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A shape optimization approach to integrated design and nonlinear analysis of tensioned fabric membrane structures with boundary cables

T.D. Dinh[a,*], A. Rezaei[a], W. Punurai[b], L. De Laet[c], M. Mollaert[c], D. Van Hemelrijck[d], W. Van Paepegem[a]

[a] Department of Materials Science and Engineering, Ghent University, Technologiepark-Zwijnaarde 903, 9052 Zwijnaarde, Belgium
[b] Department of Civil and Environmental Engineering, Mahidol University, Nakhonpathom 73170, Thailand
[c] Department of Architectural Engineering, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium
[d] Department of Mechanics of Materials and Constructions, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium

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ABSTRACT

In this article, a shape-optimization approach for tensioned fabric membrane structures with boundary cables is developed. Within the framework of shape optimization, an integrated design and analysis of the structure is studied. Assuming that the fabric membrane is initially flat and stress free, the ultimate goal of this study is to find an optimum shape of this fabric membrane so that the stress level on the resulting tensioned structure remains in a desired level while the shape difference between the resulting structure and the designed structure is minimized. While there are several studies on the integrated design and analysis of membrane structures, only a few of them have combined a shape optimization technique and nonlinear finite element analysis. Yet those studies simplify the interaction between the boundary cables and the fabric membrane and also do not include comprehensive nonlinear material models. This article aims to overcome the abovementioned limitations using a comprehensive nonlinear material model, including the geometrical nonlinearities, and considering an advanced nonlinear kinematical interaction between the boundary cables and the tensioned membrane. The shape of the fabric membrane and the length of the boundary cables are adjusted automatically during the optimization process. The obtained results show that a more realistic material model and interaction model between the boundary cables and the tensioned membrane can significantly affect the initial flat shape of the membrane.

1. Introduction

Tension fabric membrane structures are widely used for different purposes due to their superior characteristics, such as architectural appeal, fast installation, long span capability, environmentally-friendly and sustainable construction (Bridgens and Birchall, 2012; Li and Chan, 2004; Pargana et al., 2010). Architectural fabrics that are utilized as a skin for this kind of structure have negligible flexural and compression stiffness, and their weight is very low, which enables fabric structures to be widely used as large span canopies around the world. Compared with conventional structures made from concrete, steel or timber, fabric structures are more structurally efficient and cost-effective. Moreover, the material can be used optimally because there is no need to design the membrane section for bending or buckling (Bletzinger et al., 2009).

Due to the lack of bending and compression stiffness, compression stresses will lead to buckling or wrinkling in architectural fabrics. It can eventually lead to the collapse of the fabric structures (Bletzinger et al., 2015). To circumvent this issue, the fabric membrane structures have to be designed so that they will be always in tension under any kind of loads for their whole life cycle. Typically, the fabric membrane is tensioned by utilizing the supporting structures and the prestressed cables (Masahisa et al., 1989; Pauletti et al., 2010; Spillers et al., 1978; Véron et al., 1998). Generally, there are two design methods, i.e. a conventional design method and an integrated one. In the conventional one, the design process of the membrane structures can be divided into three steps viz. form-finding, structural analysis and cutting pattern generation (Bridgens and Birchall, 2012; Barnes, 1988; Bletzinger et al., 2005; Hashimoto et al., 2006; Ishii, 1999; Pauletti and Pimenta, 2008; Sánchez et al., 2007; Tabarrok and Qin, 1993; Wakefield, 1999).

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[*] Corresponding author. Tel.: +32 93310414; fax: +32 92645833.
E-mail address: tiendung.dinh@ugent.be, tiendungdinh@gmail.com (T.D. Dinh).

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Comprehensive studies for this design method can be found in the monographs of Lewis (2003), Koch and Habermann (2004) and Forster (2004). In the integrated design method, the above three steps are combined into one single step (Li and Chan, 2004; Pargana et al., 2010; Bletzinger et al., 2009; Haber and Abel, 1982; Haber and Abel, 1982; Haber et al., 1981; Kim and Lee, 2002; Punurai et al., 2012; Ohsaki and Fujiwara, 2003; Ohsaki and Uetani, 2000). A literature study of these design methods is presented in the following sections.

1.1. Conventional method in design and analysis of tension membrane structures

Different from conventional structures, the shape of a fabric membrane structure is a priori unknown. In order to find this shape, a form finding has to be performed. In the form finding stage, the layout of the boundary cables and kinematic boundary conditions are specified. The prestress distribution in the membrane, which is supposed to be uniform and isotropic or orthotropic, is prescribed and not dependent on the deformation. The shape of the membrane is formed such that the membrane is in equilibrium with the given prestress fields (Bletzinger et al., 2009; Masahisa et al., 1989). Because the stress field is supposed to be given regardless of how it has been generated, it is therefore not necessary to specify precisely the material model at this stage. However, to avoid the numerical singularities, some authors have used a very small value, but different from zero for Young's moduli of the fabric membrane and the cables. They referred to the material models in this stage as fictitious materials (Masahisa et al., 1989; Tabarrok and Qin, 1993). In (Veenendaal and Block, 2012), the most common form-finding methods, such as the force density method, the dynamic relaxation method and the updated reference strategy are presented and discussed in details. Nevertheless, in (Haber and Abel, 1982) Haber and Abel argued that in many cases the stress fields in the membrane cannot be imposed and are unknown. Moreover, a feasible shape that can be found from this approach is limited to a surface with homogeneous stress, but from an engineering viewpoint, prestress fields should deviate from a homogeneous and isotropic distribution in order to fully exploit the mechanical capacity of the membrane materials in order to resist the structural effects of loadings (Bletzinger et al., 2009).

The form-finding is followed by a materialization stage. In this stage, the actual material properties of the fabric membrane and the boundary cables are used and the support locations are held fixed (Tabarrok and Qin, 1993; Gosling et al., 2013). Once the equilibrium shape of the membrane structure is found, the three dimensional geometry of the membrane structure with its associated stress state is provided. Subsequently, the structural analysis is conducted in which the membrane structure is subjected to environmental loads. As shown in (Dinh et al., 2015), material nonlinearity should be included in this step.

However, the characterization of the mechanical properties of architectural fabrics demands data from uniaxial tests, biaxial tests and a shear test. It is time-consuming, expensive and even when these data are available, how to interpret and use them is not well-established (Bridgens and Birchall, 2012; Bletzinger et al., 2009). Today the only standard for interpreting biaxial test data is still the Japanese MSAJ/M-02-1995 standard (MSAJ/M-02-1995, 1995). Due to the aforementioned difficulties, the linear orthotropic elasticity is widely used in common practice (Bridgens and Birchall, 2012; Gosling et al., 2013; Nouri-Baranger, 2004; Dinh et al., 2014). To compensate for this oversimplification, designers have to use a very high safety factor (Yingying et al., 2014).

Because the fabric membranes are supplied in rolls of 1–5 m widths and have planar shapes, a cutting pattern generation is needed to determine the geometry of the unstressed fabric membrane panels that can be welded together to make up the complicated curved three dimensional surface resulting from form-finding (Ishii, 1999; Tabarrok and Qin, 1993; Punurai et al., 2012). Indeed, the cutting pattern generation is an inverse mechanical problem and to solve it, the deformation process needs to be traced back. In conventional cutting pattern generation, the three dimensional surface with its associated stress is divided into subsurfaces using the geodesic line technique. Subsequently, the linear orthotropic elastic material law is used in an unloading step to determine the stress-free panels. Because the membrane material used for the cutting pattern has never been loaded before, the first stress strain curve for the biaxial test of the membrane material should be used (Ishii, 1999). As can be seen in (Pargana et al., 2010; Dinh et al., 2014; Kato et al., 1999; King et al., 2005), membrane materials behave strongly nonlinear, especially, and irreversible deformation can occur in fabric membranes very early in the loading stage. Therefore, using linear orthotropic elasticity, designers exclude all of the nonlinear effects. Aware of this weakness in the method, designers have to make compensation for the cutting patterns. However, the method for applying compensation has not been well-documented yet and many problems associated with cutting pattern generation still occur, especially when the structure has a high curvature shape (Punurai et al., 2012).

1.2. Integrated approach for design and analysis of tension membrane structures

Three-dimensional curved membrane structures are undevelopable, thus the planar membrane panels cannot form these curved surfaces without deformation (Bletzinger et al., 2009; Ishii, 1999; Tabarrok and Qin, 1993). Due to the fact that in the conventional method, the form-finding and patterning generation stages are decoupled, additional stresses that arise in the planar membrane panels are not taken into account. However, these stresses are not so small and cannot be neglected (Pargana et al., 2010; Bletzinger et al., 2009; Kim and Lee, 2002; Ohsaki and Fujiwara, 2003). As a consequence, wrinkles can appear in the structure and the final shape, which is formed by assembling the planar membrane panels, might be far different from the one determined in the form-finding stage. The utilization of advanced material models for architectural fabrics is difficult in the conventional design method, because in these material models (Pargana et al., 2010; Dinh et al., 2014; Kato et al., 1999; King et al., 2005), the mechanical behavior of architectural fabrics is path-dependent. In other words, for a given stress value, there is no unique value for the strain. There are different material parameters for a material point in the fabric. The values assigned to these parameters for the material point depend on the load level, the load history as well as the stress ratio it has experienced. In the conventional approach, we do not start structural analyses with the stress-free fabric panels, but with the 3D curved surface and its associated prestresses. After materialization stage, the prestresses in the membrane are not uniform, but different from point to point. As a consequence, it is impossible to assign proper material parameters for the membrane.

In order to overcome the aforementioned drawbacks of the conventional method, the integrated design procedure was proposed by Abel et al. (Abel et al., 1986). Further developments can be found in (Pargana et al., 2010; Bletzinger et al., 2009; Haber and Abel, 1982; Haber and Abel, 1982; Haber et al., 1981; Kim and Lee, 2002; Punurai et al., 2012; Ohsaki and Fujiwara, 2003; Ohsaki and Uetani, 2000). In this method, the influence of the cutting pattern can be integrated in the form-finding and structural analysis steps based on correct nonlinear continuum mechanics, which can provide a reliable analysis of tension fabric membrane structures (Pargana et al., 2010; Bletzinger et al., 2009). Concisely, shapes of