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Uncertainty quantification of dry woven fabrics: A sensitivity analysis on material properties

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ABSTRACT

Based on sensitivity analysis, we determine the key meso-scale uncertain input variables that influence the macro-scale mechanical response of a dry textile subjected to uni-axial and biaxial deformation. We assume a transversely isotropic fashion at the macro-scale of dry woven fabric. This paper focuses on global sensitivity analysis; i.e. regression- and variance-based methods. The sensitivity of four meso-scale uncertain input parameters on the macro-scale response are investigated; i.e. the yarn height, the yarn spacing, the yarn width and the friction coefficient. The Pearson coefficients are adopted to measure the effect of each uncertain input variable on the structural response. Due to computational effectiveness, the sensitivity analysis is based on response surface models. The Sobol's variance-based method which consists of first-order and total-effect sensitivity indices are presented. The sensitivity analysis utilizes linear and quadratic correlation matrices, its corresponding correlation coefficients and the coefficients of determination of the response uncertainty criteria. The correlation analysis, the response surface model and Sobol's indices are presented and compared by means of uncertainty criteria influences on *MataBerkait*-dry woven fabric material properties. To anticipate, it is observed that the friction coefficient and yarn height are the most influential factors with respect to the specified macro-scale mechanical responses.

1. Introduction

The mechanical behavior of dry fabrics is important for the manufacturing process of textile composites. The first step of the manufacturing process of a textile composite is the placement of a dry woven fabric in a preform. Subsequently, resin is poured over it in order to form the solid shape of the textile composite. Any deformations and uncertainty factors during the placement possibly affect the elastic behavior of the final textile composite. For instance, wrinkles, folds, and tearing possibly lead to unexpected mechanical behavior of the final textile composites.

Using numerical simulation methods [1], the placement of a dry fabric in a preform can be investigated. Since not all individual yarns can be incorporated at the macro-scale due to the computational costs, meso-scale models are mostly used for this. The material properties of the meso-scale descriptions in turn depend directly on the geometry of meso-scale unit cells of the fabric and the yarn materials used. Several studies therefore focused on fitting a macro-scale continuum description on the response of meso-scale unit cell models of fabrics. Some of the earliest studies are those of Clulow and Taylor [2], Hearle et al. [3], Kawabata et al. [4,5], Testa and Yu [6] and Pan [7]. More recent studies are those of Beex et al. [8], Buet-Gautier and Boisse [9], Lomov et al. [10], Tabiei and Yi [11], Cavallaro et al. [12], Kumazawa et al. [13] and Komeili and Milani [14].

The meso-scale modeling of dry fabrics implies that all of the mechanical properties of the meso-scale constituents must be considered. These properties can be determined based on the micro-scale modeling of an individual yarn or by defining an appropriate constitutive model for the yarn material [14]. A study by Komeili and Milani [14] presented two sets of geometrical and material-related meso-level uncertainty criteria on a glass fibre plain weave fabric using two-level factorial designs. For the geometrical uncertainty factors, the yarn spacing, yarn width, yarn thickness and misalignment of the yarns angle were investigated. For material

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uncertainty criteria, the longitudinal Young's modulus, transverse Young's modulus and friction coefficient were adopted in the analysis. Gasser et al. [15] used an inverse characterization method on experimental results (experiments performed on large pieces of fabrics) to obtain the material properties of yarns. This approach uses special material constitutive models for yarns to account for the effects of the discrete fibres at the micro-level as utilized by Sherbun [16], which was adopted by [17] as well. Conversely, Peng and Cao [18] utilized classical elastic material properties and finite element procedures in defining the material properties. They also implemented homogenization to predict the effective non-linear elastic moduli of textile composites at the macro-scale similar to Takano et al. [19,20], Rabczuk et al. [21] and Bakhvalov and Panasenko [22].

Uncertainty analysis of moderate to complex computational models is costly due to the high number of uncertainty criteria that might be considered in the design process. In many cases, a structural response is dominated by only a few uncertainty criteria [23]. Correlation analysis (regression-based) and response surface models (variance-based) are the methods of global sensitivity analysis. In this paper, the influence of four meso-scale uncertainty criteria on the macro-scale response of a *MataBerkait*-dry woven fabric are investigated via these methods. The *MataBerkait*-dry woven fabric is previously generated by Ilyani Akmar et al. [24], and the meso-scale uncertainty criteria of interest are the yarn spacing, yarn width, yarn height and the friction coefficient between the yarns. According to previous studies, these properties have been the most important criteria in yarn designation. The geometry of the meso-scale unit cell is generated in TexGen and ABAQUS is used to discretise the unit cell with finite elements and analyse its response as a function of applied uni-axial and biaxial deformations under periodic boundary conditions, as explained in Section 2. The sensitivity analysis is considered in Section 3. The numerical results are presented in Section 4. Finally, conclusions are detailed in Section 5.

2. Dry woven fabric unit cell

2.1. Geometry and discretisation

The dry woven fabric unit cells used in this study are based on the unit cell models introduced by Ilyani Akmar et al. [24] and inspired by M.H.D.C. [25] who adopted *Mata Berkait* as the pattern arrangement of the yarns, see Fig. 1. Three basic dimensional values of the yarns specified in this paper are $s = 5.13$ mm, $w = 4.44$ mm and $h = 0.5$ mm for initial yarn spacing, yarn width and yarn height, respectively. The cross-sections are assumed to have an elliptical shape. The assumption of uniform fabric deformation at the meso-scale is applied in fabric unit cell modeling and periodic boundary conditions are applied to replicate its repetitive nature. Periodic boundary conditions is used to simulate a large system by modeling a small system that in order to consider the effects of adjacent unit cells. The periodicity conditions can be determined by imposing the force nodes in opposite corners to have the same transverse displacement and the same rotation over global opposite edges.

Once a unit cell model has been specified as described above, the unit cell is imported in ABAQUS. Fig. 2 contains a flowchart that explains the procedures for uncertainty quantification on *Mata Berkait*-dry fabric unit cell.

2.2. Material properties of the yarns

It is essential to have a detailed study of the fabric behavior at the meso-scale to determine its equivalent material properties for macro-scale models. The meso-scale modeling of dry fabrics implies that an appropriate constitutive description is formulated for the meso-scale constituents (the yarns and the interactions between them in this study). The material properties of the yarns are obtained from Peng and Cao [20], see Table 1 in which the materials used are pure E-Glass and Polypropylene.

2.3. Macro-scale response

At the macro-scale, the out-of-plane response is assumed to be negligible compared to the in-plane responses. For this reason, we focus on the in-plane responses and no loading will be imposed in the z-direction. This condition is crucial in the absence of a resin or matrix. Furthermore, yarns in dry fabrics can easily slide over each other which results in a substantial decrease of the shear modulus and transverse Young's modulus. It has been assumed that the longitudinal stiffness and shear moduli are given by Hooke's law

$$
\begin{aligned}
E_{xx} &= \frac{\sigma_{xx}}{\varepsilon_{xx}} \\
G_{yz} &= \frac{\sigma_{yz}}{2\varepsilon_{yz}} \\
G_{xz} &= \frac{\sigma_{xz}}{2\varepsilon_{xz}} \\
G_{xy} &= \frac{\sigma_{xy}}{2\varepsilon_{xy}}.
\end{aligned}
\tag{1}
$$

A postulation is made on the stiffness functions due to the lack of a comprehensive and consistent source of data/benchmark for the material properties of fabric yarns at meso-level. Constitutive models of yarns can also be estimated based on physical observations of yarn characteristics. For instance, due to the absence of a matrix, it is apparent that there are zero or quasi zero stiffness values in the constitutive model of yarn materials due to the fibrous nature in the fabric. The negligible longitudinal compressive response of yarns is in agreement with this observation. For the same reason, Gasser et al. [15] has introduced the crushing law in modeling the transverse behavior of fibres. As mentioned by Komeili and Milani [14], this law is developed based on the observations that the more compression is applied to the fibres, the stiffer it becomes. With respect to the crushing law, the transverse modulus of yarns is a function of contact conditions between yarns. Conversely, Kawabata et al. [4]526 defined the transverse modulus as a function of contact force. Other crushing functions in obtaining the transversal behavior can be retrieved in Badel et al. [27]. In this study, Gasser's approach is adopted as similar to Komeili and Milani's implementation. Gasser et al. [15] defined that the transversal stiffness which related to transversal behavior

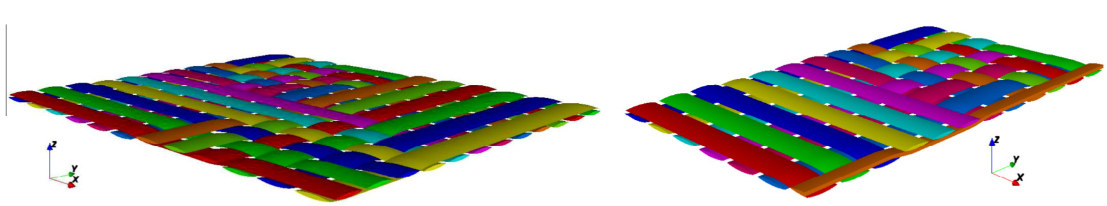

Fig. 1. The unit cell geometry used by Ilyani Akmar et al. [24]: (left) an elementary pattern; (right) the half of elementary pattern.