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A study of tension fabric membrane structures under in-plane loading: Nonlinear finite element analysis and validation

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ABSTRACT

Analysis of tension fabric structures exhibits severe nonlinearities because of the large deformation of the fabric membrane and its peculiar material behavior. At this moment, there is limited literature on analysis and design of this kind of structures. A realistic numerical simulation can serve as a driving force in the development of these structures. This article presents a nonlinear finite element analysis of a tension fabric membrane structure used in foldable architectural applications. Geometrical and material nonlinearities are considered in the finite element model which is implemented in the ABAQUS/standard software. The numerical results are validated with the experimental data obtained from digital image correlation (DIC) technique. Good agreement between the simulation and the experiments is achieved. Moreover, the case study considered in this work can be used as a benchmark for numerical simulations in the research field.

1. Introduction

Fabric membrane structures are widely used nowadays due to their noticeable advantages, such as the low weight of the membrane, ease of transportation, relatively low cost and architectural aesthetics [1–4]. The fabric membrane used in these structures is very thin and flexible. Actually flexural stiffness of these membranes is negligible and hence it is difficult to pre-assign the shape of a tension fabric structure [2,3]. Indeed, there is a tight interconnection between the membrane's shape and the stress state in the membrane. In this interconnection, the membrane configuration, the applied loads on the structure and the internal stresses interact in a nonlinear manner to satisfy the equilibrium conditions [5]. Moreover, the mechanical behavior of coated fabrics used for membrane structures is also very complicated. It includes anisotropy, plasticity, time dependency and load ratios dependency [6–9]. More than fifty years after the pioneering work of Otto et al. [10], the development of tension structures has been hampered because of limitations in analysis methodologies [11]. Therefore, the urgent need for a unifying code and consistent methodology for design and analysis was mentioned in the work of Gosling et al. [12]. Moreover, a lack of proper benchmarks for verifications of membrane structure analyses, leaves numerical simulations of these structures in dubiety [12].

Within the framework of the EU-funded Integrated Project Context-T, a dome-like structure was designed (Fig. 1). Its skin is an assembly of flat triangular PVC coated membrane parts which are welded together. By adjusting the belts, the whole structure is in tension [13]. The purpose of the project is to verify whether the Context-T structure can be stable in intermediate configurations between fully open and closed positions. To find a proper answer to this issue, knowledge about how the tension membrane behaves is required. Therefore, to gain a better assessment of the feasibility of the design concept, a single tension membrane unit is analyzed first. Moreover, through this analysis the material constitutive model, which we have developed for coated fabrics in [6], is further validated for a different load case. Because of these reasons, the success of this analysis will thus be the premise for further investigation of the feasibility of this design concept. In this work, a two-dimensional membrane which is subject to in-plane loads is considered, both numerically and experimentally. Moreover, due to the fact that there is no benchmark for membrane structure analysis yet [12], the model used in this paper

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Fig. 1. A real scale model of the context-T structure in different configurations [13].

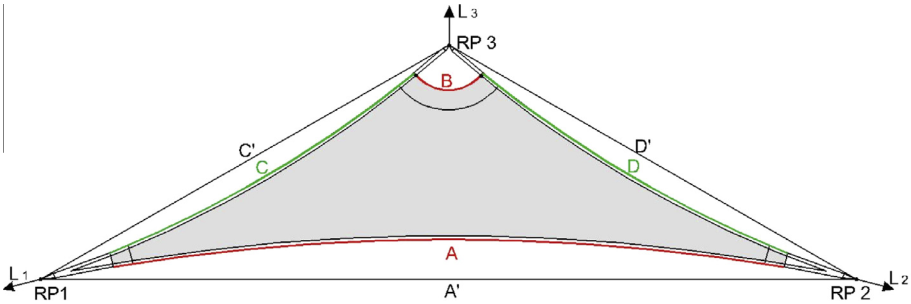

Fig. 2. Naming convention of the model.

can serve as the first benchmark for future studies in this research field.

The outline of the paper is as follows. The next section briefly explains the material behavior of coated fabrics as well as the elasto-plastic material model which has been proposed by the authors [6]. The experimental setup is then introduced. Afterwards, the details of the finite element model are presented. Finally, the results from the finite element simulations are validated with the experimental data.

2. Material behavior of the PVC coated fabric

The PVC coated fabric can be considered as a special kind of textile composite in which a woven fabric structure is coated with a very low stiffness PVC coating. In the woven fabric structure, the so called warp yarn is initially almost straight while the fill yarn has a high crimp. When the PVC coated fabric is in tension, a phenomenon referred to as crimp interchange occurs. It is one of the most important factors leading to the severe nonlinearities in the mechanical behavior of the coated fabric [6,7,14,15]. As mentioned in Section 1, there is an interconnection between the behavior of the membrane's material and its configuration. It implies that in order to have a realistic simulation of tension membrane structures, an accurate material model plays a crucial role. Moreover, membrane structures are typically large-scale structures and the numerical analyses are usually expensive from a computational viewpoint. Thus, the material model used for the PVC coated fabric should be computationally inexpensive. In [6], the present authors have proposed an elasto-plastic model for coated fabrics which has proven to capture their salient mechanical behavior. The material model has been developed in the small deformation framework, but it can also be applied to large deformation problems in ABAQUS because before the user material subroutine (UMAT) is called, the strain and stress tensors have been rotated to take into account for rigid body motion in every increment. Further, the actual strains in the membrane are small to moderate. Therefore,