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Mechanical Properties of Coated Fabric by Comparing Computational Model to Experiment

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Abstract. Coated fabrics are used in many applications such as fuel bladders for example. When subjected for testing, accurate constitutive data have to be found. However testing for strength as well as the resistance to stretching of such coated fabrics come with specific difficulties. For once, the thickness as well as the volume ratios of the fibre and coating cannot be stated very accurately. Secondly, the resilience, e.g. the stiffness of the stretching is generally low compared to metallic materials, which causes difficulties in simplifications like when using engineering stresses and strains. Both of these issues can be overcome using correlation to a finite element analysis of the actual experiment, which is uniaxial tensile testing in this case. At last, coated fabric materials are generally not isotropic, which requires tensile testing in different directions. However, an accurate finite element representation can be used to find more accurate values of constitutive parameters such as elastic moduli for each direction, and even the Poisson ratio. The strength estimates are however more difficult to represent accurately using a single material as they are still composite materials with more layers which should be represented accurately using for example the Hill criterion.

Introduction

Coated fabrics are used in many flexible applications such as tensile structures in architecture, belts for transport or flexible containers in this particular case. The fabric in this study is used in bladders for water storage. A woven textile coated in polyvinylchloride is suitable for such purpose since it is water-tight and non-toxic. However, since two different materials are used to form one inseparable material, it is basically a composite.

It is quite easy to find a constitutive model for a composite by linear mixing rules by volume fractions [1]. For example, Young's modulus for a composite E can be found by a linear combination of the Young's moduli of both materials E_T, E_C (T stands for textile, C for coating) multiplied by their volume fractionsV_T, V_C:

$$E = E_T V_T + E_C V_C \tag{1}$$

However, fabric can be looked upon as a special case. The textile in a fabric has a pattern caused by the weave of the textile, which causes non-uniform thickness of the whole, which causes problems in evaluating the fractions.

There is a possibility to disassembly the fabric into yarns and measure the properties of the yarns for purposes like in work [2] and verify the data by measuring the fabric properties. In such case, the data are not usually abstracted to variables as elastic modulus, since the geometry of the yarns is still uncertain.

These data can be theoretically used for coated fabrics with linear superposition of layer properties; however such procedure is ineffective for general properties such as the elastic modulus. The coating layer is usually small and can be considered isotropic in many cases such as in work [3]. It can be observed from figure 2 that the coated fabric is clearly made using the plain weave consisting of warp and weft yarns, which allows to consider these two axis of material symmetry. For an orthotropic description, one additional direction needs to be measured for the shear modulus. In fabrics, this is known as the bias direction which is tilted 45° to the warp and weft direction.

There is also the crimp interchange phenomenon (a term used in work [3]) present in constitutive relationships in the study. This effect is associated to the specific properties of fabrics caused by the weave which is originally fabricated with the warp yarns being tensioned and weft yarns being woven around them causing the so-called crimp. However, when weft yarns are being tensioned, they straighten first and bend the warp yarn around which is the so called crimp interchange. Since the flexural stiffness of the yarns is very low, this phase imposes virtually no additional forces and influences the deflection only. This can be seen in the evaluation part of this paper.

There is an extra difficulty with the scale of the stiffness of the fabric. The changes in geometry due to extension in length and contraction in width affects the difference of true and engineering stresses and strains significantly. This difficulty along with the uncertainty in the thickness is addressed here by making a computational model of the specimen with average width and thickness subjected to same forces as the actual experiment. By varying the Young’s modulus and the Poisson ratio of the computational model, one can find an accurate displacement corresponding to the experiment.

The strength of a composite is usually can be usually expressed in terms of layers such as maximum stress criterion or in fractions such as the Hill criterion [5]. However, since the strength of each layer is not known here, the strength is evaluated only for the material as a whole.

Test setup

The experiment was carried out on a tensile testing device. The dimensions should be as large as possible to minimize the effect of the pattern caused by the weave; however the dimensions of the specimen are limited, because they need to fit in the clamps used for the test. Although this is not a metallic material, the geometry can be set the same as for metallic specimens for reference, therefore, the specimen geometry was acc. to ISO 6892-1 [6] for all three directions. The size is limited since there is a limited supply of the material. For each direction, three specimens are made. The total number of specimens is then 9.

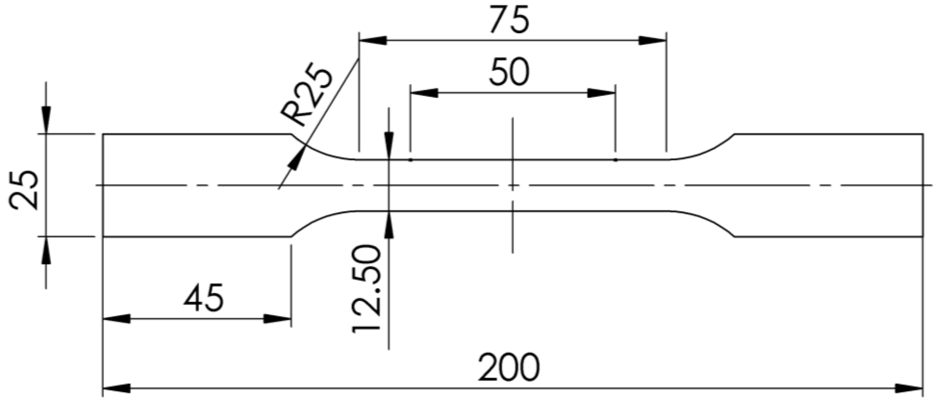

Fig. 1: Specimen geometry

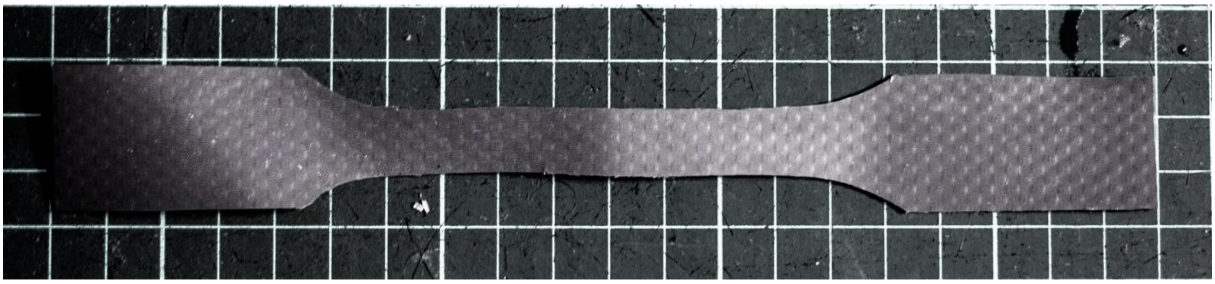

Fig. 2: Specimen example cut on the warp direction

Computation

The computation was done using the finite element method. The geometry was set according to the specimen, with the thickness set as an average of the measured thickness in different spots of the specimen. The actual average of the thickness of the specimen is around 1mm so unit thickness was used for the calculation.

The calculation was carried out using linear 2D membrane elements in MSC.Marc with updated large deformations and strains. The clamp is simulated using multi-point constraints with prescribed velocity 20mm/min according to the experiment. Only the quarter of the model is modelled with accounted symmetry. The forces can then be read as force reactions. A linear elastic constitutive model was used, where the Young’s modulus and Poisson ratio constants were varied until behaviour of the model similar to the actual specimen was obtained.

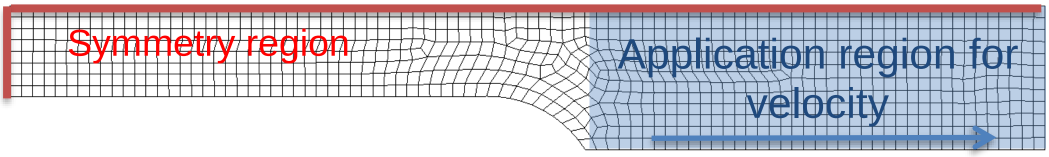

Fig. 3: Computation model with boundary conditions

Results

The test results are summarized by force vs. deflection relationships. The same data were computed by the simulation and both relationships were compared below for the warp direction, where values of 340 MPa for the elastic modulus and 0.3 for Poisson ratio used for the calculation.

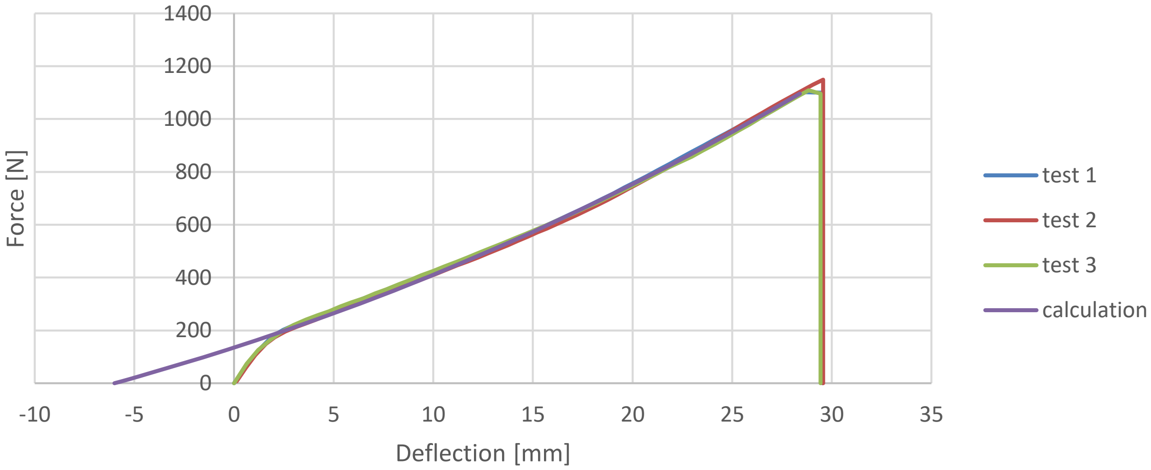

Fig. 4: Comparison of the experimental and computed values for the warp direction

For the weft direction, the same values of the elastic modulus and the Poisson ratio were used to fit the experimental data properly.

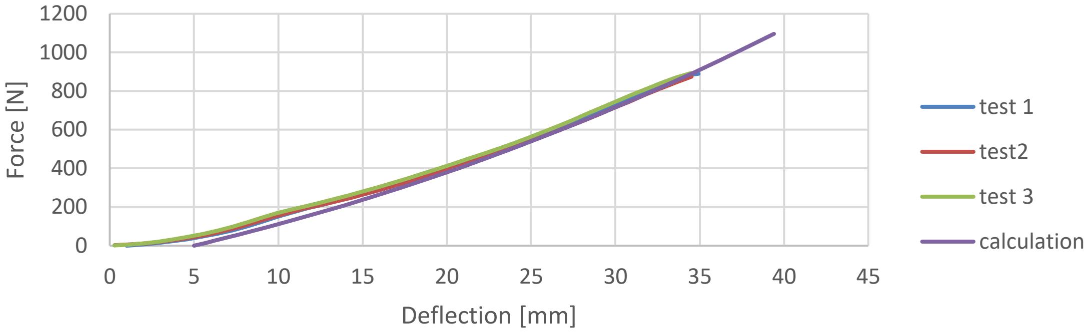

Fig. 5: Comparison of the experimental and computed values for the weft direction

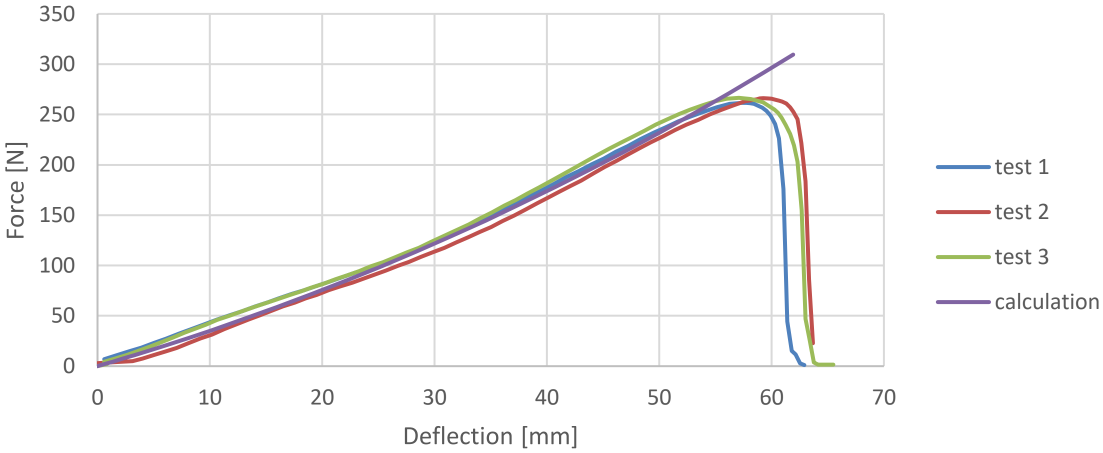

Fig. 6: Comparison of the experimental and computed values for the bias direction

The bias direction used a value of the elastic modulus 50 MPa. The results of the computation show stress levels after curve fitting on figure 4 corresponding to the maximal stress at the failure for the warp direction

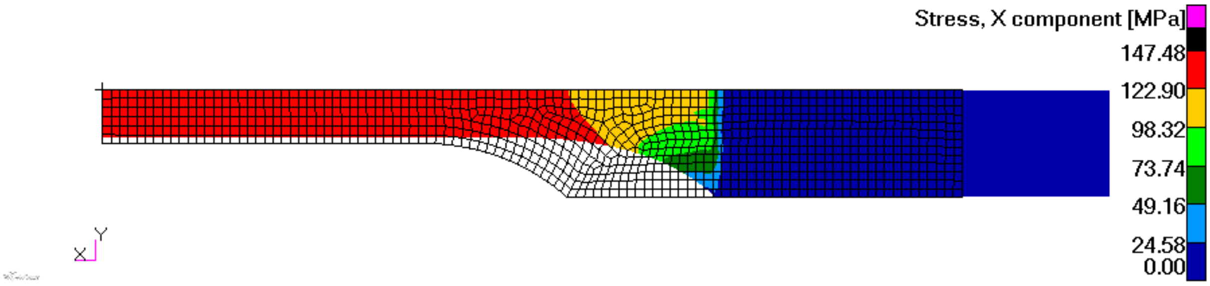

Fig. 7: Stress levels for computation in the warp direction

The failure occurred in all cases in the narrower part of the specimen at the beginning of the radius which corresponds to the maximal stress observed in the calculation. An example of a failure in the warp direction specimen can be observed below.

Fig. 8: Failure example in the warp direction

Conclusions

Based on the figure 7, the actual uniaxial strength of the material for the material as a whole in the warp direction can be associated to value somewhere around 147 MPa and 120 MPa for the weft direction. The strength here however does not account failure of single layers of the composite. Such case requires further study and experiments. Bias direction specimens have no continuous yarns from one and to the other and are held only together by the weave and the coating. Therefore, their stiffness and strength which is around 36 MPa is quite low compared to the warp and weft directions relationships.

The standard procedure in determining the Young's modulus uses a conversion of the force to engineering stresses using the initial cross-sectional area and a conversion of the deflection to engineering strains using the initial length, where regression between these two measures can be made to find the value. Such procedure would be highly inaccurate in this case due to excessive elongations and contractions which can be observed in figure 7. The excessive elongations and contractions cause the force-deflection relationships to curve concavely even though a linear stress-strain constitutive model was used, since the difference in true and engineering values differ greatly in such scale of stiffness. Since the curvature of the relationship is dependent not only on the elongation, but contraction as well, it is partly influenced by the value of the Poisson ratio, where value of 0.3 showed accurate enough for proper fitting of the curvature in the experimental data.

Unlike the bias direction relationship (fig. 6) the warp and weft directions (figure 4 and 5) show different initial slopes for the curve. These parts of the curve were omitted in the fitting process since they can be associated to the so-called crimp interchange phenomenon. The pattern of the initial slopes for both warp and weft direction seem to correspond to the shapes described in works [3,4]. The bias direction is not affected by it because the phenomenon is present only in the warp and weft directions.

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