Experimental assessment and interpretation of biaxial material parameter variation of a polyester-PVC fabric

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Abstract

Designing tensile fabric structures can be rather challenging due to the relatively complicated mechanical response of the coated textiles used in these structures. Its composition of interwoven fibres surrounded by different interacting layers of coating, and a lack of normative documents, assessing and interpreting a fabric’s mechanical response unambiguously is challenging and requires a great deal of experience and expertise. Through various biaxial tests on a single Type II polyester-PVC material, and the utilisation of different test and interpretation methods, the inherent variability of the measured mechanical response and derived material constants could be assessed in function of test and interpretation methodology. By then relating these variations to the respective alteration in test or interpretation methodology, several important relations can be derived between the test methodology and derived stress-strain response/material constants. The presented paper compares various biaxial test and interpretation procedures and shows that altering any of these can have a significant impact on the results, even when the test is conducted on the same batch of material and within the same test environment. The obtained results not only illustrate the need for a unified international framework for testing of fabrics, but also the importance of interpreting test results and acknowledging the uncertainty/variability on the obtained results.

Keywords: Biaxial testing, computational simulation, polyester-PVC, fabric, tensile surface structure

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1. Introduction

Biaxial testing forms an integral part of the design process for tensile fabric structures. Whether it serves for the derivation of generalised material constants, assessment of tear strength or shear stiffness or establishing reduction factors for the cutting patterns, being able to accurately assess a fabric’s mechanical response in a multi-axial stress state is an important aspect. (Beccarelli, 2015; Bridgens, 2004; Bridgens 2012; Uhlemann, 2016; Van Craenenbroeck, 2017)

Despite recent efforts towards a standard for designing and building tensile architecture (Stranghöner et. al., 2016), there still exist a considerable amount of variation in the way biaxial tests are conducted and the data is interpreted. Ranging from the design of the test benches and sample geometries to the mathematical process used to translate test results to a numerical material model, these inter-institutionary variations can lead to some variation, and thus uncertainties, on the test outcomes and the resulting material parameters.

Within this paper, several potential causes of uncertainties were identified and their impact on both the experimental stress-strain results as well as the derived material constants was assessed for a Type II polyester-PVC fabric (Sioen T2103) (Sioen Industries, 2018). The conducted experiments and analyses provided some insight to the effect of certain decisions and assumptions, but also allowed us to establish a base line for the expected variability for the tested material in function of commonly present differences.

2. Test and derivation methodologies

The presented research observes the three main steps in testing a fabric material and interpreting the outcome: (1) testing the material, (2) post-processing the raw data and (3) fitting a material model. For each of these three steps various variables were defined and investigated individually, assessing their impact on the stress-strain response and the material constants.

2.1. Test setup and methodology

2.1.1. Biaxial test setup

All tests described in this paper were conducted at the Vrije Universiteit Brussel. The biaxial bench used for these tests consist of four fixed actuators which stress the sample. Each actuator is equipped with a 100kN load cell which measures the applied force throughout the experiment. By constantly monitoring the force difference between two opposing actuators and adapting the actuators’ position, a balanced and uniform stress state can be maintained.

The biaxial sample consists of a central area-of-interest measuring 30cm x 30cm. Each of the four arms is equipped with twelve 25mm wide slits to reduce stress reduction in the centre of the specimen. A welded loop at the end of each arm then allows the connection of the sample to the actuators.
Figure 1: During the experiment, strains are measured using DIC through two cameras mounted above the sample (left). The sample is connected to each of the four actuators through a welded loop and bar system (right). (Van Craenenbroeck, 2017)

Strains in the sample were measured using a three-dimensional Digital Image Correlation (DIC) setup consisting of two AVT Stingray F-504 cameras mounted above the sample (Figure 1). Each of the tested sample was provided with a full-field speckle pattern which allows for the visualisation of the strain field throughout the entire sample in addition to the measurement within the area-of-interest.

2.1.2. Applied load profiles

The first, and one of the more significant, variations investigated during this research is the applied load profile. With no modern standard currently governing the biaxial testing of fabrics, many institutions have developed their own load profile in function of their needs and experience. Due to their woven and nonlinear nature the load history has however an important effect on the observed mechanical behaviour (Galliot and Luchsinger, 2011; Van Craenenbroeck et. al., 2015). During this investigation, the results obtained from five different load profiles were compared: (1) the load profile as proposed in MSAJ-M-1995 (Membrane Structures Association of Japan, 1995); (2) the default load profile used at the VUB, (3) a variation with an asymmetric warp-dominant prestress ratio, (4) a variation with an asymmetric warp-dominant prestress and normalisation ratio and (5) an interpretation of the load profile presented by EMPA (Galliot and Luchsinger, 2009) (Figure 2).
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Figure 1: During the experiment, strains are measured using DIC through two cameras mounted above the sample (left). The sample is connected to each of the four actuators through a welded loop and bar system (right). (Van Craenenbroeck, 2017)

Figure 2: This investigation compares a total of five different load profiles, each targeting a specific type of variation in the test methodology. (Van Craenenbroeck, 2017)

2.2. Parameter derivation

Although different material models to numerically describe the mechanical behaviour of fabrics exist, the presented research limits itself to the linear elastic orthotropic model. Despite some limitations, such as its inability to model the non-linear behaviour or permanent deformations occurring in the fabric, it is still a commonly used material model both in academic research and
engineering practice. The recently published European Standard regarding biaxial testing on fabrics also limits itself to this linear elastic model (CEN/TC 248, 2018), further consolidating the model’s relevance within the research presented in this paper.

The linear-elastic material model, under the assumption of a plane stress state given the negligible thickness of a textile, describes the stress-strain response by means of five constants: two Young’s moduli, \( E_{\text{warp}} \) and \( E_{\text{fill}} \), two Poisson’s ratios, \( \nu_{\text{wf}} \) and \( \nu_{\text{fw}} \), and the shear modulus \( G_{\text{wf}} \):

\[
\begin{bmatrix}
\varepsilon_{\text{warp}} \\
\varepsilon_{\text{fill}} \\
\varepsilon_{\text{wf}}
\end{bmatrix} =
\begin{bmatrix}
1 & \nu_{\text{wf}} & 0 \\
\frac{E_{\text{warp}}}{E_{\text{fill}}} & 1 & 0 \\
0 & 0 & \frac{1}{2G_{\text{wf}}}
\end{bmatrix}
\begin{bmatrix}
\sigma_{\text{warp}} \\
\sigma_{\text{fill}} \\
\sigma_{\text{wf}}
\end{bmatrix}
\tag{1}
\]

As biaxial tests aim to minimise the shear stresses introduced in the sample, the shear term is typically disregarded. Although the remaining equation contains four material parameters, these are not fully independent. Due to the conservation of energy, the compliance matrix for elastic materials must be symmetrical, which means that:

\[
\frac{\nu_{\text{fw}}}{E_{\text{fill}}} = \frac{\nu_{\text{wf}}}{E_{\text{warp}}} \tag{2}
\]

or:

\[
\frac{E_{\text{warp}}}{E_{\text{fill}}} = \frac{\nu_{\text{wf}}}{\nu_{\text{fw}}} \tag{3}
\]

The above, known as the “reciprocal relation”, effectively reduces the number of independent material constants to three. During this research, the impact of not enforcing this reciprocal relation during the process of deriving material constants has been investigated as well.

2.2.1. Selection of the data set

One of the very first steps when interpreting biaxial test data is selecting the data to be used during the regression analysis with the theoretical model. Aside from removing the permanent strain at the start of each load cycle as well as the stress-strain data obtained from the unloading cycles, we also consistently removed the very first load cycle of each group of a specific load ratio, provided more are present, to remove any residual effect of the previous load cycle and ratio.
The question which remains at this point is which experimental data points get selected to be used during the derivation of the material constants. Within this research, four different cases were considered:

1. All data points of all load ratios are considered.
2. Only the peak values of all load ratios are considered.
3. The peak values of subsequent and identical load ratios are averaged.
4. The peak value of all identical load ratios throughout the test are averaged.

2.2.2. Minimisation methodology

Once the data set is selected, the model’s constants can be fit to the experimental data through 2 methods: either by using the experimental strain as input data for the regression analysis and minimising the difference between the theoretical and experimental stresses (= “stress minimisation”) or by using the stress as input data and minimising the strains (= “strain minimisation”). Within the presented research both methods are compared.

2.2.3. Regression analysis method

Finally, two possible approaches to conduct the regression analysis were considered: minimisation of the sum of the squared differences (= “least-squares method”) or minimisation of the maximum error (= “best approximation” or “minimax method”). Both approaches are part of the MSAJ M-02-1995 guide, although a preference for the least squares method is expressed in this document. (Membrane Structures Association of Japan, 1995)

To summarise, we will be discussing the impact of a total of 5 parameters in this paper: (1) the applied load ratio, (2) the initial data selection, (3) stress minimisation vs. strain minimisation, (4) the regression analysis method and (5) the effect of not enforcing the reciprocal relation.

3. Results and discussion

3.1. Stress-strain results

Before proceeding to comparing the derived material constants, the normalised stress-strain results from the various tests were considered as a first comparison of the various load profiles (Figure 3).

At a first glance, these curves already clearly show a rather large variation amongst them, with strain variations of 1% at maximum load not being uncommon. In terms of relation between the obtained data and the load profiles, we do note that the profile as presented by the MSAJ M-02-1995 results in the least stiff response for most load ratios. In addition, the outcomes of the standard VUB profile and the EMPA-based load profile tend to lie close to each other whereas
both profiles containing the asymmetric prestress ratio tend to deviate from these results, most notably in case of a fill-dominant load ratio (1/2 and 1/5 ratios).

Figure 3: Comparing the direct stress-strain results already showed a fairly large variation when comparing the results obtained from the different load profiles. (Van Craenenbroeck, 2017)

3.2. Derived material constants

3.2.1. Impact of the load profiles

Summarising all material constants in two scatter plots, immediately shows the extent of the variation which exists on both the Young’s moduli and the Poisson’s coefficients (Figure 4). With stiffness variations of up to 300kN/m, the various alterations to the test and derivation method did have a very noticeable effect.

The most obvious factor in this is the application of different load profiles. Both scatter plots show clear groupings of material constants in function of the load profile. Following the observations made from the stress-strain curves, the MSAJ profile leads to low Young’s moduli in both fibre directions while the EMPA based profile and the standard VUB profile lead to
higher Young’s moduli. Both profiles with the asymmetric prestress load ratio show a more asymmetric set of stiffness constants where the warp stiffness is higher than the values observed from the other profiles. Also note the apparent lower consistency in the results of these two test profiles in function of the other adaptations as compared to e.g. the MSAJ or standard VUB profile.

![Figure 4: Separating the material constants in function of the applied load profile generates clear “clusters”. (Van Craenenbroeck, 2017)](image)

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#### 3.2.2. Impact of the data selection

For further investigation of the distribution of the obtained material constants in function of the different applied variations, the point cloud has been reinterpreted into box plots in function of each of the target variables. This allows us to better assess the impact each variation has on the material constants not only in terms of average value, but also in terms of its variability.

When representing the data this way for the four different data selections, no clear distinction can be made between the possibilities (Figure 5). Whether the data has been linearized, averaged or whether all intermediate data points were used didn’t seem to impact the overall outcome to a significant degree, or at least not within the scope of the existing variations due to the other variables.

#### 3.2.3. Impact of the minimisation and regression method.


Observing the different boxplots (Figure 6), shows clearly that the warp stiffness $E_{\text{warp}}$ is affected by the choice of minimisation method where strain minimisation leads to a slight increase where no such difference could be found for $E_{\text{fill}}$. Considering the Poisson coefficients however shows that utilising the minimax method instead of the least squares method not only increases the variability in the values for $\nu_{\text{wf}}$, but also has a slightly stronger tendency to result in more extreme
values for this parameter. It is thus recommended to use the least squares method for the regression analysis unless specific constraints prevent this.

![Figure 5: Comparing the constants in function of the selected data set did not reveal a clear impact. (Van Craenenbroeck, 2017)](image)

Figure 6: Whereas the choice between stress and strain minimisation affected mainly $E_{\text{warp}}$ (top left), the difference between the least squares and minimax regression analysis methods affected mainly the variation of $v_{\text{wf}}$ (Van Craenenbroeck, 2017)

3.2.4. Impact of the reciprocal constraint

As a final comparison, the impact of not enforcing the reciprocal constraint during the derivation of the material constants was investigated. Although the outcome of such analysis is physically meaningless as it violates the law of the conservation of energy, the difference between the sets on constants derived with and without application of the constraint can be a measure to how far the theoretical model deviates from the experimentally observed behaviour.
Returning to the scatter plot of the elastic constants (Figure 7), reveals that removing this constraint does not really have a notable impact on the Young’s moduli aside from a slight increase for $E_{\text{warp}}$ and decrease for $E_{\text{fill}}$. For the Poisson’s coefficients the effect is more drastic, resulting in a clear shift to the left for most results. This sudden decrease in the outcome for $\nu_{\text{wrf}}$ indicates that the experimentally observed fill strain is less affected by the stress in the warp direction than the linear elastic orthotropic model assumes. This discrepancy mainly comes from the non-uniform composition of the material and the geometrical displacements that take place within the weave, leading to a mechanical behaviour which seemingly violates the fundamental symmetry of the compliance matrix.

![Figure 7](image)

This rather significant difference in the outcome illustrates one of the main limitations of the linear-elastic orthotropic model when it is applied to coated textiles. The model’s simplicity does provide some clear advantages in terms of deriving its constants and implementing it in numerical software, but when it comes to properly characterising the complex straining behaviour of coated textiles more refined material models will yield more accurate results.

### 4. Conclusions and further research

This paper gave a short overview of how different approaches and decision can influence the outcome of biaxial tests in terms of the stress-strain curves as well as the derive linear-elastic orthotropic material constants. The impact of the applied load profile, selection of the data set for further analysis, minimisation and regression methods, and the removal of the reciprocal constraint during the derivation of material constants has been investigated.

As expected, the applied load profile lies at the cause of the biggest overall differences. The load profile as presented in MSAJ M-02-1995 results in a notably low set of Young’s moduli as compared to the other load profiles used in this research. Changing the applied prestress ratio from symmetric to an asymmetric warp-dominant stress resulted in an increase of the warp stiffness while at the same time decreasing consistency in function of the other variations.
Changing the data set which was extracted from the tests did not seem to impact the resulting material constants to any significant degree, or at least not within the scope of the other parameters that were investigated.

The difference between the stress and strain minimisation methods was however apparent with the latter leading to a small increase in the resulting warp stiffness $E_{\text{warp}}$. The other parameters did not seem to be affected by this. And although he choice in regression analysis did not seem to impact the actual values of the resulting parameters, using the best approximation/minimax method instead of the least squares method did result in a noticeable increase in the variability of $v_{\text{wf}}$ as well as a tendency to provide more “extreme” sets of material constants.

Finally, the impact of not forcefully imposing the reciprocal constraint during the derivation of material constants was investigated. Important to realise in this is that the derived material constants are physically meaningless but can be used as a measure to assess how much the observed behaviour deviates from the assumptions made by the linear-elastic model. Removing the constraint from the analysis did not seem to significantly affect the Young’s moduli aside from a small increase in the warp stiffness. A much more noticeable impact was the decrease of the Poisson’s coefficient $v_{\text{wf}}$. Considering the underlying equations, this shift suggests that the impact of the warp stress on the fill strain is much less than what the linear-elastic model suggests.

Although the presented research already allows us to draw certain parallels between specific decisions and assumptions applied during the process of biaxial testing of fabrics and deriving their material constants, the above is still relatively limited. Important causes of variations such as the influence of sample geometry and test bed design should be investigated on an international scale. Aside from merely establishing this variation, a method to cope with this material uncertainty should be developed to ensure a reliable design.

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