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Including shear in a neural network constitutive model for architectural textiles

G. Colasante[a], P.D. Gosling[a,*]

[a]*School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK*

Abstract

Even if a reliable constitutive modelling of materials is essential to finite element analyses, architectural textiles are still poorly described by making use of plane stress linear elastic models. More complex analytical models are computationally too expensive and require a large number of parameters to be calibrated, so that specific tests are often required, employing expensive and *ad hoc* designed equipment. The main reason for this is that coated textiles display a complex nonlinear, hysteretic, viscoelastic behaviour, which is difficult to model with classical analytical constitutive laws. In addition, coated fabrics involve aleatoric uncertainties due to the manufacturing process, as well as epistemic uncertainties related to the intrinsic difficulty of measuring certain quantities (e.g. the properties of yarns when embedded in a continuum matrix). Within this framework, Artificial Neural Networks (ANN) seem to be promising in reproducing the material mechanical behaviour, since they can be trained to learn the relation between input (strain) and output (stress) without the need of setting any explicit analytic stress-strain law. An existing ANN able to reproduce the biaxial tensile response of coated fabric membranes is here extended to include shear behaviour. After a description of the neural network architecture and its implementation, picture frame test data are employed for training and validation. The influence of different subdivisions of the experimental data into a training set, a validation set, and a testing set is investigated. Neural networks having different numbers of neurons are analysed, in order to establish the number of nodes required to accurately represent the experimental behaviour of the material, whilst avoiding overfitting at the same time.

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* Corresponding author. Tel.: +44-191-208-6422; fax: +44-191-208-5322.
E-mail address: peter.gosling@newcastle.ac.uk

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1. Introduction

Artificial Neural Networks (ANN) belong to "soft computing", which is a branch of computer science that tries to find solutions to uncertain, complex, unpredictable or fuzzy problems. A back-propagation neural network is essentially a computing system that maps an input vector (**x**) into an output vector (**y**) by using an internal architecture that simulates in a simplified way the human brain. Some neurons receive the inputs, elaborate it and produce an output, which is passed to another layer of neurons through connections.

Perhaps the most fascinating aspect of ANNs is that, like the brain, they can learn, even from noisy and fuzzy data, and generalize to situations never experienced before. This makes ANNs a powerful tool to model the complex behaviour of architectural coated fabrics, which have been demonstrated to be not only nonlinear, hysteretic, and viscoelastic, but also subjected to uncertainty due to the manufacturing process (aleatoric uncertainties) and difficulty in measuring some material quantities (epistemic uncertainties). Within this framework, ANNs could be a smart alternative to analytical constitutive laws for coated fabrics, which are usually either too demanding in terms of calibration and computational time or too simple to capture the real response of the fabric (see, e.g., plane stress orthotropic linear elastic model).

ANNs have been applied to a wide range of problems, including the prediction of properties, machine control, pattern recognition, optimization, constitutive modelling and many others. A review of the current applications in the textile field can be found in [1]. It appears that the only attempt to apply ANNs in modelling the shear stiffness of fabrics has been made by Chen et al. in [2], which describes the development of a neural network based on a selection of the most significant yarn properties and fabric parameters. Nevertheless, the model presented in [2] is referred to a specific kind of uncoated fabric.

To the author's best knowledge, ANNs have not been applied yet as a tool for modelling the shear stiffness of coated fabrics employed in architecture. According to [3], most of the analysis methodologies used by industry disregard this property or model it as linear, using available rule-of-thumbs estimates, even though the shear stiffness can significantly influence the final analysis results.

The work described here aims to design an ANN capable modelling the shear behaviour of coated fabrics. This will add an extra feature to the one presented in [4] and [5], which was limited to the prediction of the mechanical behaviour of fabric membranes when subjected to biaxial tensile loads. At present, most of the finite element codes for membrane structures model the material behaviour as orthotropic linear elastic, with plane strain assumption and no coupling between the shear and warp/fill stresses, as shown in Eq. 1:

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} E_x/(1-\nu_{xy}\nu_{yx}) & E_x\nu_{yx}/(1-\nu_{xy}\nu_{yx}) & 0 \\ E_y\nu_{xy}/(1-\nu_{xy}\nu_{yx}) & E_y/(1-\nu_{xy}\nu_{yx}) & 0 \\ 0 & 0 & G_{xy} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \mathbf{E}\boldsymbol{\varepsilon} \tag{1}$$

The biaxial ANN described in [4] and [5] was implemented in a finite element code in the form of an implied material stiffness matrix, which substitutes some of the stiffness matrix coefficients as follows:

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \mathbf{E}^{implied} & & 0 \\ & & 0 \\ 0 & 0 & G_{xy} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \mathbf{E}\boldsymbol{\varepsilon} \tag{2}$$

The parameters of the implied stiffness matrix were obtained by derivation of the neural network output with respect to the inputs. The shear stiffness was still modelled by means of a constant coefficient (linear shear response).

The shear ANN described in this paper does not remove the assumption of no coupling between the stresses in warp and fill directions and the tangential stresses. Due to the interactions exhibited by a coated fabric mainly because of the weaving, this hypothesis might be not ideal, but it is indeed useful to circumvent the complexities

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