Engineering Structures 124 (2016) 376–387

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Integrated analysis of kinematic form active structures for architectural applications: Design of a representative case study

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ARTICLE INFO

Article history:
Received 18 November 2015
Revised 18 May 2016
Accepted 23 June 2016

Keywords:
Tensile fabric structures
Kinematic structures
Numerical simulation
Structural design

ABSTRACT

Today's architecture is characterized by a growing demand for flexibility and adaptability, allowing to adjust to meet the current needs. Both covering spaces for weather protection and improving energy performance of buildings ask for dynamic architectural solutions. The integration of lightweight technical textiles offers great possibilities for these kinematic structures, due to their inherently high flexibility.

Unfortunately, until now, there is a lack of in-depth knowledge on the material properties of technical textiles, their structural behaviour during deformation and the use of available design tools. The inability to keep the fabric properly pretensioned in all deployment stages within the structure's limitations, obstructs the use of fabric structures for kinematic applications.

In order to make a good design and analysis possible, we investigated the material properties of a standard polyester-PVC fabric and implemented these properties in a simple linear elastic computer model of a case study. Afterwards, we performed a parameter study to derive a set of conceptual design considerations for the kinematic prestressed fabric structure. The specified parameters to verify in the design process are (i) the boundary configuration in which form-finding is conducted (i.e. the reference state), (ii) the prestress levels and ratios, (iii) the control of the deployment and (iv) the used material parameters. The paper discusses how the computed model can serve as a design tool.

An exhaustive preliminary study is essential to enhance the overall structural behaviour of the membrane structure in all stages of its transformation, within the application range, keeping the membrane properly tensioned and avoiding excessive stress concentrations.

In a next step, a large-scale experimental model is set up, measuring the geometry, reaction forces and strains in the membrane. This model will serve as an experimental validation of the numerically obtained results.

1. Introduction

During the last decades, the use of membrane structures for architectural applications has gained popularity - and it still is. These lightweight, highly flexible fabric materials allow creating a wide variety of shapes and minimizing the installation time and operational cost. Their advantageous properties make that lightweight structures are highly suited not only for permanent, often wide span constructions, such as roof coverings for stadiums, but also for temporary architectural assemblies.

On the other hand, a growing interest can be noted for an adaptable and transformable architecture. The great advantage of these transformable structures lies in their ability to change their form in function of changing boundary conditions. They can, for instance, be used to create a transformable building skin which reacts to changing solar and light incidence and thus can contribute to the energy consumption and internal comfort of the building.

Until now, analysing and conceiving complex mechanical deployment mechanisms such as hinged scissors structures [1] has been the main point of development for kinematic structures. However, fabrics possess, with their inherent flexibility, ideal properties to be used in dynamic structural skins. Implementing the fabric material as a structural and kinematic element unifies the

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http://dx.doi.org/10.1016/j.engstruct.2016.06.038
0141-0296/

advantages of both the tensioned fabric structures and kinematic structures, making light and transformable building elements.

The main idea behind the structural design of Kinematic Form Active Structures (KFAS) is to keep the membrane properly tensioned in a defined range of stages of the transformation, in order to carry external loads no matter the geometrical configuration. The initial structural stability is provided by the applied prestress in the membrane. Transforming the membrane structure, involves changes in membrane stresses and requires thus to investigate if the structure remains tensioned when deployed to avoid the loss of structural stability and wrinkling of the membrane.

However, the available design tools for fabric structures do not (or insufficiently) allow to incorporate the kinematic aspect, but also lack the possibility to incorporate the complex non-linear material properties for these particular systems. Therefore, fabric structures have mainly been conceived static or semi-kinematic. This latter means that the structure is designed to be only tensioned in its predefined unfolded state, but loses prestress when folding the membrane, like for example the roof of the courtyard 'Alte Residenz', Austria [2] (see Fig. 1).

The goal of this research is to investigate how to use the existing design tools that apply simplified linear elastic models for developing a KFAS that remains tensioned during the transformation between different configurations. Firstly, an overview is given of the current design methodology, the used material model and the available protocols for deriving material properties. Next, the case study of the KFAS is presented. Then, the influence of changing a set of well-chosen design parameters of the KFAS on its kinematic and structural behaviour is investigated by means of this case study, to finally come to an improved structural response of the structure.

2. Current design approach

2.1. Current methodology

The structural analysis of fabric structures greatly differs from regular building typologies due to the high flexibility of the fabric material. As tensile fabric structures translates all the forces and external loading into tension forces, these type of structures have a high structural performance and material efficiency. There where regular structures have a predefined shape which is loaded during the analysis, the initial geometry of fabric structures greatly varies depending on the imposed boundary conditions and the applied pretension. Small changes in the geometry of the boundary conditions or the pretension of the fabric or cables can lead to different geometries and can consequently influence the behaviour of the structure under loading.

The methodology used for the design of fabric structures will thus not only incorporate the analysis under loading but also the determination of an equilibrium shape [3,4]. The latter, also called the form-finding, is mostly the first step and takes into account the geometric constraints and the imposed pretension in the fabric and cable elements. By determining the equilibrium of all combined elements, the resulting shape of the structure can be found. Important to note is that this first step generally does not account for material properties.

After the form-finding process, the correct material parameters are applied to the model and an analysis under loading is carried out. During this step, material stresses and deformations are evaluated. Based on the results of this analysis, boundary conditions and prestress in the model can be adapted, optimizing the structural response. The level of pretension should ensure the preservation of positive stresses in the membrane under all load combinations (see Fig. 2).

The third step in the design of fabric structures is generating the cutting patterns. Since the geometry of a fabric structure consists of a doubly curved surface, which is not developable out of one membrane panel, several flat pieces of fabric are formed into cutting patterns that approximate the three dimensional geometry as closely as possible. These patterns are then shrunk down, using an experimentally derived factor, to account for the initial permanent deformation of the material and to guarantee the pretension. This latter step is called the compensation [5,6].

2.2. Material model

Architectural fabrics typically consist of orthogonally oriented woven fiber yarns, covered with a coating. The strong interaction between the two fiber directions, i.e. the warp and weft (or fill) direction, cause a highly nonlinear orthotropic behaviour. An important point of discussion when analysing fabric structures is the numerical simulation of this complex non-linear material behaviour of fabrics. Although research is done on characterising and modeling this complex behaviour [7–9], currently an approximative linear orthotropic plane stress material model is often used as proposed in [10]. This material model assumes a linear elastic behaviour and represents the material behaviour by means of one elastic modulus and one Poisson coefficient for each of the two yarn directions. This material model can be extended to incorporate the shear stiffness of the fabric due to the coating. The orthotropic linear-elastic constitutive law can be described as follows:

$$\begin{bmatrix} \epsilon_w \\ \epsilon_f \\ 2\epsilon_{wf} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_w} & \frac{-\nu_{fw}}{E_f} & 0 \\ \frac{-\nu_{wf}}{E_w} & \frac{1}{E_f} & 0 \\ 0 & 0 & \frac{1}{G_{wf}} \end{bmatrix} \cdot \begin{bmatrix} \sigma_w \\ \sigma_f \\ \sigma_{wf} \end{bmatrix}$$

where:

- ϵ_w, ϵ_f and ϵ_{wf} are the strains in respectively warp (w) and fill (f) direction and the shear strain [–];
- ν_{wf} and ν_{fw} are the Poisson's ratios in warp and fill direction [–];
- E_w is the E-modulus in warp direction, E_f in fill direction [kN/m^2];

Fig. 1. Retractable roof "Alte Residenz", Kugel Architekten.