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# MECHANICAL PROPERTIES OF TECHNICAL COATED FABRICS UNDER AXIAL AND OFF-AXIAL TENSILE TESTS

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**Key words:** technical coated fabrics, membrane structures, laboratory tests, numerical simulation, digital image correlation

**Summary.** In the paper, laboratory tests carried out by the authors with axial (0° - warp, 90° - weft) and off-axial (15°, 30°, 45°, 60°, 75°) tensile and also with biaxial tensile with shear with different load ratios are described. The purpose of the research was to determine the mechanical properties of material used at numerical simulations of membrane structures. Two different types of a technical coated fabrics used in the experiments - with and without Precontraint® technology. To measure the displacement and strain fields on the surface of specimens, the method of digital image correlation has been used. Numerical simulation of technical coated fabrics, imitating carried-out laboratory tests, has been executed with using of software program Ansys Workbench. It is revealed owing to analysis of results of numerical simulations that shear stresses make a significant contribution to the stress-strain state of material in off-axial and biaxial tensile with shear. The possibility of applying several classical criteria for fracture strength of composite materials in order to predict and evaluate the behavior of technical coated fabrics under load is shown.

## Introduction

Technical coated fabrics (further in the text – TCF) are used in membrane structures. From pneumojacks to inflatable rubber dams (figure 1), from tanks to rescue equipment, from coating roofs of large-span structures to air-supported structures (figure 2), from pneumatic formwork to aqua parks, from aerostats and airships to inflatable structures of furniture and advertising, etc. – some areas where membrane structures made of TCF are used.

Figure 1. Inflatable rubber dam

Figure 2. Air-supported structures («The Verde Dickey Dome»)

Increasing number of buildings and structures made from TCF around the world, and also in Russia (for example, the form of coating roofs on a metal frame for two stadiums for the 2018 FIFA World Cup) requires detailed research of the behavior of the material taking into account its complex stress-strain state (further in the text - SSS).

The purpose of the research was to determine the mechanical properties of TCF used at numerical modelling of membrane structures. Also, it was important to establish necessary and sufficient number of laboratory tests in order to predict complex SSS of TCF at numerical modelling of material in tensile structures.

Laboratory tests under axial uniaxial and biaxial tensile until recently were considered the main tests for the research of the mechanical properties of the material used in the modelling of TCF and the estimation of the SSS of the material in the membrane structures. As noted in many modern researches, for example in[1], usually in analysis of tensile structures made from TCF, the shear modulus of the material is neglected. According some normative documents, in particular in the American standard[2], shear stresses in a material are usually small compared to normal tensile stresses, and for simplicity of calculation the influence of the shear modulus can be neglected. In many works, the modelling of TCF and principal verification of strength are carried out without taking into account the shear modulus, neglecting shear stresses, which in some cases leads to an overestimated strength of the material.

Recent reports have shown the importance of taking into account the shear modulus in the design of membrane structures made from TCF[3–8]. In work[3] it is said that the shear modulus of the material essentially affects the SSS tensile structures. For example, in inflatable beams or "Tensairity" type structures in which large shear deformations occur, taking into account the shear modulus contributes significantly to the accuracy of the structural behavior evaluation under load. Therefore, the research of the mechanical properties of the material, based only on the results of uniaxial and biaxial axial tensile tests, is not always sufficient for modelling a TCF in membrane structures. This is due both to the complex structure of the composite material and the features of the SSS of tensile structures.

Usually, the shear modulus is determined in the "pure shear" tests. This type of laboratory testing of TCF is researched well enough in the following works[8–15]. In work[5], the possibility of determining the shear modulus from the test data under uniaxial off-axial tensile is shown. However, the material is assumed to be linearly elastic, which is only valid after applying several load cycles and in the range up to 20% of the ultimate tensile strength (further in the text - UTS).

## Laboratory tests

In the paper, laboratory tests carried out by the authors with axial (0° - warp, 90° - weft) and off-axial (15°, 30°, 45°, 60°, 75°) tensile and also with biaxial tensile with shear with different load ratios are described.

The test equipment was a biaxial tensile machine. To manage the experimental equipment and read the results, a specialized program STRAIN v1.0 was used.

In the laboratory tests, it was used TCF of the French company Serge Ferrari (402 Precontraint®) and the German company Mehler (Polymar 8212). Technical characteristics of the materials under study according to the manufacturer's data are presented in table 1. TCF 402 Precontraint® was manufactured with Precontraint® technology (the balanced and constant tension of the warp and weft threads before applying the polymer coating to the textile base), that is the main difference. It is known and investigated in many works that TCF manufactured with Precontrain® technology are less deformative in the direction of the weft threads than in the case of the material without the Precontrain® technology. Such comparison has been shown in work[16].

Table 1. Specifications of tests materials

| Type of TCF | Weight, g/m² | Thickness, mm | Type of weaves | UTS, N / 5 cm (warp / weft) |
|---|---|---|---|---|
| Polymar 8212 (Mehler ) | 650 | 0.5 | Panama 2/2 | 2500 / 2500 |
| 402 Precontraint® (Serge Ferrari) | 490 | 0.4 | Panama 2/2 | 2500 / 2500 |

To measure the displacement and strain fields of the material, as well as to calculate the Poisson's ratio, the method of digital image correlation was chosen. This method has been successfully applied in many works in laboratory tests of TCF, for example, in articles[4,8,17]. GOM Correlate 2016 software was used for date processing.

*Uniaxial axial tests.* The preparation of specimens and the test procedure was carried out in accordance with GOST 30303-95 "Fabrics coated with rubber or plastic. Determination of breaking strength and elongation at break". Laboratory tests of TCF under uniaxial axial tensile were carried out before the specimens were fracture at a constant speed of 100 mm/min. On surface of the material, black paint was sprayed in order to use the optical method of digital image correlation.

By results of laboratory tests under uniaxial axial tensile (table 2), one can speak of satisfactory convergence between the UTS of the material obtained in experiments and the standard values given in the technical catalogs of the TCF. A difference approximately 20% in the direction of the weft threads in both types of TCF can be explained in the following ways:

- inevitable errors in the conduct of laboratory tests;
- possible overstating of the tensile strength of the TCF in the direction of the weft threads by the material producers.

Table 2. Comparison of the UTS TCF

| | UTS, N / 5 cm | Polymar 8212 | 402 Precontraint® |
|---|---|---|---|
| Warp | Normative value | 2500 | 2500 |
| | Experiment | 2444.12 | 2283.74 |
| **Difference** | **%** | **2.23** | **8.65** |
| Weft | Normative value | 2500 | 2500 |
| | Experiment | 1975.82 | 2014.31 |
| **Difference** | **%** | **20.97** | **19.43** |

*Uniaxial off-axial tensile.* Off-axial is understood as test under uniaxial tensile test, in which the load application direction does not coincide with the direction of the main axes of the TCF (warp and weft yarns). For this purpose, the specimens in the form of rectangular strips or dumbbells are cut at a certain angle to the direction of the warp threads.

Normative documents by techniques of carrying out tests of TCF under uniaxial off-axial tensile are absent. The correct shape of the specimen was found by the results of preliminary experiments, which included a series of tests of various forms of material under uniaxial off-axial tensile. The main criterion for the quality of the found form of the specimen were the types of failure mechanism. Three main types of TCF fracture are distinguished in the case of off-axial tensile: even fracture (pure tensile failure), yarns pulled out (pure shear failure) and mixed fracture (mixed failure of tensile and shear)[5,6].

All these types of fracture were obtained in a dumbbell specimen with dimensions of the central part of the specimen of 20x100 mm (figure 3). The shape of the material under uniaxial off-axial tensile tests is consistent with[6], which uses a dumbbell specimens with similar dimensions and also shows three main types of TCF failure.

The material was tensile at a constant speed of 100 mm/min. The tests were carried out before the specimens were fracture. Under uniaxial off-axial tensile, method of digital image correlation could not be applied due to with the twisting of specimens, which already appeared at the very beginning of the experiment, which is explained by the peculiarity of the structure of the TCF.

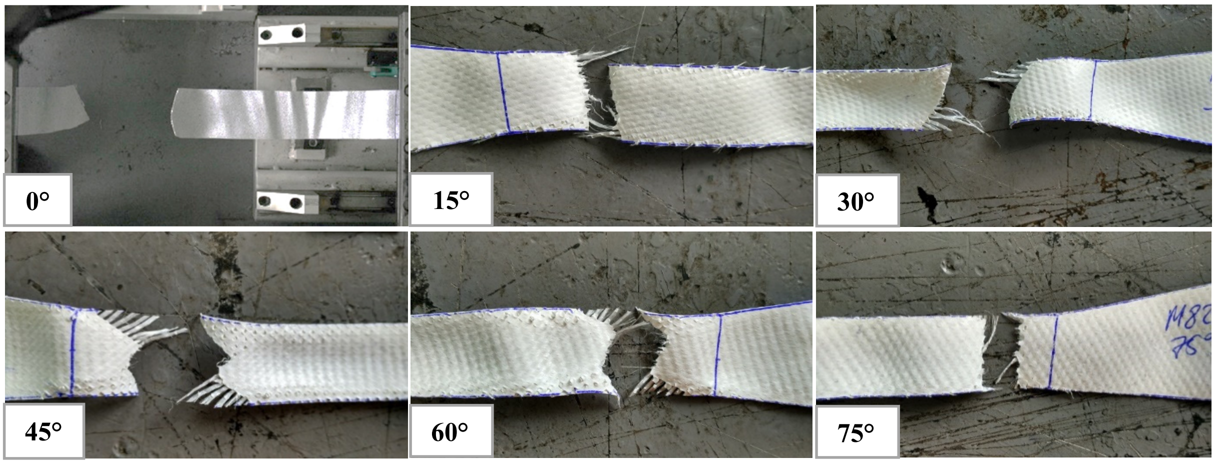

Figure 3. Three main types of TCF fracture:
even fracture (0°, 15°, 75°), yarns pulled out (45°), mixed fracture (30°, 60°)

*Biaxial tensile with shear.* There are no domestic standards for laboratory tests under biaxial tensile of TCF yet. The foreign normative documents regulating and describing tests under biaxial tensile of TCF are the following: the Japanese standard[18], the American standard[2], the European design guide[19].

The specificity of the laboratory tests carried out by the author consisted in the fact that the tests were carried out under biaxial tensile with shear. This is due to the fact that SSS of TCF in different membrane structures is complex. In particular, with wind influences on the structure, often the directions of the principal stresses in the TCF do not coincide with the principal axes of the material (directions along the warp and weft threads), which inevitably leads to the appearance of shear stresses. Usually, the influence of the shear modulus is neglected, which simplifies the SSS of the orthotropic material, however, it does not always reflect the real picture of stresses and strains distribution in the TCF.

In the work[20], the material was studied not only under axial and off-axial uniaxial tensile, but also under off-axial biaxial tensile. The importance of such studies is shown, the results of experiments are presented and valuable conclusions in the end of the work are given.

Due to some characteristics of the tensile machine, the overall dimensions of the specimens were 400x400 mm. Next, a specimen was cut out in the form of a cross with an area of 80x80 mm in the center, the arm width has been 80 mm. The distance between the grips was 240 mm and 50 mm from each side are required for the grips of the testing machine. Two grips of the test equipment were stationary, the other two were moving at a constant speed of 100 mm/min. The tests were carried out before the specimens were fracture.

As well as in work[21], two different types of material specimens have been chosen and tested: with cuts (type A) and without them (type B). The idea was to avoid the effect of transverse deformation on the material SSS. It was found that stress-strain curves of two different types (type A and B) of the TCF specimens are qualitatively and quantitatively almost identical, which agrees with the results of [21]. Figure 4 shows the measurement of displacement fields on the surface of two different types of specimens by the method of digital image correlation.

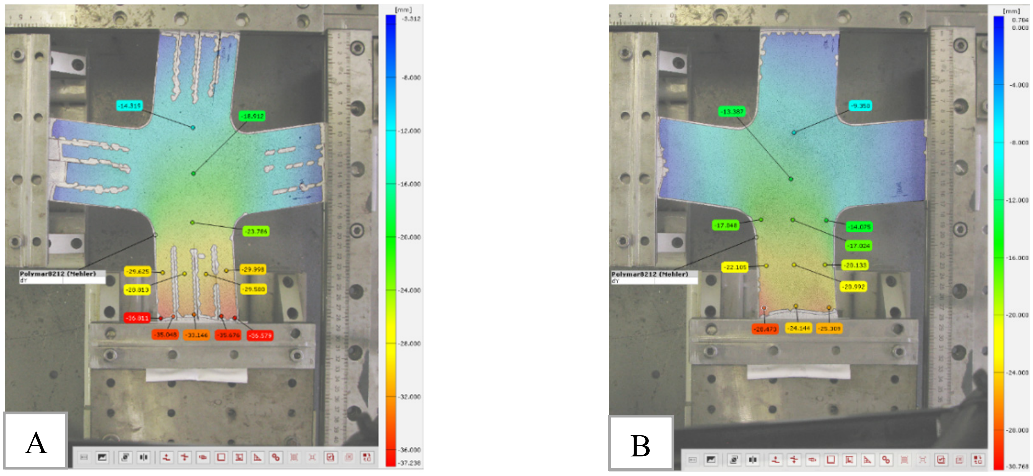

Figure 4. Measurement of the displacement fields on the surface of the specimen along the direction of the weft threads under biaxial tensile tests with shear of two types of specimens (type A and B)

The fracture of specimens occurred at the most intense point of material (figure 5), namely in places of concentration of the largest normal and shear stresses. It should be noted that shear stresses contributed approximately 15-25% of the total strength of the material.

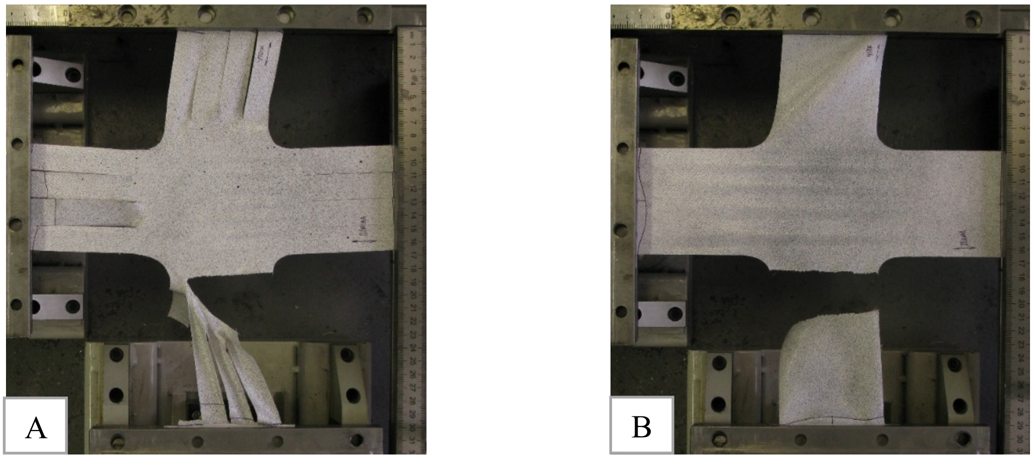

Figure 5. Fracture of specimens (type A and B) under biaxial tensile tests with shear

In laboratory tests, the ratio of modules of elasticity and Poisson's ratios for biaxial SSS was not observed. In the relation given in[2] for linear orthotropic material in biaxial SSS, it is necessary to introduce the coefficient $K$:

$$\frac{\nu_{fw}}{E_f} = K \frac{\nu_{wf}}{E_w} \tag{1}$$

where $w$ – direction along warp threads, $f$ – direction along weft threads.

In one article[22], this coefficient is approximately equal to 0.6, in another paper[23] - 0.14. In our case, in laboratory tests under biaxial tensile with shear with load ratio 1:1, we obtained a coefficient $K$ approximately equal to Polymar 8212 - 0.61, for 402 Precontraint® - 0.82. It is noticeable that for a material with the Precontraint® technology, the coefficient $K$ is closer to 1.

By results of the carried-out laboratory tests stress-strain curves (figure 6 and 7) in which physically nonlinear and an orthotropic properties of the material is visually traced have been constructed. Engineering stresses are given in kN/m due to the fact that the mechanical properties of the TCF are not proportional to their thickness[8].

Figure 8 shows the nonlinear dependence of the Poisson's ratio on the stress along the direction of the warp and weft yarns in two different types of TCF: with and without Precontraint® technology.

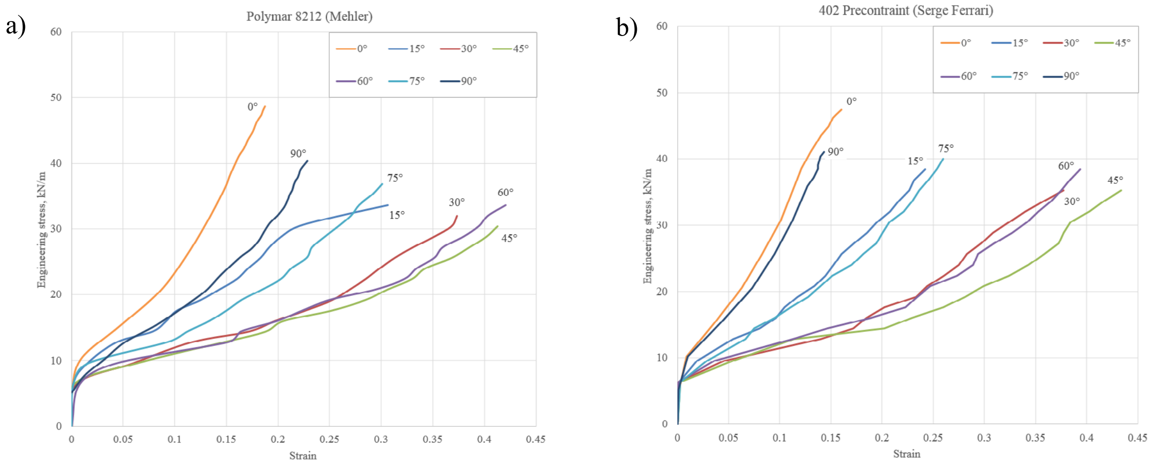

Figure 6. Stress-strain curves under uniaxial axial and off-axial tensile tests:
a) Polymar 8212, b) 402 Precontraint®

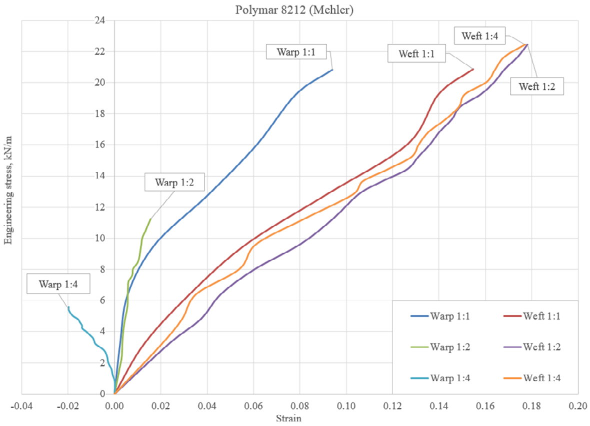

Figure 7. Stress-strain curves under biaxial tensile with shear with different load ratios for Polymar 8212

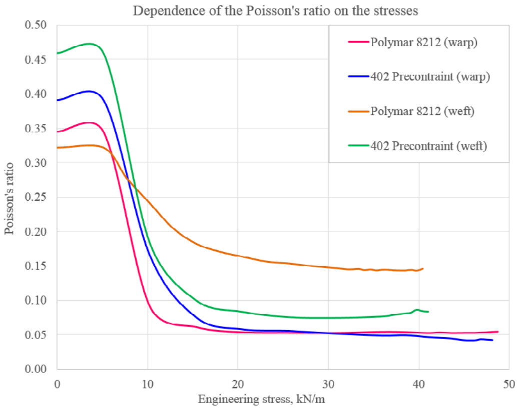

Figure 8. Dependence of the Poisson's ratio on stress under uniaxial axial tests

## Numerical simulations

The numerical simulations, imitating the carried-out laboratory tests, have been executed in Ansys Workbench. In numerical simulations under uniaxial axial tensile tests, the material was assumed isotropic and physically nonlinear that was considered by means of curve plasticity, which was set in the form of multilinear isotropic hardening. However, in numerical simulations of uniaxial off-axial and biaxial tensile with shear material must be specified as orthotropic and physically nonlinear. Modelling physically nonlinear orthotropic (a particular case of nonlinear anisotropic) materials is not a simple task.

To take into account the physically nonlinear orthotropic material, an anisotropic plasticity model was chosen that uses the Hill's yield criterion, taking into account the differences in yield stress in orthogonal directions. According to the Ansys manual[24], the necessary six constants were calculated and necessary command APDL was registered in Ansys Workbench to take into account the anisotropic plasticity model. The analysis was performed taking into account the geometric nonlinear (large deflection).

TCF can only resist tensile load, almost without any flexural resistance. Therefore, in numerical simulations, the element type SHELL181 with a membrane option was used, which assumes that the element has only membrane stiffness. According to Ansys[25], in numerical simulations with geometric nonlinear (large deflection) and with a membrane option in the elements of SHELL181 type, it is recommended to use the triangular shape of the element as more reliable. The load was set by the compelled displacement, simulating the carried-out laboratory tests.

The analysis of the work on the study of the shear modulus in a TCF showed that it can be taken with a sufficient accuracy linear. In articles[4,5,7,8,17,26–28] the value of the shear modulus of a TCF varies on average from 20 to 60 kN/m. In this work, the value of the shear modulus in the TCF was found in numerical simulations and amounted to 25 kN/m for the Polymar 8212, and 28 kN/m for the 402 Precontraint®.

Convergence between laboratory tests and numerical simulations was determined:

- in numerical simulations – fracture of the specimens (maximum stress), coinciding with the place of fracture of TCF in laboratory tests (figure 9);

- on the qualitative and quantitative convergence of the "force-displacement" curves, obtained both in laboratory tests and in numerical simulations (figure 10 and 11);

- stresses in the TCF equal to the ultimate stresses, which were determined from the UTS of the material given in table 1 of this work.

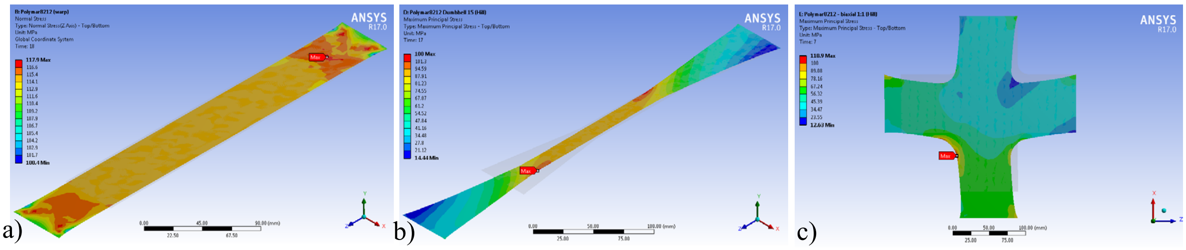

Figure 9. SSS of TCF Polymar 8212 in numerical simulations: a) under uniaxial axial tensile, b) under uniaxial off-axial tensile of the specimen 15°, c) under biaxial tensile with shear with load ratios 1:1

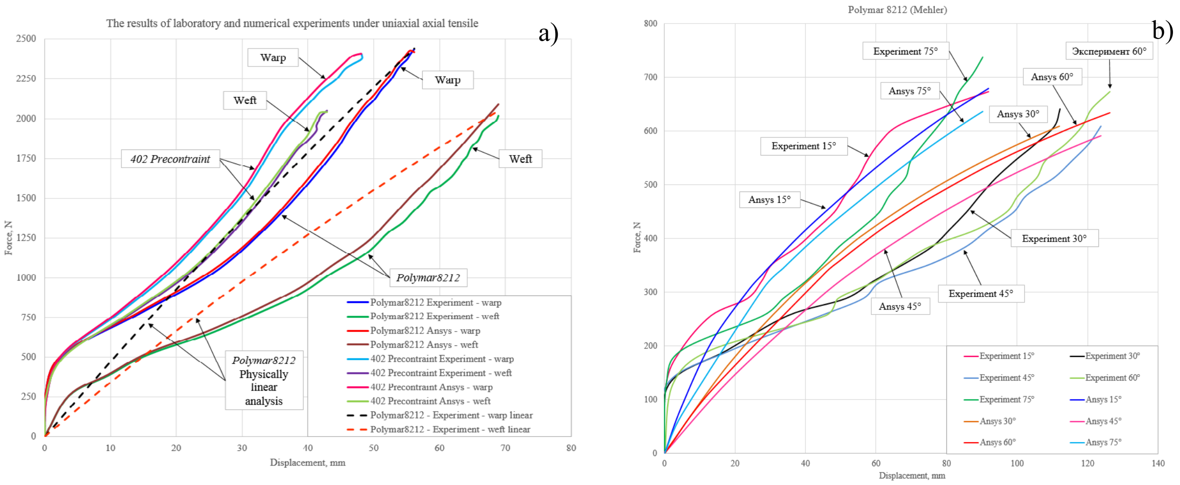

Figure 10. Comparison of the results laboratory tests and numerical simulations of TCF: a) under uniaxial axial tensile tests Polymar 8212 and 402 Precontraint®, b) under uniaxial off-axial tensile tests Polymar 8212

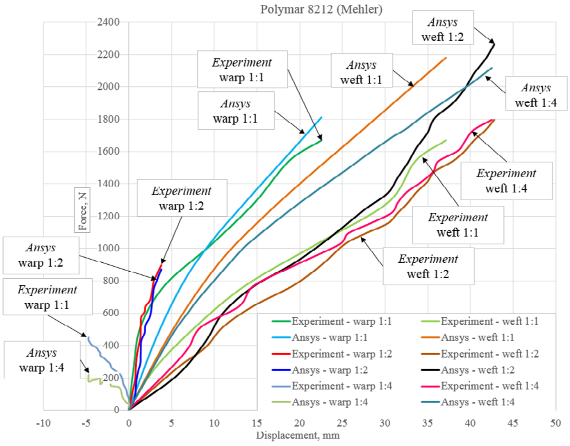

Figure 11. Comparison of the results laboratory tests and numerical simulations of TCF under biaxial tensile tests with shear with different load ratios Polymar 8212

## Strength criterion

At structures analysis, made from TCF, mechanical properties directed along the thickness of the material are always ignored, i.e. material work only in plane SSS is supposed. In this regard, some strength criteria of composite materials can be applied to TCF.

Here, several classical strength criteria are chosen to predict the UTS in numerical simulation under uniaxial off-axial tensile tests and estimates the factor of safety of a TCF under biaxial tensile with shear:

$$\text{Tsai-Hill: } \frac{\sigma_x^2}{X^2}+\frac{\sigma_y^2}{Y^2}-\frac{\sigma_x\sigma_y}{X^2}+\frac{\tau_{xy}^2}{S^2}=1 \tag{2}$$

$$\text{Yeh-Stratton: } \frac{\sigma_x}{X}+\frac{\sigma_y}{Y}-\frac{\sigma_x\sigma_y}{X^2}+\frac{\tau_{xy}^2}{S^2}=1 \tag{3}$$

$$\text{Hashin: } \left(\frac{\sigma_{11}}{X}\right)^2+\left(\frac{\tau}{S}\right)^2=1 \tag{4}$$

$$\text{Norris: } \left(\frac{\sigma_x}{X}\right)^2+\left(\frac{\sigma_y}{Y}\right)^2-\frac{\sigma_x\sigma_y}{XY}+\frac{\tau_{xy}^2}{S^2}=1 \tag{5}$$

where $\sigma_x$ and $\sigma_y$ are the normal stress in warp and weft, $\tau$ – is the shear stress, $X$ and $Y$ – are the UTS in warp and weft, and $S$ is the shear strength.

Figure 12 shows comparison of the UTS under uniaxial axial and off-axial tensile tests TCF between laboratory tests and numerical modelling with physically linear and physically nonlinear material model (anisotropic plasticity model), as well as predicting of the UTC by the Tsai-Hill strength criterion.

In table 3 shows a comparison between factors of safety calculated from the results of laboratory tests and determined using different strength criteria in numerical simulations. Factor of safety is the ratio of the technical characteristic UTS TCF to the breaking force obtained in the laboratory tests at the time of fracture material.

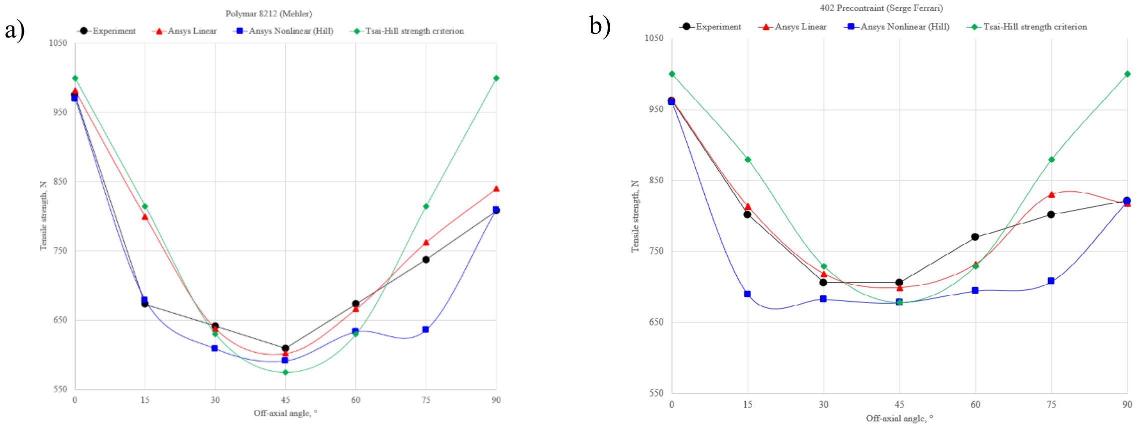

Figure 12. Comparison of the UTS TCF under uniaxial axial and off-axial tensile tests:
a) Polymar 8212, b) 402 Precontraint®

Table 3. Comparison factor of safety by different strength criteria

| Laboratory tests under biaxial tensile with shear for Polymar 8212 | | | | | |
|---|---|---|---|---|---|
| Load ratios | Strength criteria / Factors of safety | | | | |
| | Experiment | Tsai-Hill | Yeh-Stratton | Hashin | Norris |
| 1:1 | 2.46 | 2.19 | 2.56 | 2.09 | 2.19 |
| 1:2 | 2.23 | 2.02 | 2.38 | 1.63 | 2.02 |
| 1:4 | 2.23 | 1.97 | 2.31 | 1.61 | 1.97 |

It can be seen that in a complex SSS (under biaxial tensile with shear), the TCF has a much smaller UTS than the UTS presented in the technical catalogs for the material. Also, in laboratory tests under uniaxial off-axial tensile, it is seen that the UTS decrease with increasing load angle to the warp yarns. The specimen of 45° have a 35-50% lower UTS that the UTS of TCF specimens under uniaxial axial tensile (specimens 0° and 90°).

Figure 13 shows factors of safety at Yeh-Stratton strength criterion in numerical simulations under biaxial tensile tests with shear with different load ratios.

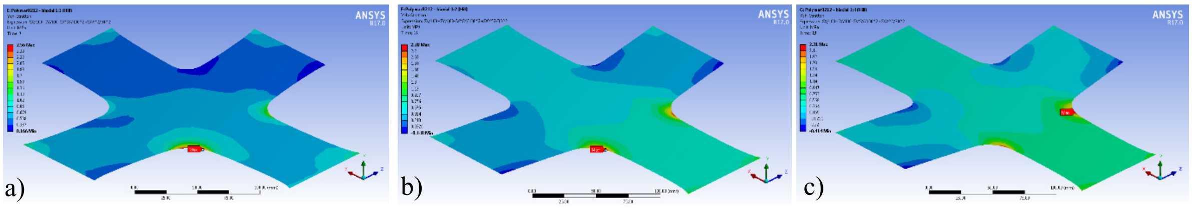

Figure 13. Factors of safety in numerical simulations of TCF Polymar 8212 under biaxial tensile tests with shear with different load ratios : a) 1:1, b) 1:2, c) 1:4

## Conclusions

*The most important findings of the research in laboratory tests:*

- the optical method of digital image correlation was the most suitable for measuring displacement and strain fields on the surface of the specimen in laboratory tests under uniaxial and biaxial tensile with shear;

- a TCF is an orthotropic and physically nonlinear material and the Poisson's ratio is not a constant that is consistent with the results of other researchers;
- shape of the specimen was revealed, which allows to determine correctly the mechanical properties of TCF under uniaxial off-axial tensile;
- found necessary and sufficient number of laboratory tests to determine the main mechanical properties used in modelling structures made from TCF.

*We got following results in numerical simulations:*

- satisfying quantitative and qualitative convergence between the results of laboratory tests and numerical simulations with a nonlinear material model was shown;
- shear stress make a significant contribution to the SSS of a TCF under uniaxial off-axial tensile;
- the Tsai-Hill strength criterion is suitable enough for prediction of the UTS TCF under uniaxial axial and off-axial tensile tests, except the specimens of 15° and 75°, which is explained by the peculiarities of the structure of TCF;
- the Yeh-Stratton strength criterion is quite suitable for estimating the factor of safety under biaxial tensile with shear with different load ratios.

*The following research tasks:*

- to find the most suitable nonlinear material model for describing of complex SSS;
- to perform laboratory test of tensile structures made from a TCF and numerical simulations with a nonlinear material model.

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