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CONCEPTUAL DESIGN AND ANALYSIS OF MEMBRANE STRUCTURES

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ERICA HENRYSSON*, JENS OLSSON†, AL FISHERΔ AND MATS ANDER¤

* Department of Architecture, ¤Department of Applied Mechanics,
Chalmers Univeristy of Technology
SE-412 96 Gothenburg, Sweden

ΔBuro Happold, Bath, England

*Email: henrysson@gmail.com, ¤Email: mats.ander@chalmers.com

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Summary. In this work one approach for formfinding and analysing tension membrane structures is described. Focus has been on the conceptual stage. For this the computer software SMART Form has been further developed, enabling the possibility to do real-time formfinding and analysis of fabric structures. The software is based on a method where the orthotropic membrane is modeled with a triangular mesh, where the mass is lumped on the nodes. As a computational tool dynamic relaxation is used to find the static equilibrium configuration for the structure. The advantage with this is that there is no need for formulation and manipulation of matrices common in the finite element method.

1 INTRODUCTION

With the ability to span large distances in a structurally efficient way, tension membrane structures offers a lot of interesting possibilities; from a sustainable, engineering and an architectural perspective. These elegant structures' complex designs require an understanding of shape and form, and the behaviour of the materials and the forces acting on it (and in it). The flexibility of the structure means that applied loads have a big impact on the shape.

The design process is made more complex by the fact that the shape of tensioned cable net and membrane structures cannot be described by simple mathematical methods. They have to be found through a form-finding process either using physical or computer models. However the increasing capabilities of computers make it possible to more efficiently perform calculations for these structures.

1.1 Background

On the market today there are several computer softwares that can form-find tension structures. A lot of the softwares are however relatively difficult to use and it takes a lot of time and effort to set up a model. As a result of this engineers are switching back and forth between a set of different design and analysis programs. When several concepts are to be evaluated this process becomes very time consuming. A conceptual tool would therefore be useful, in which it is possible to quick and easy create the geometry, set up different properties and analyse the shape and the effect of changing the shape and materials in different ways.

1.2 Dynamic Relaxation

Originating from an analogy for computations for tidal flow, drawn by Day, Dynamic Relaxation (DR) has been developed as an explicit solution method for the static analysis of structures[2]. Non-linear material effects were firstly introduced to the method by Holland[3]. Later Day and Bunce applied DR to the analysis of cable networks[4], and finally Brew and Brotton developed the method to the form most widely used today; a vector form which does not entail a formulation of an overall stiffness matrix[5]. DR is especially suitable for highly non-linear problems, such as the focus of this work; finding the form of membrane structures and the analysis of them.

The method is based on a model were the mass of, in this case, a continuum is concentrated to a set of points (nodes) on the surface or in the "joints" of a cable net. By specifying the relationship between the nodes (how they are connecting to each other) the system will oscillate around its equilibrium, under the influence of the out of balance forces. By damping the movement of the nodes the system will, with time, come to rest when static equilibrium is achieved.

The process is based on Newton's second law of motion: $Force = Mass * Acceleration$

$$a = \frac{F}{m} \tag{1}$$

$$v = v_0 + a * \Delta t \tag{2}$$

$$u = u_0 + v * \Delta t \tag{3}$$

v_0 and u_0 are velocity and position from the previous iteration and Δt the time step used.

2 MODELLING

In computation models of a fabric structure it is convinient to represent the fabric weave as an ortotropic 2D material/surface, as shown in Figure 1.

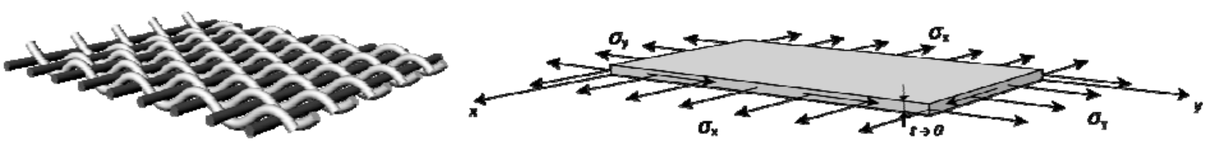

Figure 1. On the left: the weave of a textile, on the right: stresses in an idealised 2D membrane

In order to do calculations on a tensile fabric structure the membrane is, in this work, simplified even further in a computation model, by representing the membrane with a triangulated mesh. This allows the system to represent the different properties for warp and weft, as well as the shear properties for the textile.

2.1 Solution procedure

The model of the structure, in the software, consists of a system of nodes, connected to each other by a set of links. These links can be of different kind, depending on where they are located in the model. In between the links are membrane panels, this class of object inherits all the information contained in the parent class “face”, which has all necessary geometrical information. On top of this the membrane object has information about the stresses and properties, such as stiffness, of the membrane. It is also containing methods for calculations specific for membranes.

The algorithm is based on the principle of transferring all information to the nodes (see Figure 2). This is done by first calculating the stresses in the membrane, or, in the case of formfinding, dictating the stresses, and converting them to tensions in the edges of each panel. The calculated force is applied on the links of the system. If a link is located on the edge of the structure, it also has structural properties of its own (they are representing an edge cable). Then the forces are transferred on to the nodes. From here the acceleration, velocities and finally displacements, of the nodes, can be calculated. In the next iteration the deformations in the geometry of the membrane panels and the cables will generate new forces.

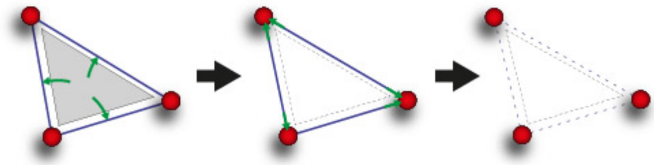

Figure 2 Illustrating the algorithm. Step 1: tension from the membrane is added on to the links, step 2: forces in the links is added to the nodes. Then the nodes have all the information needed to calculate their new positions.

3 EXAMPLE: HYPAR

An often seen shape in fabric structures is the hypar (hyperbolically shaped membrane). The geometry of this structure is relatively simple, but it is still difficult to analyse it without a computer, which is the reason for why it was chosen for this case study. The analysed hypar is 10x10 m in footprint and the corners are lifted 5m. A 16x16 mesh is used. The chosen fabric is a PVC of type 2 (see Table 1) and galvanised spiral strand steel cables, with a diameter of 10mm (see Table 2), are used as edge cables. A prestress of 2 kN/m^2 is applied to the membrane, for both warp and weft, the edge cables are not prestressed. In Figure 3 the three main steps of the analysis can be seen, from the starting geometry to the final stage, where the form found shape is analysed with applied loads. The results from the analysis were compared with results from Tensyl (analysis software for membrane structures).

Weight	EA		G	Unfactored Tensile Strength	
	Warp	Weft		Warp	Weft
1,05 kg/m2	670 kN/m	400 kN/m	10 kN/m	84 kN/m	80 kN/m

Table 1 Material properties for the membrane used.

Nominal Strand Diameter	Characteristic Breaking Load	Limit Tension	Metallic Cross Section	Weight
10,1 mm	93 kN	56 kN	60 mm2	0,5 kg/m

Table 2 Material properties for the cable used.

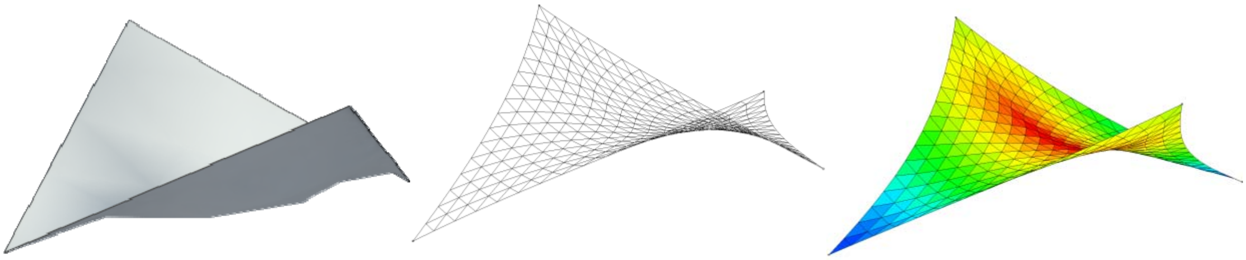

Figure 3. From the left: starting geometry, form found shape, and the structure analysed with 1 kN pressure load applied (the colours are visualizing the warp stress)

3.1.1 Results

The warp stress calculated in the developed tool were ranging from 11.59 kN/m^2, in the middle to 1.75 kN/m^2. Analys of the same hypar in Tensyl generated values ranging from 11.52 kN/m^2 in the middle to 1.76 kN/m^2.

4 CONCLUSIONS

In terms of developing a simple conceptual tool for designing membrane structures, the work has been successful. It is quick and easy to find the geometry for the structure and the analysis of the structure gives a good indication of how well the structure works, even though there is a lot to do, still, before the program is completely stable and can be fully relied on.

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