn and weave. Coating properties also have an effect upon the composite's mechanical behavior, albeit to a lesser extent than the properties of the base cloth. Fabric is commonly modeled utilizing LST or CST membrane finite elements or a network of string elements. Both of these modeling approaches have been widely used with success while each has attendant limitations that the analyst must consider. Development of membrane elements that better simulate the non-linear behavior of woven composites have been developed (5). While fabric material non-linearity is typically not modeled, it will likely prove to be useful when the mechanics of fabric failures are better understood and utilized quantitatively in a limit states design approach.

Construction and Stressing Analysis

The ability to create, analyze, design and fabricate complex membrane forms has in turn created difficult construction problems. Prestress is a much a property of these structures as say element properties and/or geometry. A prestressed state for a structural system can be created without direct regard for the manner in which the prestress is developed in the structure. In a wide variety of structures, this is in fact preferred. Consequently, with redundant structures techniques to establish the sequence of stressing is necessary to assure that the structure will in fact realize the prestressed state desired. Moreover, in many complex tensile systems analysis of the stressing sequence is necessary to assure that various components of the system are not over stressed during stressing. A technique developed by Geiger Associates of analytical disassembly of a prestressed structural system in reverse order of stressing has been utilized by the author, as well as others at Geiger Engineers and Birdair Inc. with great success. The erection and stressing of some structural systems such as Geiger's Cabledome, its variants, and other complex prestressed structural systems can be determined in this manner. Generally, the accurate construction of these structural systems would not be possible prior to the development of appropriate software and suitable techniques for determination of stressing sequences. This was the key in the realization of many significant membrane structures including, the Haj Terminal at Jeddah, Lindsay Park Athletic Centre, Calgary Alberta, the Ontario Pavilion Roof at Expo'86, Vancouver, B.C. and all the Cabledomes including the Florida Suncoast Dome Roof and the Georgia Dome roof system.

Hardware

The hardware demands of tensile structure design and analysis are somewhat greater than that needed for more conventional structures as a consequence of the relatively large models involved and their non-linear nature. Until very recently, typical analysis models were too large for desk top hardware. Even with the current generation of powerful desk-top processors, modeling of large and/or complex structures requires larger capacity machines. Clearly, if current trends in hardware continue this will change.

All three firms represented by speakers in this session utilize mini computers for their work in membrane structures. The various mini systems have proven to be quite serviceable for a wide variety of structural models. As with structural analysis in general, this has been a relatively recent development. Earlier complex models necessitated the use of very large mainframes. For example, the first commercial time-share use of the Cray I "supercomputer", was Geiger Berger's erection and stressing procedure analysis for the world's largest fabric roof, the Haj Terminal at Jeddah, Saudi Arabia in 1978. Both design and stressing sequence analysis of the Lindsay Park roof structure were conducted in 1982 on a Cray II. Similarly, form finding requires graphic display hardware and plotters that were unique in the 70's, but are common place and relatively inexpensive now with the widespread use of CAD for general architecture and engineering.

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