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ORTHOTROPIC PROPERTIES OF DIAGONALLY STRUCTURED WOVEN FABRICS

S. Brnada, I. Schwarz*, Ž. Šomođi and S. Kovačević

Abstract

Woven fabric as a complex structured orthotropic material has two axes of symmetry: in the warp and weft direction. In the ideal case of symmetrical woven fabric (in plain weave and in its derivatives) orthotropic main axis lay on the axis of structural principal directions of the fabric, but in the case of asymmetric woven fabric - geometrical diagonally structured woven fabric (in twill and satin weave and in their derivatives) at normal stress, axis displacement i.e. angular deformation occurs. This phenomenon is not the result of shear stress, but rotation of orthotropic main axis with regard to the axis of structural principal directions of the fabric. With this research, the knowledge about the behaviour of asymmetric woven fabrics at normal stress will be expanded, which will lead to insights about important material properties that will define its qualitative and use values in the field of small and large surface axial stress.

Key Terms

Asymmetric fabrics, orthotropic axis, axis of symmetry, axial stress, angular deformity.

Introduction

Woven fabrics for technical applications have to maintain their mechanical properties (as standalone) or provide (as reinforcement within a composite) certain stability under high stress conditions. In this respect, controlled characteristics of deformability can be achieved by designing fabrics of certain structural characteristics such as weave, yarn density, raw material composition and structural characteristics of warp and weft, surface mass and so on.

When the mechanical and thermal properties of the material are equal in all directions, the material is isotropic and, if different, is anisotropic [1]. Orthotropic materials are a special type of anisotropic material having mutually vertical planes of elastic symmetry called the planes (axes) of orthotropy. The material has a plane of elastic symmetry if the reflection of the coordinate system on that plane does not change the components of the elasticity tensor, ie compliance tensor. Examples of orthotropic materials are wood, many crystals, etc. The fabrics also belong to a group of orthotropic materials.

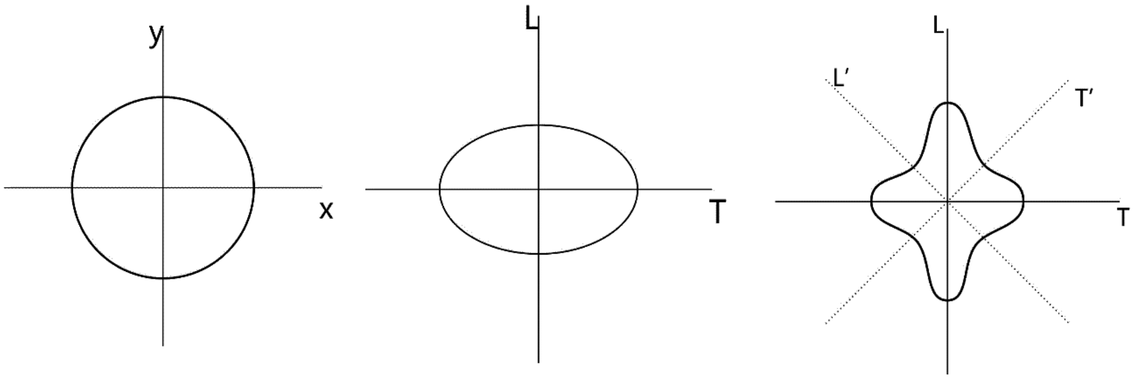
Textile materials vary widely from other engineering materials [2,3]. In general, woven fabric could be described as inhomogeneous, very anisotropic, deformable, prone to high stresses and displacements at low loads. However, woven fabrics also have unique properties that are compatible with many physiological requirements of human being.

The geometrical structure of the fabric is very complex. The whole system is made up of several subsystems, each of which can be viewed as a separate complex entity and each in a certain proportion affects the physical and mechanical properties of the fabric.

For diagonally structured fabrics, such as ones in twill and satin weave, the main axis of orthotropy are not laying on the main structural directions but somewhere between the structural diagonal and the main axis [4-6]. Therefore, it is more practical to observe them with a rotated coordinate system. The appearance of angular deformation at the normal tensile load here is not a consequence of the shear but normal stress, i.e. the result of the geometry of the fabric.

Hook's Law for anisotropic material (the general case) will be valid here, where α is a normal shear coefficient. The anisotropy of the material can be roughly represented by polar diagrams. On the main structural axis of the fabric (the direction of the warp and weft) or the main axes of orthotropy, the stress or strain values of the fabric at a particular force acting in normal and tangential directions are observed, after which the distribution of stress / strain in arbitrary directions can be seen.

Figure 1a shows that the polar diagram of the isotropic material is the circle. Fig 1b shows an orthotropic material whose property value on the longitudinal and transversal axis of the orthotropy is different and has no pronounced angle effect at an angle of 45 ° as is the case on the Fig 1c where, the tensile stress values are lower than the stress value in the main directions of orthotropy (typically for woven fabrics).



a) b) c)

Figure 1. Polar diagrams: a) isotropic material; b) orthotropic material without a pronounced effect on the diagonal; c) orthotropic material with a pronounced effect in the diagonal axis

1.1. Hook's law for anisotropic material

Woven fabrics, according to their characteristics, can be described by Hooke's Law for Anisotropic planar Material. For woven fabrics that are geometrically structured in the direction of the main structural symmetry axes, the expression matrix of orthotropic materials is valid, whereas in the case of diagonal structured fabric geometry is applied the normal shear coefficient α appears.

a) Compliance matrix- general case

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_x} & \alpha_x \\ -\frac{\nu_{xy}}{E_y} & \frac{1}{E_y} & \alpha_y \\ \alpha_x & \alpha_y & \frac{1}{G_{xy}} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}$$ where α is a normal shear coefficient

b) Compliance matrix for orthotropic materials

$$\begin{Bmatrix} \varepsilon_T \\ \varepsilon_L \\ \gamma_{TL} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_T} & -\frac{\nu_{TL}}{E_T} & 0 \\ -\frac{\nu_{TL}}{E_L} & \frac{1}{E_L} & 0 \\ 0 & 0 & \frac{1}{G_{TL}} \end{bmatrix} \begin{Bmatrix} \sigma_T \\ \sigma_L \\ \tau_{TL} \end{Bmatrix}$$ where T and L are the main axes of orthotropy

where:

- Elastic constants: G- shear module; E- Young's modulus; ν- Poisson ratio.
- Deformation tensors: ε_x, ε_y- deformation by x and y axes; γ_{xy}- shear deformation.

- Tensile stresses tensors: $\sigma_{x,}$ σ_y- normal stresses in x, y direction; τ_{xy}- shear stress.
- G: ratio between tensile stress and associated angular deformation ($G = \tau/\gamma$) in the linear range in which Hooke's law applies.
- E: ratio between strain caused by the tensile force and relative length change: $E = \sigma/\varepsilon = (F/P)/(\Delta L/L0)$, where σ is stress, ε linear elastic deformation, F tensile force, P initial cross section area, ΔL length change, L0 initial length. The smaller the modulus of elasticity, with the same strain, gives the greater → deformation.
- υ- Poisson ratio: Poisson ratio (υ) is determined as a ration of transverse width reduction and lengthwise extension of a material during tensile elongation.

In diagonally structured materials, the occurrence of shear deformation can be result of normal stress (Figure 2).

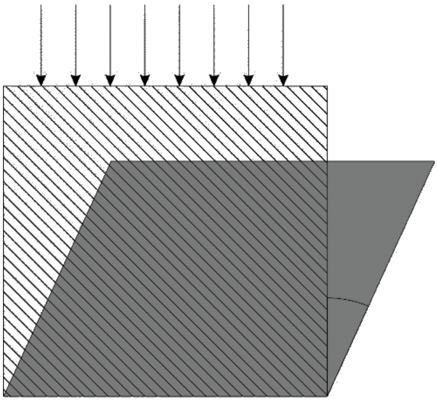


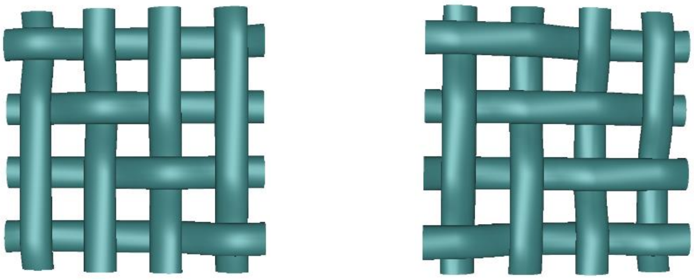
Figure 2. Angular deformation as a result of normal stress [7]

Experimental

2.1. Samples for testing

Two samples of woven fabric in two different weaves, twill 3/1 (Figure 3a) and twill 2/2 (Figure 3b) were investigated. The fabric production, weaving conditions and all other fabric parameters are the same. The yarn for the warp and weft is carded, 100% cotton, fineness 35.7 tex and produced in the same production line. Fabric density is 200 threads / 10cm in both directions.

When selecting test samples, a balanced (equal number of threads per length in both systems) and asymmetric fabrics, i.e. geometrically diagonal structured fabrics, were chosen.



a) b)

Figure 3. 3D simulation of twill weave: a) twill 3/1 weave, b) twill 2/2 weave

2.2. Testing methods

Sample preparation:
The specimens are cut in dimensions of 30 x 30 cm and are notched at the clamping positions of the dynamometer clamps and clamps of the lateral force measuring device as shown in the Figure 4.

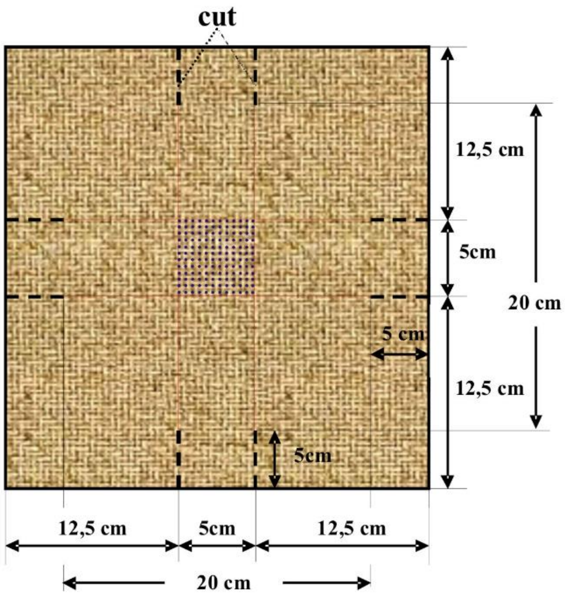


Figure 4. Sample for testing

At the centre of the 5cm x 5cm surface, 5 mm spacing points are defined, which will later be used to analyse fabric behaviour (displacement) due to tensile stress with lateral restriction.

a) Testing of tensile stress at the certain extension in the area of orthotropy axis expectation
  - Determination of the angle between the twill weave diagonal and the main structural axis of the woven fabric (warp direction) is performed by measuring on the fabric.
  - Determination of stress at a given extension in the direction of the main structural axis of the fabric, in the direction of the diagonal and on the quarter angles between these two directions by measuring on the dynamometer
  - Determination of the lateral force of the sample produced by the tensile extension by measuring with the upgrade device on the dynamometer (Figure 5).

Figure 5. Innovative, lateral force measuring device

b) Testing of angular deformation as a result of normal stress

- Angular deformation and skew direction of the woven fabric subjected to normal stress was determined by the observation method as it is shown on Figure 6. It is performed by analysing the video frames in the selected phases of the test. The analysis is done by processing the video in that open source program "Tracker".

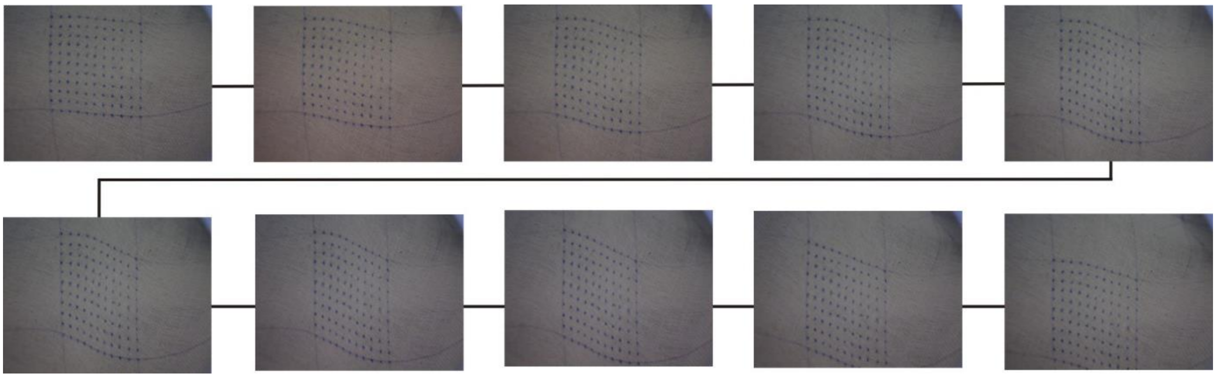


Figure 6. Direction of the point displacement

2.3. Results and discussion

Fabric samples in twill K2/2 and K3/1 weaves were tested on a dynamometer using a lateral force measuring device at the tensile stress. During the testing, videos were created and analysed to determine the deformation associated to normal tensile stress. The mechanical behaviour of the fabric at the break was observed and the polar diagrams show the values of break forces and elongation at break of the samples in the directions of the warp and weft and in the direction of 22.5°, 45°, 67.5°, 112.5°, 135° and 157.5° angular displacement in relation to the warp direction.

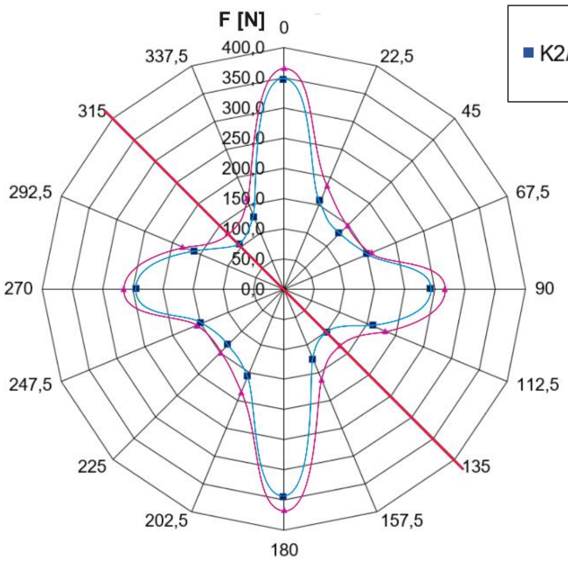


Figure 7. Breaking force of the samples in main and rotated directions

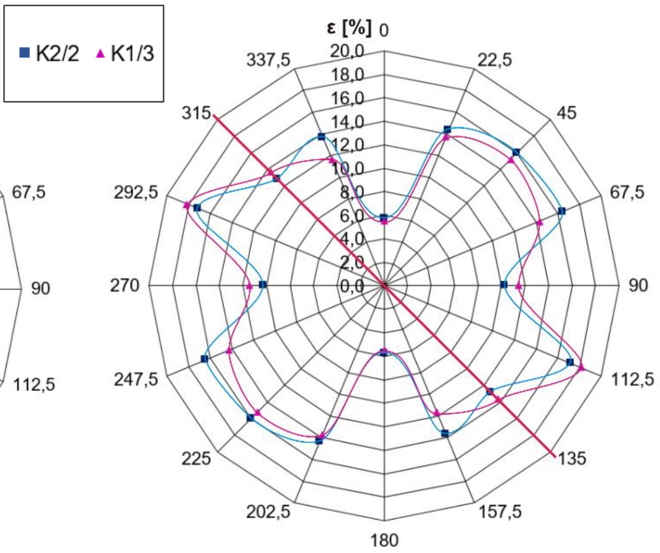


Figure 8. Elongation at break of the samples in main and rotated directions

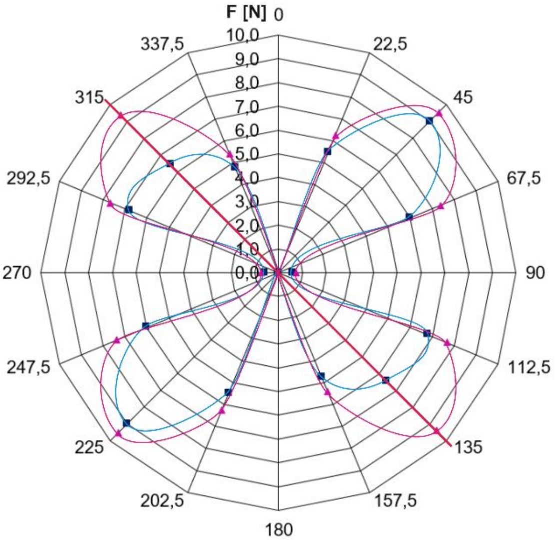


Figure 9. Lateral force at break of the samples in main and rotated directions

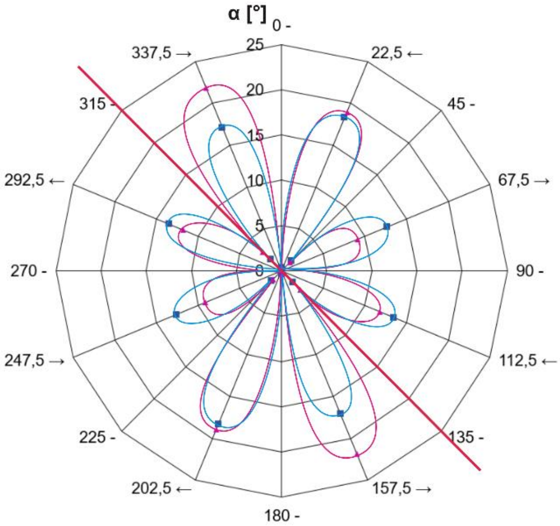


Figure 10. Angular deformation at normal tensile load just before the break

From Figures 7 and 8 it can be seen that the extremities of the tensile modulus of the fabric are on the main axes (the direction of the warp and weft) and in the direction of the angular displacement of 45° in relation to the main directions. It is also apparent that there is latent deviation in the symmetry of the polar diagrams and that is more pronounced in the sample K 3/1. The reason for that is lower compactness of K3/1 structure due to greater number of floatation than the K2/2 structure.

The polar diagram in Figure 9 show the distribution of lateral forces at break in different directions. The deviation from orthotropic behaviour in the area of diagonal geometry of the sample is also visible in the diagram. The lateral forces reach the maximum extremities in the direction of the diagonal, or in the directions in which the fabric has the highest extension values.

Figure 10 shows the angular deformation of the fabric subjected to the normal tensile stress at break. From the diagram it is apparent that the angular deformation of the sample is larger in rotated direction, closer to warp direction, in both cases with the same deviation of orthotropic behaviour in the same directions. At the tensile stress in the different directions, there is a significant horizontal angular deformation of the fabric. The highest angular deformation values in ° are measured at the angle of 22.5° and 112.5° in relation to warp direction. Angular deformations at tensile stresses occur at 22.5° and 112.5° in a counter clockwise direction, while at 67.5° and 157.5° are angular distortions are relatively smaller and in clockwise direction. With tensile stress woven fabric in directions of 0°, 45°, 90° and 135° in relation to warp direction, there is no significant angular deformations of the fabric.

2.4. Conclusion

Since the twill diagonal passes through the 2nd and 4th quadrants (if the fabric is viewed in a two-dimensional coordinate system) it can be concluded that the directions close to the twill diagonal of the fabric have a greater tendency for angular deformations that occur at normal, tensile stresses.

Two factors have the influence on tensile properties of diagonally structured fabric:

The main directions: the direction of the warp and the direction of the weft in which the stiffness of the fabric reaches the maximum extreme values while approaching the angle at an angle of 45° the stiffness of the fabric decreases to reach the minimum extremity. At a 45°

angle, the shear module G is considerably smaller than it would be for an isotropic material, and the polar diagram of the module has a shape of the cross with equal or unequal arms, depending on the thread density and properties in the direction of the warp and the weft.
Direction of the twill diagonal: which is in the twill weave fabric with the same thread densities in both systems directed at an angle of 45° with respect to the direction of the warp (and weft). The proportion in which the twill diagonal contributes to the deviation from the orthotropic behaviour of the fabric is relatively small, but it is sufficient enough to cause angular deformation, i.e. distortion of the weft, after taking off the woven fabric from the cloth roller and its relaxation.

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