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Patterning of tensile fabric structures with a discrete element model using dynamic relaxation ☆

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ABSTRACT

Tensile fabric membranes present opportunities for efficient structures, combining the cladding and support structure. Such structures must be doubly curved to resist external loads, but doubly curved surfaces cannot be formed from flat fabric without distorting. Computational methods of patterning are used to find the optimal composition of planar panels to generate the form, but are sensitive to the models and techniques used. This paper presents a detailed discussion of, and insights into, the computational process of patterning. A new patterning method is proposed, which uses a discrete model, advanced flattening methods, dynamic relaxation, and re-meshing to generate accurate cutting patterns. Comparisons are drawn with published methods of patterning to show the suitability of the method.

1. Introduction

Tensile fabric structures are lightweight structural forms comprising a fabric membrane tensioned between a boundary of rigid structural elements and/or flexible cables. Such structures are characterised by their ability to resist external loading only through increased tension in the membrane surface, which is in turn resisted by compression and bending in supporting elements. To gain adequate stiffness, surface curvatures must be relatively high [1], and such doubly curved forms provide greatest stability under external loading. The surface shape of tensile fabric structures cannot be defined geometrically by the designer, but must be generated through *form finding* [2,3] – a computational process that finds the equilibrium position of a structure for a given stress state.

Prescribing a uniform pre-stress at the form finding stage results in a stable minimal surface – a surface with minimal area [4,5]. Combining a uniform pre-stress and a boundary with an appropriate number of alternately high and low points gives a minimal surface with sufficiently high curvatures to resist external loading. Such a structure can be considered optimal owing to: (i) an absence of stress concentrations under permanent loading, and (ii) a minimum of material used to achieve the form. Uniformly tensioned membranes are superior in their performance under external load, as they are less likely to wrinkle or fail by fatigue, as stated in the European Design Guide for Tensile Surface Structures [6].

Unfortunately, doubly curved surfaces are not developable – they cannot be flattened into a plane without distorting [2,7,8]. Structural fabrics are manufactured as flat panels, and consequently tensile fabric structures cannot be formed without incurring stresses in the surface. Structural fabrics are manufactured with a typical width of 2–3 m [9], and a maximum width of 5 m [10], requiring multiple panels for larger structures. The shape of these panels affects the final form and stress distribution of the membrane.

The combination of double curvature and manufacturing constraints necessitates a specialist design process, patterning, be conducted. Patterning seeks to determine the arrangement of planar fabric panels such that, when the panels are assembled, the desired 3D form is achieved, and the stress distribution is as close as possible to that intended during form finding. Fabric usage should also be minimised.

This paper presents a review of existing patterning methods, and proposes a new methodology for patterning. Insights into the computational process of patterning are presented, challenges are highlighted, and solutions are proposed through discussion of the new method. Comparisons with two published methods are included to demonstrate the suitability of the proposed method for tensile fabric structures patterning.

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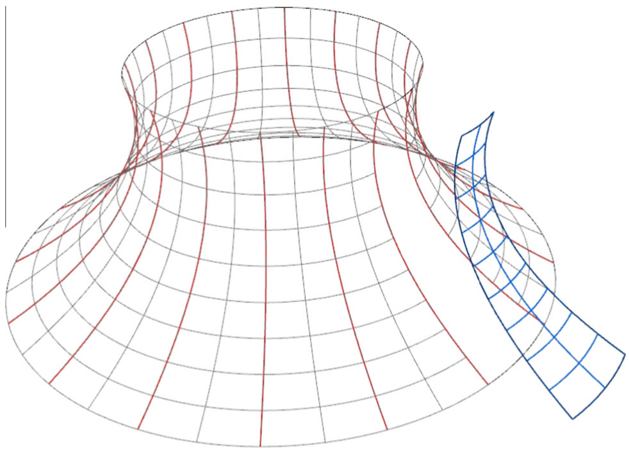

Fig. 1. Seams and extracted panel for a catenoid surface.

2. Computational patterning

Historically patterning was conducted using physical models. Computational methods of patterning are now used, and the general process of patterning is divided into four steps:

1. **Subdivision** of the membrane into panels by seams
2. **Flattening** of each 3D membrane panel into 2D
3. **Stress reduction** to reduce stresses from flattening
4. **Compensation** to give panels which are mostly stress-free and suitable for cutting

An additional fifth step can be included:

5. **Assembly of panels** to realise the final 3D form and stresses.

Step 1 – Seam definition, concerns the division of the form-found membrane surface into panels (Fig. 1). The divisions are defined by seams which generally take the form of sewn and/or welded overlapping panels of fabric [11].

It is considered good practice to establish seam lines along geodesics [7,9,12]. Geodesics are lines of minimum distance over a surface [7,13], and are the path adopted by a constant stress cable stretched over the surface. Consequently, geodesic seams do not introduce undesirable stresses into the membrane. Seams physically dictate the panel size, and affect the subsequent flattening, stress reduction and compensation of the individual panels. For practical reasons, seams should, run through the regions of low curvature to avoid possible wrinkling during sewing and welding. At the same time, they should be spaced reasonably, to ensure the curvatures across the panels remain low.

Step 2 – Flattening, concerns the development of a portion of the 3D form-found membrane surface into the 2D plane. Flattening is discussed further in Section 3.1.

Step 3 – Stress reduction, concerns the application of iterative methods to the flattened panel geometry to reduce stresses. Stress reduction is discussed further in Section 3.2.

Step 4 – Compensation, concerns the shrinking of the pattern to account for tensioning of the membrane during construction. Steps 3 & 4 can be performed in one process [8], and the relationship between the two is discussed in Section 3.3.

Step 5 – Pattern assembly, can be included in patterning schemes to calculate the final geometry and stresses in the constructed membrane. The cutting pattern is assembled according to the physical boundary conditions, and relaxed into its equilibrium shape, giving the final geometry and stresses.

3. Approaches to computational patterning

Whilst the general computational process of patterning follows the above structure, there are differences in its implementation, particularly at the stress reduction and compensation stages.

3.1. Flattening

As stated earlier, the panels defined on the form found membrane surface must be flattened into the plane, and this incurs distortions. Historically, flattening was undertaken using so called "cloth unfolding" [14] (Fig. 2) – membranes were reduced to a series of developable polyhedral strips that were unfolded [14–16]. These strips were then compensated in consideration of the pre-stress [9], and did not include stress reduction methods. Such strips required a compromise on accuracy [16], as high curvatures across a strip rendered polyhedral approximations to the surface inadequate [14].

Because of the poor patterns that trivial unfolding processes (in the absence of stress reduction procedures) produce, recent methods use more complex computational techniques to minimise flattening distortions [16], as discussed further in the following section. With the introduction of methods of stress reduction, flattening is now most commonly used to generate an initial geometry prior to using these procedures. Different flattening methods are highlighted in Section 5.1.

3.2. Reduction of flattening stresses

The problem of minimising flattening stresses can be formulated in two ways; as (i) a geometrical problem, independent of mechanical properties [17], and as (ii) a mechanical problem in which material properties are included (Fig. 3).

Solutions to both problem formulations may be further categorised. The first of the two main solutions, may be termed the '*minimisation solution*', and is more common. Here, flattening is formulated as an optimisation problem, where the intention is to minimise (i) in the case of a geometrical problem formulation, *distortions* induced by flattening [17], and (ii) in the case of a mechanical problem formulation, the *stresses* induced by flattening, or the deviation of the actual stress from the design stress [2,14]. This is achieved by seeking to minimise an objective function representing the strain or stress deviations. Minimisation solutions to geometrical [18] and mechanical [2,14] problems have been achieved, using, for example, methods such as least squares.

The second solution may be termed the '*structural solution*', as the un-equilibrated pattern is relaxed into an equilibrium state

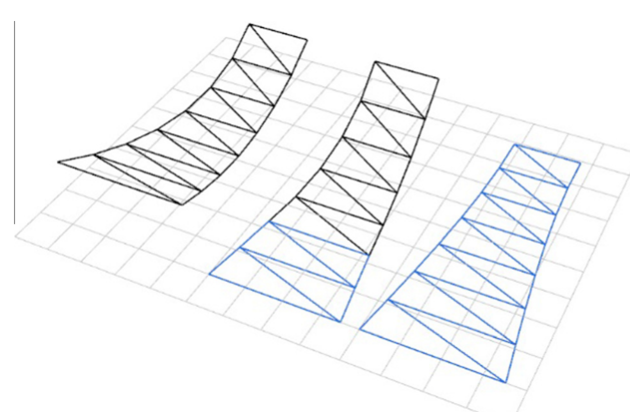

Fig. 2. Cloth unfolding.