



## **Biaxial testing of fabric materials and deriving their material properties – A quantitative study**

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### **Abstract**

Fabrics have been used in tensile surface structures for over 50 years. Their unique properties, such as their high flexibility and low self-weight, make that these materials can be used in very efficient and architecturally unique constructions.

However, because these materials are constituted of woven fibres and different interacting layers, deriving their mechanical properties unambiguously has proven difficult. Current biaxial testing methodologies differ between institutes and much discussion exists as to how the obtained test results should be interpreted.

To quantify the impact of the used testing protocols on the obtained results as well as the method for deriving the elastic constants from said results, we tested fabrics following the method described in MSAJ M-02-1995 (Membrane Association of Japan [1]), one of the only official biaxial testing guides for fabric materials currently existing. By then changing the provided standard protocol, the direct impact on the test results could be quantified. Following these tests, material parameters were derived using various methods to show the impact of the used methodology in this step.

This paper describes the research conducted on a PVC coated polyester material (Sioen T2107), quantifying deviations in both the immediate test results and the derived material parameters. As a closing, the biaxial testing protocol is adapted to match the expected stresses in a prototype structure, after which the obtained material parameters are compared to the parameters obtained through the general testing protocols.

The results obtained from this research show a large impact when the standard protocol is replaced by a biaxial test protocol which mimics the expected stresses in a structure. And although the differences in the obtained results through variations on the standard protocol were not as big, the method for deriving the material parameters proved to have an important impact on the value of the obtained elastic constants.

**Keywords:** Biaxial testing, fabrics, material parameters, digital image correlation, tensile surface structures

## **1. Introduction**

### **2.1. Fabric structures and fabric behaviour**

Technical textiles have been used in engineering for over half a century and still enjoy a growing interest from engineers and architects alike. Their unique look, low self-weight (0.7 – 1.3 kg/m<sup>2</sup>) and general versatility in both form and function make that these structures stand out in the built environment. In these structures, the pretensioned fabric acts as both a load-bearing element (structural) as well as covering/cladding (functional) of the structure.

Using a flexible material in structures however, poses some challenges when it comes to designing and engineering these structures. Unlike regular steel or concrete structures, fabric structures possess a strong interaction between boundary conditions, form and load-bearing behaviour. The initial shape of the structure has to be designed, and is a direct result of the imposed boundary conditions and the applied prestress, and this shape afterwards influences the load-bearing behaviour. This makes designing tensile surface structures and iterative process where different interacting parameters have to be matched to each other to come to an optimal structure (Lewis W. J. [2]).

The fabric as a material by itself also has some unique qualities and behaviour. Due to its composition it has a strong non-linear behaviour which is still an important subject of various studies. A typical technical textile consists of fibres which are woven in two orthogonal directions, often referred to as respectively the warp and the fill (or weft) direction. This weave is then coated by one, or multiple, layers of plastics to give it a higher resistance to, amongst others, water, dirt and UV radiation. It is this complex composition of layers and fibres which gives the fabric its complex behaviour, not unlike similar composite materials.

It is this complexity in material behaviour that has led to a multitude of approximations in computer models, ranging from a relatively simple linear elastic orthotropic material model, to more extensive models like custom programmed elasto-plastic models (Dihn T. D. *et al.* [3]), each demanding their own specific input of material properties which have to be determined experimentally. All these different methodologies in determining material parameters as well as the different software approaches make that there currently are still a lot of differences between different design tools used for fabric structures (Gosling P. D. *et al.* [4]).

### **2.2. Testing fabrics**

When it comes to testing fabric materials and deriving their parameters, methods tend to differ from institute to institute. And although it is generally recommended to at least conduct a biaxial tensile test, a general code describing how these tests should be conducted is currently non-existent and guidelines tend to be interpreted in different ways, leading to vastly different testing methodologies amongst laboratories (Gosling P. D. and Bridgens B. N. [5]; Ambroziak A. and Klosowski P. [6]; Galliot C. and Luchsinger R. H. [7]). Currently, only one code exists, namely the Japanese code MSAJ M-02-1995 (Membrane Association of Japan [1]), which is often regarded as a starting point when testing fabrics. It describes a general lay-out when dealing with biaxial testing and imposes some values when it comes to sample dimensions and imposed loads. Dating back 20 years however, this code can currently be regarded as dated somehow and many discussions exist concerning the decisions made in this document, again leading to different adaptations of this code (Gosling P. D. and

Bridgens B. N. [5]; Ambroziak A. and Klosowski P. [6]; Galliot C. and Luchsinger R. H. [7]), making the existence of this code currently overshooting its goal.

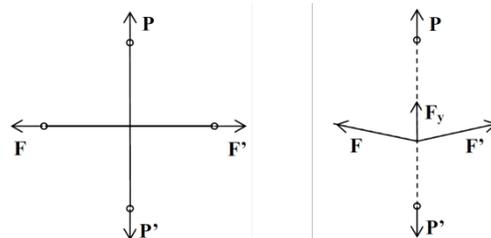
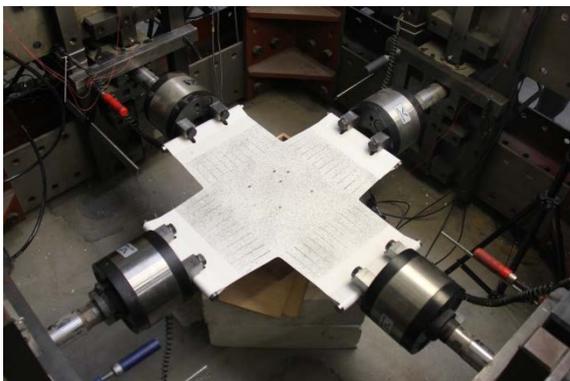
But how big are the differences between different adaptations really? And do they in fact influence the design of a full scale structure? These were the questions that came up when reviewing the existing methods and ongoing discussions regarding testing of fabric structures. This paper describes the result of testing the same type of fabric using four different protocols. Global material parameters were derived using two of the methods described in MSAJ M-02-1995. The biaxial stress-strain data, as well as the derived material parameters are compared to each other, so that variations resulting from different protocols could be quantified.

## 2. Test Methodology

### 2.1. Experimental setup and protocols

#### 2.1.1. Biaxial setup

The biaxial bench used for the experiments was constructed at the Vrije Universiteit Brussel and consists of four independent movable hydraulic rams, each of them equipped with a 100kN load cell (Instron 2518-111).



**Figure 1: The biaxial test bench used at the VUB (left) uses a control mechanism which monitors load differences between opposing load cells and adapts displacements accordingly to keep the loads symmetrical (right).**

When conducting symmetric biaxial testing, the control mechanism monitors the difference between the two opposing cells and tries to keep the opposing loads balanced by increasing/decreasing the displacement of the appropriate cell. This however means that this bench cannot test samples at very low load situations, since this control mechanism fails when the applied load becomes lower than the reliable measurement of the load cells. For this setup we found that the applied load should be higher than 0.4kN for the control mechanism to work fully reliable.

During the biaxial test, loading and displacement data is directly read out from the load cells. In order to measure the strains in the fabric, a stereoscopic Digital Image Correlation (DIC) system is hung

above the bench. This three dimensional optical measurement setup consisted of two AVT Stingray F-504 digital cameras, with a CCD resolution of 2452 x 2056 pixels (Stingray F-504 [8]), each equipped with a Schneider-Kreuznach Cinegon 1.4/12mm C-mount optical lens (Jos. Schneider Optische Werke Kreuznach [9]). Using this measuring technique rather than deriving strains based on displacements and/or localised strain gauges allowed for accurate measurements in all parts of the sample.

The samples used in this study were fabricated from a Sioen T2107 polyester-PVC fabric material. This fabric has a rated tensile strength by Sioen of 80kN/m and weighs 1050 g/m<sup>2</sup>. All samples were cut from the same material batch to evade variations in the results which can exist when comparing different batches of the same material. The cruciform specimens have a central area of 300mm by 300mm, with 15mm wide and 100mm long slits in the arms, limiting the reduction factor for these samples to 95%. The sample is connected to the load cells by a high frequency welded loop which goes around a steel bar connected to the load cell.

### 2.1.2. Description of the used protocols

During this experiment, we focused on four different protocols. Each protocol was used on two independent samples, resulting in a total of eight different test results. These results were then further processed and the final result described for each protocol is an average of both tests.

The first protocol is the variation of the test protocol described in MSAJ M-02-1995 (Membrane Association of Japan [1]). An important difference between this protocol and the one suggested in MSAJ M-02-1995 is the 30min period at the beginning where a prestress of 2.5% of the tensile strength is held, allowing the fabric to settle before the loading cycles are applied. We also extended the single 1:1 (warp:weft) load ratio between each load ratio to consist out of three cycles as well as replace the 1:0 and the 0:1 ratio by respectively 5:1 and 1:5. Like MSAJ M-02-1995, the loads cycle between a minimum of 2.5% UTS (2kN/m) and 25% UTS (20kN/m).

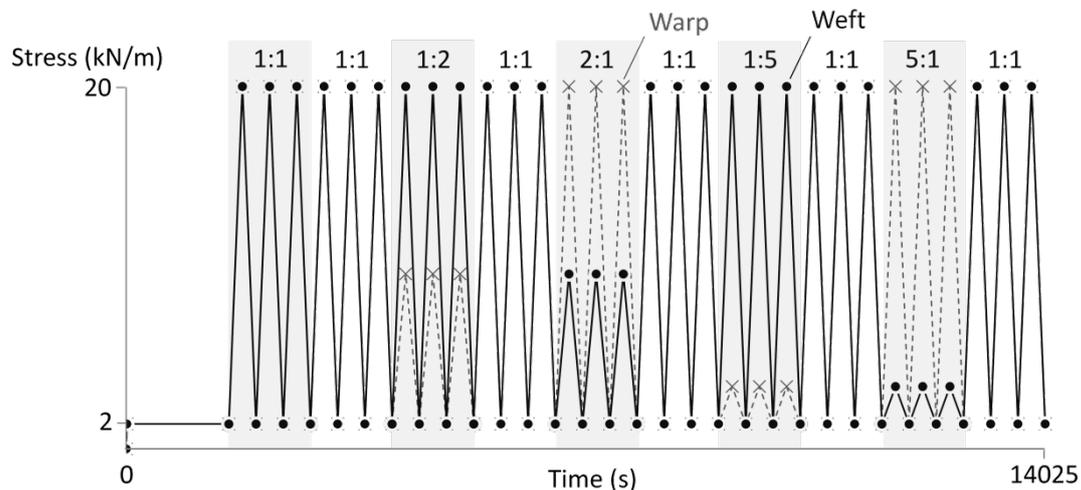
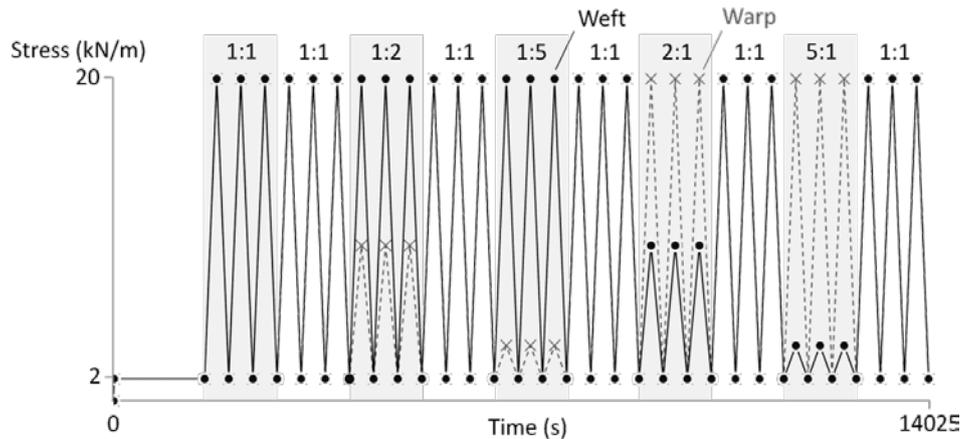


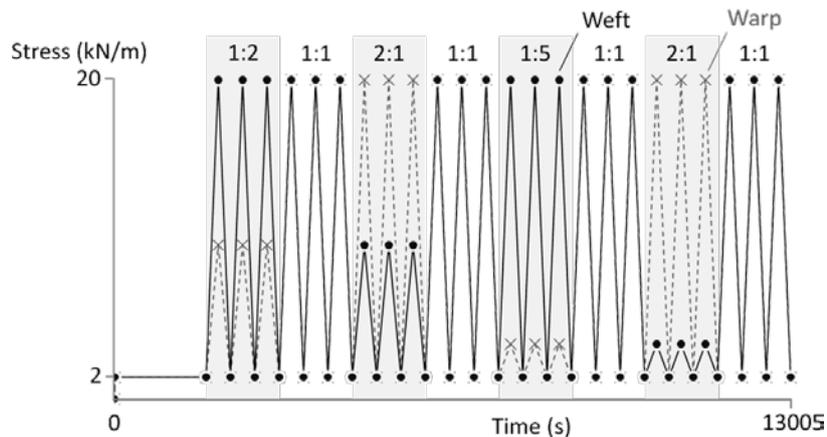
Figure 2: This variation on the protocol described by MSAJ M-02-1995 is used as the “default” protocol throughout the experiments.

As a first variation (= “variation 1”) on the default protocol, the order of the load ratios was altered. By default, each ratio is followed by its inverse, separated from each other by a 1:1 ratio. For instance, in the first protocol, the 1:2 ratio is followed by a 1:1 ratio and then by its inverse 2:1 ratio. In this variation we clustered the ratios so that one direction is fully loaded consistently and then the other direction. Note that this is the only difference between these protocols, so all intermediate 1:1 ratios remain unchanged (Figure 3).



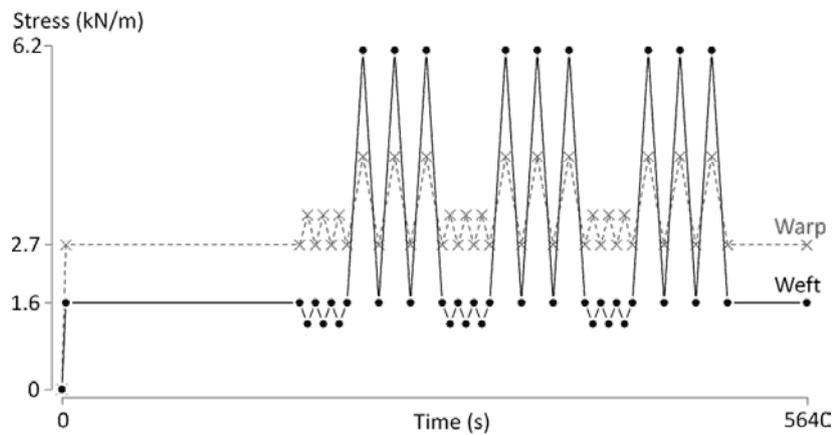
**Figure 3: As a first variation, the order of the load ratios was switched around (= “variation 1”).**

As a second variation (= “variation 2”), the starting ratio was altered. Now, instead of starting with a more neutral 1:1 ratio, the first load ratio the fabric experiences is a 1:2. Since this first loading incorporates the initial deformation, and knowing that the load history can influence a fabric’s behaviour, rearranging the initial protocol this way might lead to a different outcome in material parameters.



**Figure 4: The second variation consisted of a protocol which starts with a 1:2 load ratio rather than a 1:1 ratio (= “variation 2”).**

Finally, a test protocol was conceived which differed completely from the previous ones. Instead of taking the MSAJ M-02-1995 as a start, this test mimics predicted stresses occurring in a real structure, derived by the computational model of said structure (= “custom protocol”). The protocol used for this step is based on a foldable fabric structure, where stresses vary due to the structure folding and unfolding (Mollaert M. *et al.* [10]). This also results in stresses in warp and weft direction which do not necessarily correspond to a predefined load ratio.



**Figure 5: As a last protocol, predicted stresses were derived from a computational model and applied to a test sample (= “custom protocol”).**

### 2.1.3. Derivation of the material properties

From the stress-strain data obtained by the various biaxial tests, linear-elastic orthotropic material parameters ( $E_x$ ,  $E_y$ ,  $\nu_x$  and  $\nu_y$ ) were derived. This has been done according to the least-squares method described in MSAJ M-02-1995, both minimising the stress term and minimising the strain term (Membrane Association of Japan [1]).

When minimising the stress term, the following equations are assumed:

$$\begin{bmatrix} N_x \\ N_y \end{bmatrix} = \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \end{bmatrix} \quad (1)$$

$$\frac{E_x}{E_y} = \frac{\nu_x}{\nu_y} \quad (2)$$

Where:

$$E_{11} = \frac{E_x}{\nu} \quad (3)$$

$$E_{22} = \frac{E_y}{\nu} \quad (4)$$

$$E_{12} = E_{21} = \frac{\nu_y E_x}{\nu} = \frac{\nu_x E_y}{\nu} \quad (5)$$

$$\nu = 1 - \nu_x \nu_y \quad (6)$$

Note here that combining equations (1) and (2) results in a system of equations containing two equations and three unknowns. In order to solve this system, at least two different load ratios are required, making the system over-determined since each load ratio results in two equations according to equation (1), which is where the least-squares approximation comes in. For this research, material parameters were derived taking into account all tested load ratios, apart from the first cycle of each ratio in order to discard both the permanent straining of the fabric and the hysteresis going from one load ratio to the next. The remaining two load cycles for each ratio are then averaged and the result entered into the system of equations above.

Minimising the strain term, a similar set of equations is used but here the stress-strain relation has been inverted, resulting in the following system of equations:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \end{bmatrix} = \begin{bmatrix} E_{11} & -E_{12} \\ -E_{21} & E_{22} \end{bmatrix} \cdot \begin{bmatrix} N_x \\ N_y \end{bmatrix} \quad (7)$$

$$\frac{E_x}{E_y} = \frac{\nu_x}{\nu_y} \quad (8)$$

Where:

$$E_{11} = \frac{1}{E_x} \quad (9)$$

$$E_{22} = \frac{1}{E_y} \quad (10)$$

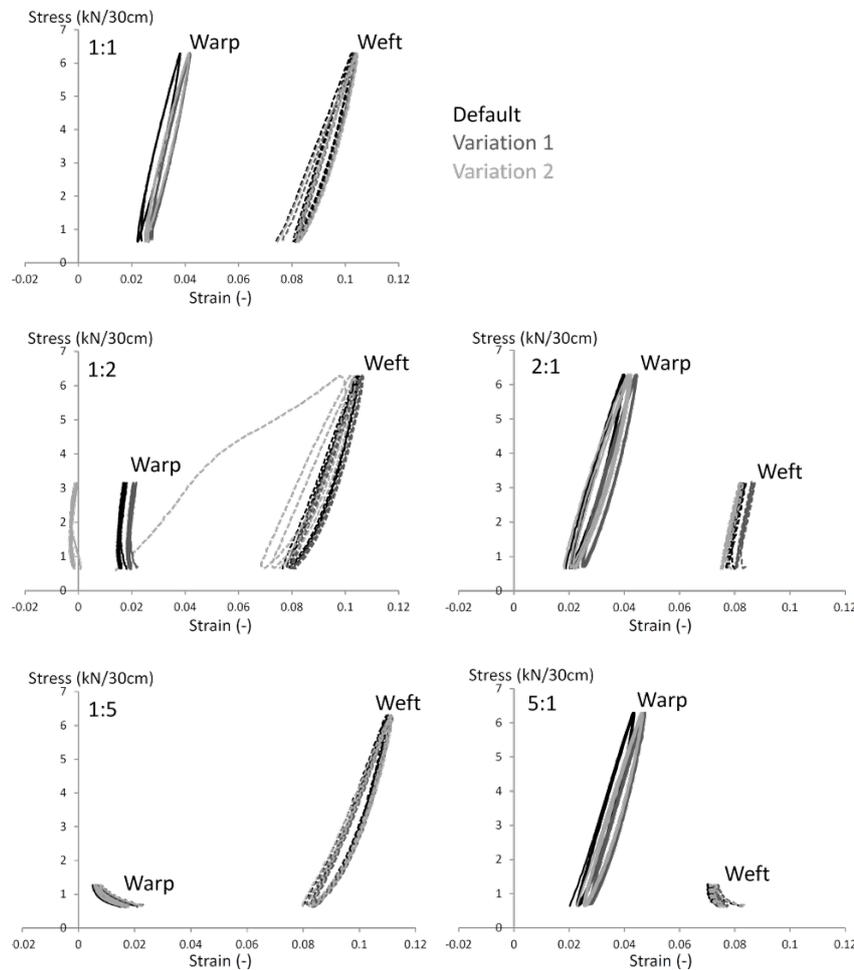
$$E_{12} = E_{21} = \frac{\nu_x}{E_x} = \frac{\nu_y}{E_y} \quad (11)$$

### 3. Results and Discussion

#### 3.1. Biaxial test results

##### 3.1.1. Stress strain data

When dealing with biaxial data, there are several ways to interpret the data such as a time-strain diagram or a global stress-strain graph. Since we're looking for differences in the resulting data, the first three experiments are presented as stress-strain diagrams per load ratio. Since there are multiple 1:1 ratios, the figure below only shows the measurement taken during the last 1:1 cycles (Figure 6).



**Figure 6: In general, different variations on the protocol show only small differences in stress-strain behaviour, except when the initial load ratio is changed which shows a significantly different result for the 1:2 load ratio.**

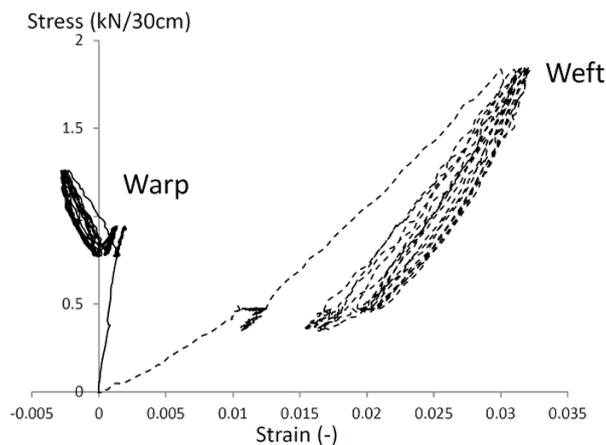
The above results show that in most cases, the direct stress-result does not change significantly when the protocol is changed, except for the 1:2 ratio for variation 2. Since this variation has this specific ratio as starting ratio, the result will be partially determined by the initial deformation. However, although the weft direction more or less settles in the area where the other protocols find themselves after the initial deformation, the warp direction remains less strained than is the case with the other two protocols for all three load cycles. This indicates the importance of the 1:1 ratios between the different load ratios in normalising the strain state of the fabric. It however poses the question as to how well regular (thus starting with a 1:1 ratio) test results approximate the material behaviour when dealing with a structure with an asymmetric prestress (e.g. conical shapes).

The fourth test that was conducted addresses this very question to a degree. Instead of using a general protocol to determine the global material properties, we designed a structure-specific protocol which mimics the stress behaviour predicted by the computational model of a structure. In this case, the protocol mimics the computationally predicted stress variations which occur in a kinematic fabric structure when it is opened and closed (Figure 7).



**Figure 7: The fourth protocol uses the predicted stress variations occurring while opening and closing the foldable kinematic fabric structure.**

The resulting stress-strain diagram (Figure 8) shows significantly lower stresses than the general protocols impose. This is mainly due to the lack of external loads apart from the kinematic deployment, but showed the importance of the actual load value (see 3.1.2.). The behaviour is also very asymmetric comparing both yarn directions due to the lack of a well defined load ratio as is the case with the more general protocols. Due to the highly asymmetric stress conditions, and the crimp interchange, warp strains tend to be negative while weft strains are positive. Based on this diagram, we can already estimate that this will most likely result in very asymmetric material parameters and relatively high Poisson's coefficients.



**Figure 8: Mimicking the structural response of a foldable fabric structure results in much lower stresses and a highly asymmetric response between yarn directions.**

### 3.1.2. Derived material parameters

For each of the described protocols, orthotropic elastic constants were derived using the least squares method described in MSAJ M-02-1995. Both stress minimisation and strain minimisation were carried out to verify the inherent differences due to the slightly different approach. In practice, we will usually take the average of these two approaches as the final resulting material parameters to be used in the computational model(s).

	Default protocol		Variation 1		Variation 2		Custom protocol	
	Stress min.	Strain min.	Stress min.	Strain min.	Stress min.	Strain min.	Stress min.	Strain min.
<b>Ex (kN/m)</b>	819.1	753.3	833.5	767.4	770.7	706.5	1536.5	1314.9
<b>Ey (kN/m)</b>	651.4	641.3	663.1	652.9	589.7	584.1	357.9	326.1
<b>vx (-)</b>	0.366	0.368	0.372	0.375	0.378	0.379	1.130	1.020
<b>vy (-)</b>	0.317	0.288	0.321	0.294	0.316	0.287	0.270	0.255

**Table 1: For each protocol a set of material parameters was derived by using a global least squares approximation.**

Looking at the results above (Table 1), we can see that for the three variations, differences in the global parameters are rather limited. Between the different protocols, a maximum difference of around 60kN/m can be noted in the Young's modulus and differences in Poisson's ratios are limited to 0.01. Comparing stress minimisation to strain minimisation for the first three test procedures shows similar variations. However, keeping in mind that these values are already averaged values for similar tests using these protocols, there still is a consistent difference, with an order of magnitude corresponding to the variation occurring when taking another minimisation technique, when changing the protocol even slightly.

Comparing the first three protocols with the custom protocol however, shows very significant differences in both the elastic moduli and the Poisson ratios. While  $E_x$ , the warp stiffness, increases by at least 500kN/m,  $E_y$  decreases with 200kN/m. This is most likely due to the significant lower maximum stress. As expected from the stress-strain diagram, a highly asymmetric behaviour is displayed through the material parameters: both the elastic moduli as well as the Poisson coefficients differ with a factor five comparing yarn directions.

## 4. Conclusions

The conducted comparative biaxial testing shows that there can be a significant impact on material parameters when changing the used test protocol. Factors, such as load ratio order and maximum load value, can in fact change the outcome of the biaxial test.

These differences might however not always be relevant when using them in a computational model. Going further into depth and applying the resulting material parameters on different computational models using various material models and applying different load cases, will show the impact these differences will have on the actual design process and its dependency on the material model used.

Further comparative biaxial tests will also study other variables such as the impact of the intermittent 1:1 load ratios and look more in depth at the effect that the highest/lowest applied load has on the calculated material parameters. Next to these tests, a comparative study is ongoing comparing biaxial results from different institutions on the same material.

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