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Strength parameters of polyester reinforced PVC coated fabric after short term creep loading in biaxial mode

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ABSTRACT: This study addresses the analysis of tensile strength parameters of the technical fabric VALMEX, which is composed of two orthogonal polyester thread families (named the warp and fill) and both sides PVC coated. The material was firstly subjected to 48-hour biaxial creep loading with the equal stress level in both orthogonal directions of the fabric. The stress levels were established as follows: 4.6 kN/m, 10.4 kN/m, 16.4 kN/m, 22.4 kN/m, 28.4 kN/m, 34.4 kN/m. The samples after creep loading were left unloaded in laboratory conditions for the subsequent 6 months and then subjected to biaxial tension till rupture. For all tests, the basic tensile properties of the fabric have been identified for the warp and weft directions separately. The evolution of parameters demonstrates how the level of biaxial material prestressing affects tensile strength properties of the VALMEX fabric.

1 INTRODUCTION

1.1 *Architectural fabrics*

Architectural fabrics (also known as technical fabrics or coated textile membranes) are one of the most impressive and challenging building materials. The high strength, low dead weight, simple production (prefabrication), low construction costs (usually without formworks or decks) are the crucial advantages of the membrane structures (Kazakiewicz MI, Miełaszwili JK 1988) Two structural models are possible to implement architectural fabrics (Stanuszek M 2002): the air-supported structures (Fig. 1) and the tensile cable-membrane structures (Fig. 1).

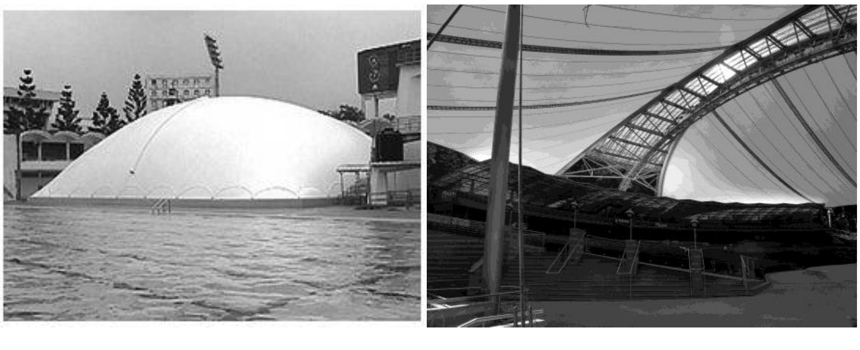

Figure 1 Examples of architectural fabrics applications: air supported structure - Air dome, China (left), tensile cable-membrane structure - Forest Opera, Poland (right).

They are often assembled in the form of wall coverings or roof structures over large size public gathering places, e.g. sport stadiums, entertainment halls, open-air theatres, shopping malls, communication terminals, pavilions and in smaller cubature buildings, like car parks, temporary shelters or decorative objects. They give designers almost endless possibilities to form canopies of different shapes.

The so called “hanging roofs” are characterized by geometric non-linearity, which is manifested by change of the covering original configuration under an applied load. Shape reconfiguration is accompanied by the redistribution of acting forces and occurrence of wrinkles. To overcome this problem the form finding analysis must be performed and the initial tensioned configuration of the canopy established (Bridgens and Birchall 2012). In order to assure proper conditions of the tensioned canopy in a long time domain, it is necessary to regard the viscoelastic behavior of the technical fabrics and the global structural dynamics, due to its sensitivity to wind load.

1.2 *Composite nature of architectural fabrics*

The structure of standard architectural fabric is presented in Figure 2. The reinforcing fiber yarns are responsible for material tensile strength, while exterior coating protects yarns from damage, stabilizes weave structure, as well as provides water resistance and shear stiffness. The reinforcement base can be manufactured in two variants, resulting in woven or knitted fabrics. Typical weave patterns include plain, 2/2 twill, leno, mock leno, panama, 4H satin and 8H satin, while knitting patterns contain mainly the warp-knit fill inserted method and raschel knit (Air, Tent & Tensile Structures, Fabric Specifier’s Guide, Fabric Architecture 2013).

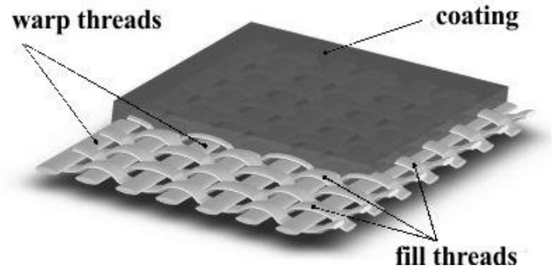

Figure 2 Composite structure of plain weave architectural fabric.

The geometric non-linearity of the twisted fiber structure, complex interactions of orthogonal yarns under the bi-axial in plane stress state (friction, crimp interchange, locking effect) and influence of coating lead to the time-dependent, hysteretic and anisotropic material behavior of technical fabrics (Allaoui et al. 2012; Boisse et al. 2001).

During prefabrication the threads in one or two major directions (called commonly the warp and fill direction) are prestressed, while covering (e.g. PVC layer) is placed on the reinforcement base. Next, during the membrane structure assembly, the architectural fabrics must be pretensioned to a given level to guarantee stress equilibrium in the material prior to loading. The level of prestress seems to have impact on the material behavior. The problem becomes more complex, when the biaxial character of stress distribution in the fabric is taken into account. Some studies were realized to evaluate the behavior of textile composites under biaxial cyclic loading (Ambroziak and Kłosowski 2014b; Ambroziak 2015b; Ambroziak 2015a), in high and low temperatures (Ambroziak and Kłosowski 2014a) and after natural and laboratory ageing (Zerdzicki, Klosowski, and Woznica 2018). This study aims to analyze the influence of the biaxial prestressing of the ready-to-use material on the basic tensile properties of the polyester reinforced PVC coated VALMEX fabric.

2 EXPERIMENTS

2.1 *Samples and laboratory equipment*

The technical fabric VALMEX FR 1000 was examined in this research. It is a polyester reinforced PVC-coated fabric with the P 2/2 weave pattern, which means that two threads always go together composing orthogonal reinforcing mat with the major anisotropic directions approximately parallel with the warp and fill of the material. The warp direction threads are straight, while the fill direction threads are interspersed through them (also going in pairs). The producer's specification of the VALMEX FR 1000 is summarized in Table 1.

Table 1. Basic information of the VALMEX FR 1000 technical fabric (Mehler Texnologies 2010).

Trade name	VALMEX FR 1000 MEHATOP F - type III
Total weight	1050 g/m^2
Tensile strength (warp/fill)	120 / 110 kN/m*
Base fabric material	PES
Base fabric yarn count	1670 dtex
Base fabric weave type	P 2/2 (Panama 2/2)
Type of coating	PVC
Type of finish layer	PVDF-lacquer on both sides

*thickness material is usually not established for technical fabrics (Bridgens and Birchall 2012; Ambroziak 2015b), therefore all mechanical characteristics in this paper are defined for the unitary thickness e.g. kN/m^2 * m = kN/m.

All laboratory tests were realized on the Zwick biaxial testing machine with data registration obtained by the video extensometer following four markers on the samples surface (Fig. 3). The samples had a shape of cross, with directions of orthogonal arms coincided with the warp and fill material directions. The sample arm width was 10 cm and the total length of the cross arm was 40 cm. The markers were set in the middle of the cross (gauge length about 40 mm in both directions), in the anticipated biaxial stress location.

Figure 3 Biaxial testing machine with cross-shaped sample during test.

2.2 *Testing protocol*

The working stress usually ranges between 0.1 and 0.2 of the uniaxial strength in particular fabrics direction, depending on the fabrics' surface curvature and weave pattern (Heidrun Bogner-Baltz 2009). Taking 5 as the safety factor, the prestress would be five times lower than the working stress. Thus, taking the data from Table 1, it was calculated that the prestress should be 120 kN/m /5/5 = 4.8 kN/m and 110 kN/m /5/5 = 4.4 kN/m, for the warp and fill directions, respectively. The identical for both directions prestress value of 4.6 kN/m was finally taken for further analysis as the first prestress level. The following subsequent prestress levels were: 10.4 kN/m, 16.4 kN/m, 22.4 kN/m, 28.4 kN/m and 34.4 kN/m. It is seen, that most of the loading levels are below the working stress level, only cases of 28.4 and 33.4 kN/m exceed the working stress level and are beyond elastic region of stress-strain relation for both directions. The prestress was performed in the form of creep loading of 48 hours duration with the constant force control, executed on the Zwick biaxial testing machine. After the creep, the samples were unloaded and left in the laboratory, at room temperature for the subsequent six months. Then, the samples were tensioned to rupture with the constant force increase of 20 N/s in both orthogonal directions using the same Zwick biaxial testing machine and the video-extensometer. For each prestress level at least three samples were tested and the presented results were calculated always as the mean value obtained from all the tests performed.

3 ANALYSIS OF THE TENSILE STRENGTH PROPERTIES

The demonstrative stress-strain curves for the uniaxial and biaxial tensile tests (force increase of 20 N/s till rupture) are presented in Figure 4a. Comparing the obtained outcomes, it is clearly seen, that the biaxial loading resulted in lowering the uniaxial ultimate tensile strength (*UTS*) for both material directions significantly. For the warp direction case it dropped from 110 kN/m (uniaxial) to about 76 kN/m (biaxial), and for the fill one from 90 kN/m (uniaxial) to 76 kN/m (biaxial). The obtained uniaxial results are lower than the ones stated by the producer (see Table 1) that can be a result of different experimental protocol.

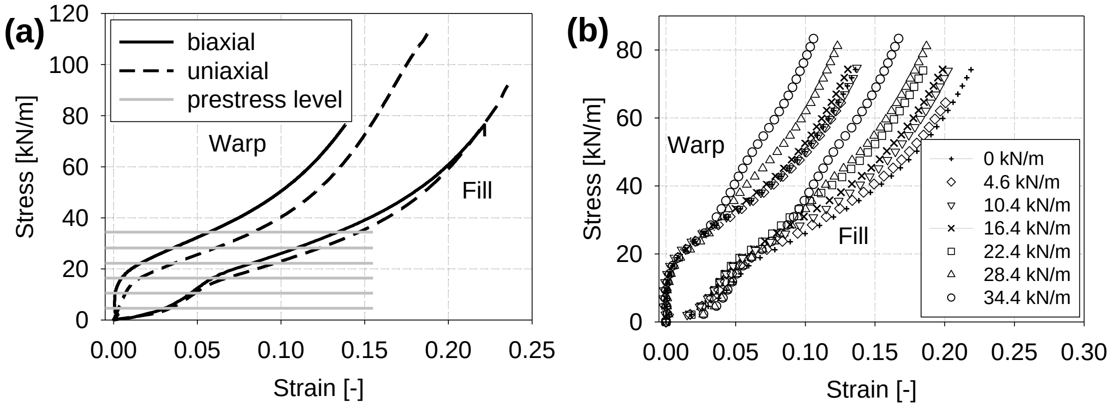

Figure 4. The uniaxial and biaxial results of tension till rupture of the VALMEX fabric. Gray lines indicate the prestress levels tested in the study (a); Comparison of the tension till rupture stress-strain curves for samples with different prestress levels (b).

Another remark concerns the curves' trajectories. For the warp direction we can distinguish three, and for the fill direction four particular ranges, where the stress-strain relation is almost linear. It has been confirmed before that for the same material type and producer, for the warp direction the tangent of the line found in the first strain range 0 – 0.01 is related to the Young's modulus of the material (Klosowski, Zerdzicki, and Woznica 2017). For the fill direction, the line found in the strain range 0 – 0.03 is related to the stiffness of the PVC covering, while in the strain range 0.03-0.06 the Young's modulus for the fill direction can be evaluated. However, for accurate identification of the elasticity moduli, the cyclic load-unload tests are necessary.

The illustrative stress-strain curves for biaxial tensile tests till rupture, for different prestress levels, for the warp and fill directions of the VALMEX fabric, are presented in Figure 4b. It can be observed, that increase of the prestress level resulted in stiffening of the material in both directions, while the curve shapes remain similar to each other. Only the highest prestress level of about 33.4 kN/m resulted in different stress-strain curve above the stress of 30 kN/m, which is fortunately far above the working stress 22-24 kN/m, which is an acceptable limit in real membrane structures. Figure 5a shows that the *UTS* for the warp and fill directions are similar (about 76 kN/m), regardless of the prestress level.

It could be concluded, that biaxial loading used in this research uniformed the *UTS* values for both directions to the comparable level. On the other hand, the elongation at break (ε_{ult}) found for biaxial tests decrease for both material directions with the prestress level increasing (Fig. 5b). The evolution of ε_{ult} and *UTS* values over prestress level can be described by linear functions of satisfactory high determination coefficients between the fitted lines and the obtained results, independently for the warp and fill directions of the VALMEX fabric (Fig. 5a, b). The established equations can be used for calculating the ε_{ult} and *UTS* for different prestress levels limited by the 33.4 kN/m value, for the warp and fill directions separately. The ratio between elongation at break for the fill direction ($\varepsilon_{\text{ult-FILL}}$) and the warp direction ($\varepsilon_{\text{ult-WARP}}$) is constant throughout different prestress levels and approximately equals $\varepsilon_{\text{ult-FILL}} / \varepsilon_{\text{ult-WARP}} = 1.5$.

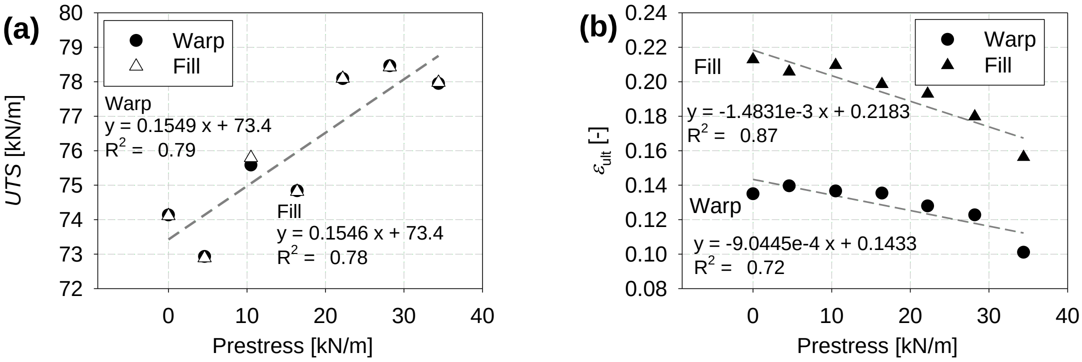

Figure 5. Ultimate tensile strength *UTS* (a) and elongation at break ε_{ult} (b) for different prestress levels, for the warp and fill directions of the VALMEX fabric.

In order to calculate the elasticity moduli for the technical fabrics the cyclic load-unload tests are necessary, but not provided in the current research. Therefore, to highlight the influence of biaxial prestress on tensile properties of the VALMEX fabric, an alternative approach was introduced. The strain values corresponding to the working stress (24 kN/m and 22 kN/m for the warp and fill directions, respectively) and to the half of the working stress (12 kN/m and 11 kN/m for the warp and fill directions, respectively) were found for different prestress levels. The obtained results are plotted in Figure 6a and Figure 6b, for the warp and fill directions, respectively. The values of the achieved strains for different prestress levels always oscillate in the strain range of 1% not composing any particular, clear tendency (for instance low determination coefficient of the fitted straight lines). This observation stays true for the warp and fill directions of the fabric and for working stress level and its half. It could be an evidence that the prestress level does not affect the elongation level when considering the stress range below working stress. However, for confirmation of this conclusion, the analysis of the cyclic load-unload tests is suggested and it will be performed at the next research stage concerning the same fabric.

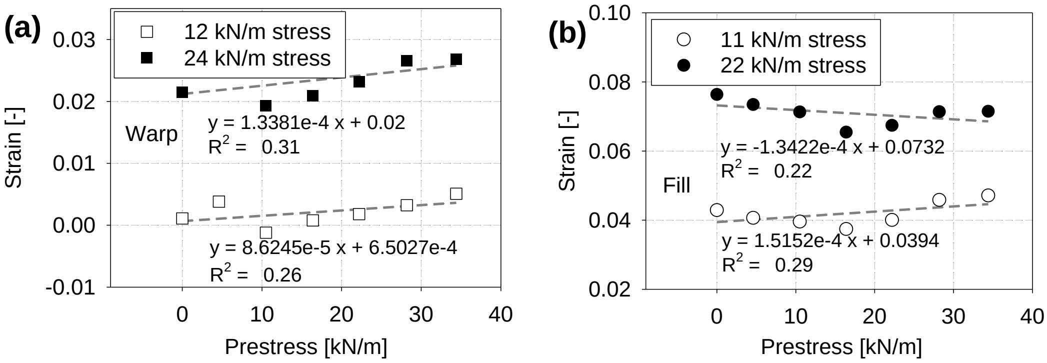

Figure 6. Strains at the working stress and for half of the working stress level for the warp (a) and fill (b) directions of the VALMEX fabric.

4 CONCLUSIONS

In the presented study of the tensile strength properties of the VALMEX fabric, the biaxial prestressing of the levels 4.6 kN/m, 10.4 kN/m, 16.4 kN/m, 22.4 kN/m, 28.4 kN/m, 34.4 kN/m.

(equal in both orthogonal material directions) was realized as the creep loading of 48 hours duration. Firstly, it was observed that the biaxial results, when compared with the uniaxial outcomes, led to reduction and uniforming of the ultimate tensile strength (*UTS*) for the warp and fill directions of the fabric. Next, taking into account the prestress influence, it was witnessed that the greater the prestress level was, the lower the elongation at break (ε_{ult}) and greater the *UTS* were. The material stiffness raised up with the prestress increment. Additionally, the variations of ε_{ult} and *UTS* with the prestress levels can be easily described by linear functions providing a methodology to interpolate these values for another prestress levels. However, it seems that the biaxial prestress proposed in this research did not affect the material parameters below the working stress level, equals 24 kN/m and 22 kN/m for the warp and fill directions, respectively. Nonetheless, the cyclic load-unload tests are suggested to confirm the observed behavior of the VALMEX fabric.

The overall conclusion is that when designing the structure made of technical fabrics, the biaxial tests results should always be taken into account, as the biaxial loading mode influences the material behavior significantly compared to the uniaxial loading mode. This impact differs due to various material types and woven/knitted techniques used for particular fabric manufacture and therefore should always be tested and analyzed for every fabric material considered for structural application.

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