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Integrated analysis of kinematic form active structures for architectural applications: Experimental verification

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ABSTRACT

Technical textiles used in lightweight tensile fabric structures are inherently highly flexible, which makes these materials very suited to, for instance, make lightweight adaptable façade or roof systems.

Until now, however, kinematic fabric structures are mostly designed to transform between a prestressed, structural state and a compact state where the fabric becomes untensioned using fixed geometrically determined paths. The goal of this research is to design and validate the structural behaviour of a kinematic fabric structure which remains prestressed in all its possible geometric states by taking advantage of the out-of-plane flexibility of the material rather than the high stretchability.

To make the design and the use of such a kinematic fabric structures possible, we investigated the material properties of a standard polyester-PVC fabric. Afterwards, we implemented these properties in a computational model and performed a parameter study to come to a conceptual design of a kinematic prestressed fabric structure where its geometry follows the reorientation of forces rather than restricting its movement to a geometrically determined path. Finally, the designed kinematic structure was built and tested as a prototype, comparing reaction forces and strains to the ones predicted in the computational model.

This paper describes this experimental validation by comparing the experimentally obtained results to the values predicted in the computational simulations using a cable-net approximation and a linear elastic orthotropic material model.

Although this comparison showed some deviations in the absolute values of the forces and strains, the general behaviour of the prototype was correctly predicted using a standard analysis method. The majority of the deviations could be contributed to the fact that the strains in the computational model do not take into account the compensation applied to the prototype and the high permanent straining of the boundary belts.

The investigated prototype thus showed both the potential and the difficulties of using lightweight, highly flexible fabrics as structurally stable, kinematic elements.

1. Introduction

Tensioned fabric structures form a still growing part of the built environment. Their unique properties, such as a high strength-to-weight ratio, fast construction process and a wide variety of possible shapes, make that fabric structures are currently used in a broad range of applications, both temporary (e.g. coverings during festivals or tents) and permanent (such as stadium roofs). Current research regarding fabric structures focuses largely on characterising the complex nonlinear material behaviour [1–3] and the testing methodologies used to determine the material properties [4–7]. Due to the material complexity and wide variety in computational modelling methodologies and results [8], as well as practical limitations, only few sources have compared computational results to full scale experimental verifications.

Next to the structural lightweight solution that fabric structures are, an increased attention can also be noted for kinematic structures. This typology relies on a mechanism to transform itself between different states, offering the ability to change their shape

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and function depending on external factors. Currently however, research in this field focusses mainly on the development and analysis of complex mechanisms, such as scissor structures, and studying the mathematical description of the movements inside these structures [9,10].

Since both fabric and kinematic structures are often used in a temporary context, there is already common ground between these two typologies. Until now however, combining kinematic concepts with fabric structures has resulted in fabric structures which can adapt their shape to a degree, but lose their prestress, and thus the fabric's structural stability, doing so (Fig. 1). Yet, the inherent material flexibility of fabrics makes this type of material very interesting when designing kinematic structures. Combining the high structural efficiency and lack of bending stiffness of fabrics with the adaptability offered by kinematic structures could, for instance, make for a very light-weight façade system which responds to external factors such as solar radiation or light incandescence. Key in this concept is that the fabric remains structurally stable in all intermediate positions of the adaptable structure.

The latter means that pretension should be preserved in the fabric regardless of the structure's configuration. Moreover, these structures should ideally not only rely on straining the material to change their shape, but rather use the inherent out-of-plane flexibility provided by the thin membrane.

This paper describes the experimental verification process of a foldable kinematic fabric structure where prestress is preserved in all configurations. The experimental results are compared to the predictions from the computational model composed during the design stage [11]. The first part shortly explains the origin of the test case and the envisioned results. Afterwards, the experimental process is documented and the relation between the full-scale prototype and the computational model is discussed.

2. Concept: description of the case study

The case studied in this paper has been derived from a prototype designed within the framework of the EU-funded Contex-T project. During this project a group of European researchers designed a foldable dome composed of flat, triangular PVC-coated polyester panels [12]. Being based on a rigid origami concept, this dome, which consists of eight modules each constructed from two flat triangular pieces of fabric, can rotate radially to create different degrees of openness by folding and unfolding the fabric modules (Fig. 2).

Although the underlying concept proved to be feasible to some extend, the low initial prestress of the fabric, combined with the geometrical circular movement imposed by the rigid frame during deployment, led to wrinkles and thus a loss of structural stability of the fabric while closing the units. By redesigning the prototype and removing the geometrical constraint imposed by the fixed frame [11], we were able to overcome the limitations imposed by the original structural system which restricted the movement of the units. For this re-evaluation of the system a single foldable unit, consisting of two flat triangular pieces, has been isolated and investigated.

In order to create a working prototype, we removed the frame in which the fabric was initially contained. This also eliminated the geometric constraint along which the deployment took place. Instead, a force-oriented approach was used during the design process starting from the prestressed geometry. By taking the reaction forces after the formfinding and reorienting them, the shape of the structure can be changed due to the form-active nature of prestressed fabric structures. However, unlike what happens in a geometrically controlled actuation, the magnitude of the external forces remains constant throughout the transformation, and thus the strains in the fabric will remain relatively constant throughout the transformation, since no energy is added. Thus solely by reorienting the reaction forces, the shape of the structure changes along a path which is preferred by the structure itself. Hence an optimal actuation path was derived during the design stage along which the prototype should move in order to retain prestress despite the large geometrical displacement [11].

3. Experimental program

3.1. Set-up

3.1.1. Geometry and materialisation

The experimental prototype, comprising one single unit of the dome, was constructed using a Sioen T2103 fabric. This PVC-coated polyester fabric has a tensile strength of 80 kN/m in both warp and fill direction and a thickness of 0.83 mm. Material parameters were derived by extensive uniaxial and biaxial testing. The latter was initially conducted using an adaptation of the test profile described in MSAJ M-02-1995 [13] and afterwards using a project-oriented protocol imitating the stresses expected in the prototype.

All biaxial tests were conducted on the biaxial rig at the Vrije Universiteit Brussel [14]. This rig consists of four independent actuators, each equipped with a 100 kN capacity load cell (Instron 2518-111). During the tests, each of these actuators move laterally and symmetry is ensured by measuring and balancing the opposing forces. Each actuator has only one degree of freedom (lateral translation), which requires the careful centring of the sample at the start of each test. Strains in the fabric were measured using a full-field stereoscopic Digital Image Correlation (DIC) system.

The initial test protocol consisted of an adaptation of the test protocol described in MSAJ M-02-1995. The load cycles between 2.5% and 25% of the fabric's UTS, thus respectively resulting in a prestress of 2 kN/m and a maximum applied stress of 20 kN/m.

Fig. 1. Most adaptable fabric structures are only prestressed, and thus functional, in one configuration (left) and transform by folding the fabric. However, during this process the prestress is usually lost resulting in the fabric becoming slack (right) [© Kugel Architekten (http://www.kugel-architekten.com)].