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Specific Properties of Woven Multiaxial Structures

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Abstract
The development of the construction and technology of multiaxial fabrics should be accompanied by exploring their specific properties. On the one hand, there is a need to assess the behaviour of such woven structures under complex loading, while on the other there are no appropriate tools to conduct such research. This paper presents a prototype of a bi-directional load testing machine which was used to generate complex stress in tri- and foura-xial fabrics. Fabrics used for the tests were made of woven polyester tapes subjected to the thermal stabilisation process in order to unify their properties. As was expected, the results confirmed that increasing the number of axes in the fabric results in improved directional properties and increases the transfer of oblique loads in relation to the main axis. In the case of multiaxial fabrics, longitudinal rigidity in both directions can be increased by either increasing the number of axes or reducing working-in of threads (tapes) in the fabric. A multiaxial fabric may replace a package composed of many orthogonal fabrics when reinforcement of a composite exposed to complex multidirectional loading is required.

Key words: *multiaxial woven structure, fabric mechanical properties, testing machine.*

Introduction

Nowadays it is possible to program the performance characteristics of textiles which determine their physical and chemical resistance. Such materials are commonly used as construction materials or the reinforcement of composite structures. Expectations on the part of designers and end users require a more detailed study of their properties under complex loading. So far most studies and analyses have been devoted to triaxial fabrics, among others: F.L. Scardino and F. K. Ko [1], C. Bruno [2], M. S. Schrama [3], S. V. Hoa [4 - 7], S. Z. Sheng [4], P. Quellette [4, 6] & Q. Zhao [5 - 7]. Openwork tri- and fouraxial fabric structures are offered on the market , but due to clearances occurring in them at the Institute of Architecture of Textiles, Lodz University of Technology works are carried out in order to attain technical capabilities of producing new structures of such fabrics with industrial methods. Moreover design and construction works aiming to develop new multi-axial fabric structures, particularly with a high cover factor, are also ongoing. Lately algorithms have been developed which make it possible to produce fabrics with a number of axes from 3 to 12 with mechanized methods. A stand was built for forming such woven structures manually and prototypes of fabrics were produced with 3, 4, 5 and 6 axes. Directional properties of the fabrics formed were tested on a stand for measuring the circular response of a fabric sample to a central force (concentrated input function) acting perpendicular to the surface of the fabric. According to expectations, test results confirmed that when the number of axes increases the response of the multiaxial fabric to such a force becomes more uniform and closer to circular. At the same time, a new need arose to assess the behaviour of such woven structures under complex loading, when tensile forces in the plane of the fabric are accompanied by shear forces, or when the directions of tensile forces are not in accordance with those of the main axes of the fabric [12]. The aim of this study was to build a prototype of a bi-directional load testing machine and use it to generate complex stress states in tri- and fouraxial fabrics.

Method of testing directional properties of fabrics

In cooperation with the Central Research and Development Centre of Textile Machines CENARO in Łódź and the engineering company KONTECH, a bi-directional load testing machine with programmable testing scenarios was designed and built. The machine works in a vertical position, and its supporting structure is open-ended, expandable with further functions. The supporting frame is built on a cruciform plan and on each arm it has a clamp guide with a screw gear, driven by a stepper motor (***Figure 1***). The supply system of the drives

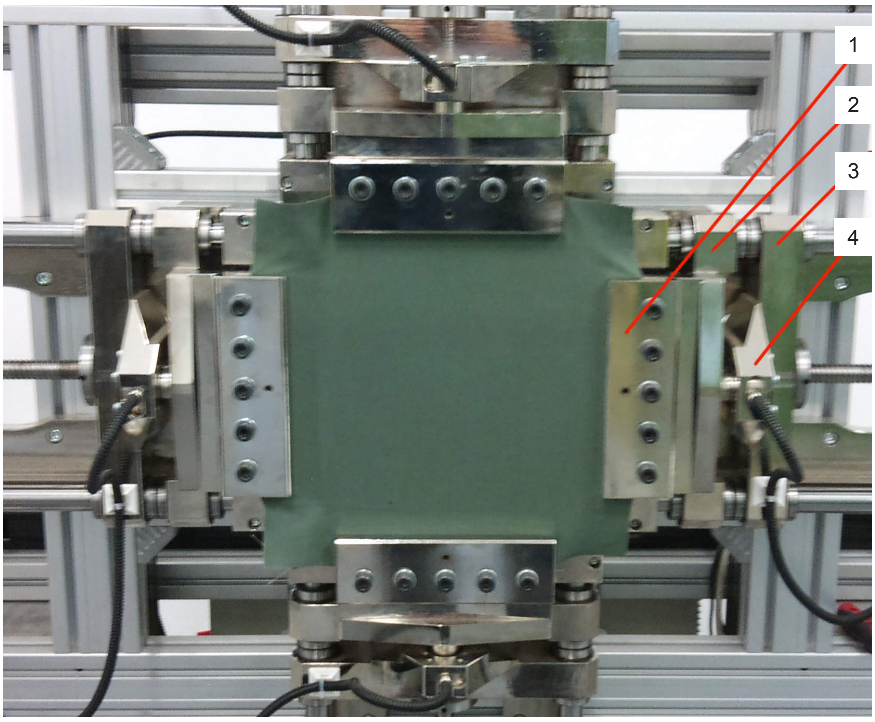

Figure 1. *System of four clamps with a fabric sample: 1) clamp 2) clamp slide, 3) slide of the clamp actuator, 4) force transducer.*

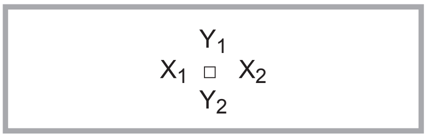

Figure 2. *Symbols for clamps of the load testing machine.*

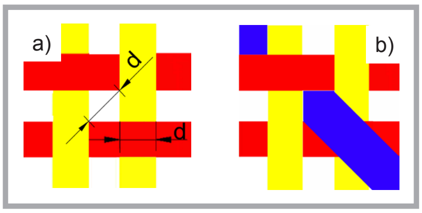

Figure 3. *Basic fabric; a) method of planning the width of the clearance in relation to tape d, b) tape of the oblique system of width d covers the clearance [13].*

of individual clamps is integrated into the basic structure. The system controlling the drives of the machine clamps is independent and is based on a programmable computer system enabling the programming of all work activities and to combine them in different testing scenarios. The load capacity of the construction ensures the loading of the test sample up to a value of 10 kN on each clamp, with a safety factor of 2.5.

In the power transmission system of each of the clamps, between the working element and clamp, an extensometric force transducer of a maximum value of 10 kN was installed. Technical specifications of the drive and control systems are protected by copyright, and no consent was obtained for their publication.

To program the control system of the load testing machine, the following symbols were introduced for the clamps (***Figure 2***).

A square fabric sample of a length of 200 mm is placed in the clamps of the machine.

Preparation of test material A woven, thermally stabilised polyester tape was used to prepare the test material. Its characteristcis were as follows: tape width - 7.5 mm, tape thickness - 0.35 mm, tearing strength F_R = 263.86 N, relative elongation at break εL = 6.76 %, Poisson ratio for width = 40, Poisson ratio for thickness = 54, coeficient of longitudinal friction 0.72, coefficient of transverse friction 0.76, coefficient of oblique friction 45° = 0.64, 60° = 0.66. The selection of stabilised polyester tapes instead of tapes was determined by the need to ensure stable physico-mechanical parameters, so as to avoid mistakes resulting from the unevenness of tape properties. The structures of multiaxial fabrics adopted for the tests differ in terms of weaves, and unlike multiaxial fabric structures, which were the subject of previous studies [2 - 7], they have no clearances - holes. If a common plain weave was adopted for all fabric structures, bringing the neighbouring tapes (acting as tapes) closer to each other, in order to maximise the cover factor, would be impossible. This is the main requirement when using a fabric for reinforcing composites, because it ensures the maximum participation rate of one layer of the reinforcing structure in the weight of the composite, together with the minimum weight of the layer. It also ensures the most uniform distribution of the reinforcement in the composite structure. Increasing the number of axes in the fabric structure, together with the requirement of the maximum cover factor always leads to tape accumulations. For engineering the design of fabrics a principle was adopted that tape spacing should be a function of the diagonal of the clearance, which is to be equal to the width "d" of the tape of the oblique system covering this clearance [13]. This rule is illustrated in ***Figure 3***.

In order to minimise the growth of the take-up of oblique tapes, complex weaves had to be used. Various structures of four-axial fabrics are shown in ***Figures 4*** and ***5***. The first one involved a simple interlacing of two orthogonal fabrics rotated towards each other at an angle of 45°. ***Figure 4*** presents the schematic interlacing of the tapes and schematic view of the fabric.

Due to the characteristic way of interlacing the two component orthogonal fabrics, where each of the tapes of the fabric rotated by 45° passes alternately over and under the base fabric, this fouraxial fabric structure was denoted as NP. Analysis of the method of interlacing tapes in the NP fabric shows that the tapes of the base fabric are straight and those of the rotated one are more wavy, which means that the fabrics differ in tape take-up, and hence their behaviour during testing may also vary. Therefore

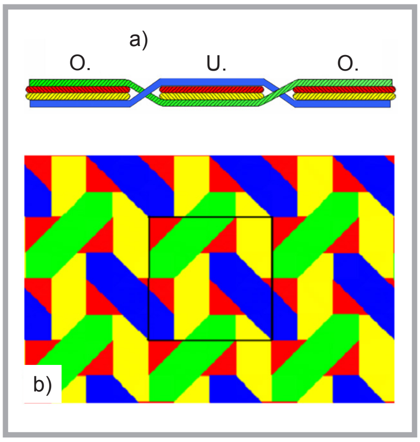

Figure 4. *a) Diagram of tape interlacing, b) schematic view of a four-axial NP fabric [13].*

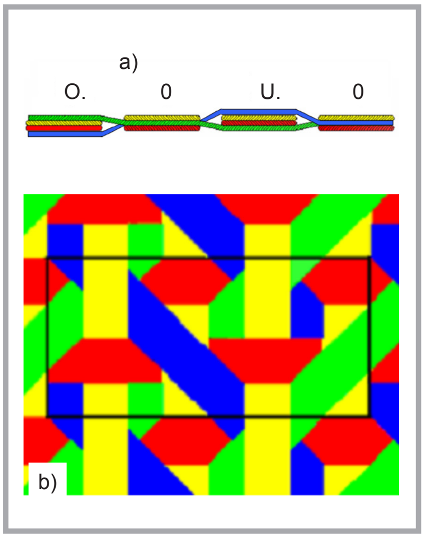

Figure 5. *a) Diagram of tape interlacing, b) schematic view of a fouraxial NO/PO fabric [13].*

another construction of a fouraxial fabric was proposed, as shown in ***Figure 5***.

Due to the characteristic way of interlacing the two component orthogonal fabrics, where each tape of the fabric rotated by 45° passes alternately over, inside and under the base fabric, this fouraxial fabric structure was denoted as NO/PO. In that way the wavy characteristics of the interlaced tapes were minimised, which should lead to better test results of the NO/PO fabric compared to the NP structure. Fabrics for the tests were formed manually on a loom [13] built at the Institute of Architecture of Textiles for the production of multiaxial fabric samples within the project "Modeling and forming of multiaxial woven structures for high strength composites".

Research methodology

The following principles were adopted while fixing fabric samples in the clamps of the load testing machine:

- in the case of a classic fabric warp tapes were fixed vertically in clamps Y1 and Y2 and weft tapes horizontally in clamps X1 and X2, so that there were 25 tapes in clamps Y and 25 in clamps X,
- in the case of triaxial fabric, samples were oriented according to one of the systems arbitrarily accepted as the warp, and they were fixed in clamps Y1 and Y2, while the remaining sides of the square samples were fixed in clamps X1 and X2. In that way, in clamps Y there were 25 tapes extending straight between them, whereas in clamps X there were 6 tapes arranged at an angle of 60° (including three left-skewed +60° and three right-skewed -60°). The remaining tapes of the triaxial fabric were fixed in clamps X2Y1 – 11 left-skewed tapes + 60° and in clamps X1Y2 - 11 right-skewed tapes -60°,
- in the case of fouraxial fabrics of NP and NO/PO structure there were 16 tapes in clamps X and Y, and the remaining tapes of the fouraxial fabric run between clamps Y1X2 - 9 tapes at an angle of 45°, between clamps Y2X2 - 9 tapes at an angle of 45°, between clamps X1Y1 - 9 tapes at an angle of 45° and between clamps X1Y2 – also 9 tapes at an angle of 45°.

The arrangement of samples in the clamps of the load testing machine presented above remained the same throughout the whole research program. Views of fabric samples fixed in the clamps of the load testing machine are shown in ***Figures 6***.

The study included two scenarios: the first assumed cyclic loading of the samples by stretching with a displacement of the clamps of 2.5 mm, and the other - the stretching of samples until total destruction. The value of clamp displacement was established after preliminary studies, where it was found out that the initial displacement of the clamps of 0.5 - 0.7 mm leads to the stabilisation of the structure of the fabric tested, which manifests itself in the transition of the force - displacement from a curvlinear to rectlinear course. Thus, moving the clamps by 2.5 mm will generate a load corresponding to about 25% of the elongation breaking a single tape of which the fabric samples were made. The speed of the clamps' movement was constant and equaled 1 mm/s.

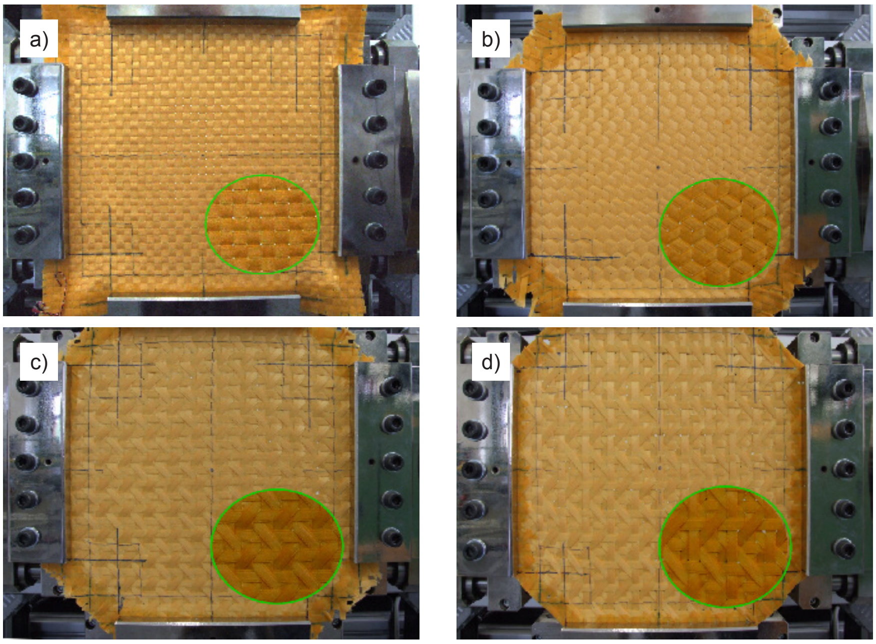

Figure 6. *View of: a) an orthogonal fabric sample, b) a triaxial fabric, c) a fouraxial NP fabric, d) a four-axial NO/PO fabric in the clamps of the load testing machine.*

1. Comparative studies of fabrics stretched cyclically and simultaneously in the X and Y direction. The fabric sample tested was fixed in the clamps of the load testing machine and after being stressed to an initial value of 50 N, each of the clamps moved by 2.5 mm and then returned to the initial position. Displacements of the clamps, the force on each of them and the current time of the experiment were registered.
2. Comparative studies of fabrics cyclically loaded due to the displacement of clamps X by 2.5 mm from the initial position and backwards, in a state of constant pre-stress towards Y. The fabric sample tested was fixed in the clamps of the load testing machine and after being stressed to an initial value of 50 N in every direction, the clamps in the X direction moved by 2.5 mm and then returned to the initial position. Displacements of the clamps, the force on each of them and the current time of the experiment were registered.
3. Comparative studies of fabrics cyclically loaded by movements of clamps Y by 2.5 mm from the initial position and backwards, in a state of constant pre-stress towards X. The fabric sample tested was fixed in the clamps of the load testing machine and after being stressed to an initial value of 50 N in every direction, the clamps in the Y direction moved by 2.5 mm and then returned to the initial position. Displacements of the clamps, the force on each of them and the current time of the experiment were registered.
4. Comparative studies of fabrics stretched in directions X and Y with simultaneous shear in the plane of stretching. The fabric sample tested was fixed in the clamps of the load testing machine and after being stressed to an initial value of 50 N in every direction it was subjected to cyclical stretching by moving clamps X2 and Y2 by 2,5 mm and backwards, while clamps X1 and Y1 remained motionless. The displacements of clamps X2 and Y2, the force on each of them and the current time of the experiment were registered. This testing method was used to identify the relation between the structure of the fabric and its behaviour under complex loading.
5. Comparative studies of fabrics stretched bidirectionally until destruction. The fabric sample tested was fixed in the clamps of the load testing machine and after being stressed to an initial value of 50 N in every direction it was subjected to simultaneous stretching in all directions. Displacements of the clamps, the force on each of them, as well as the current time of the experiment were registered.

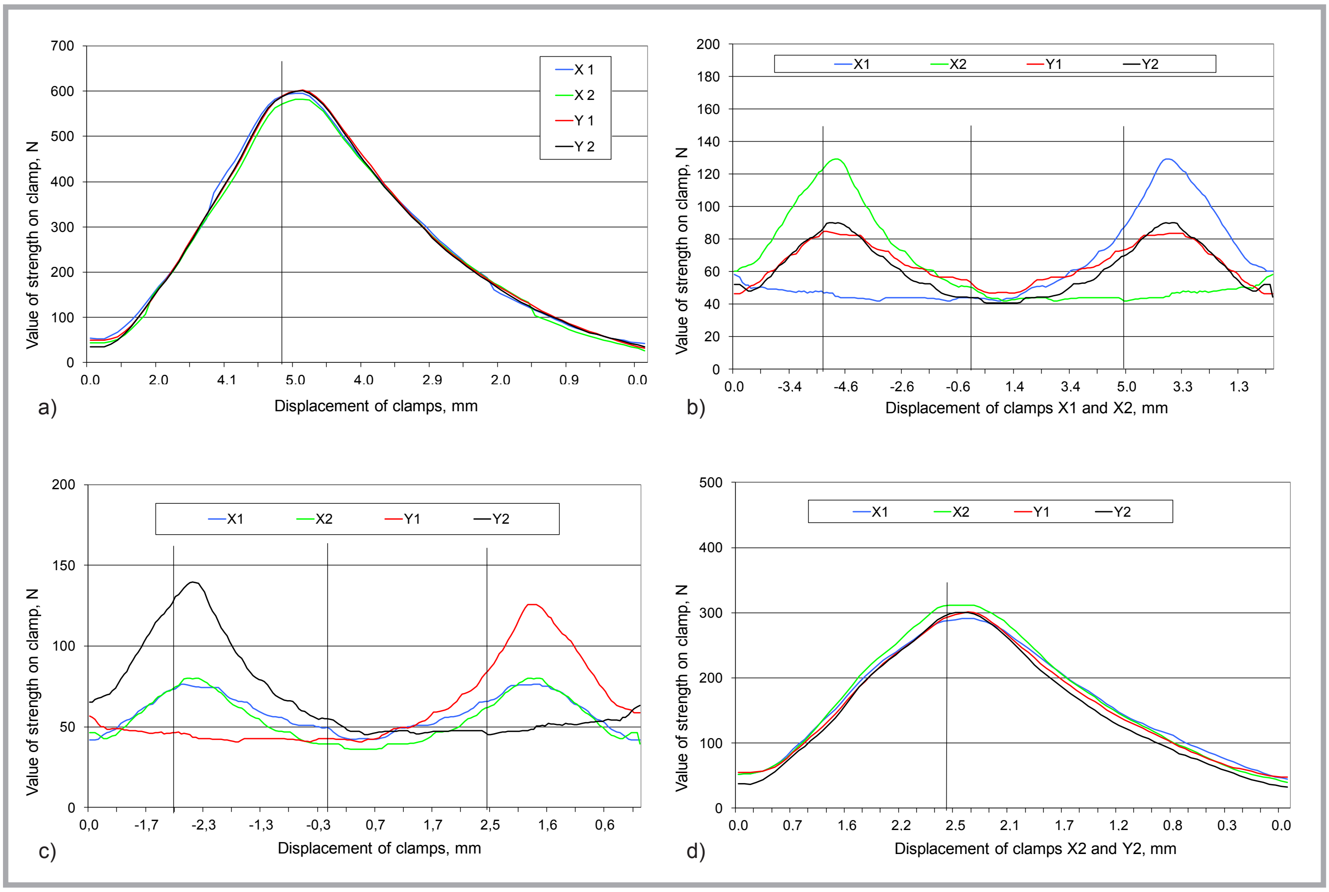

Figure 7. *Orthogonal fabric; a) bi-directional stretching, b) oscillation towards X, c) oscillation towards Y, d) stretching with shear.*

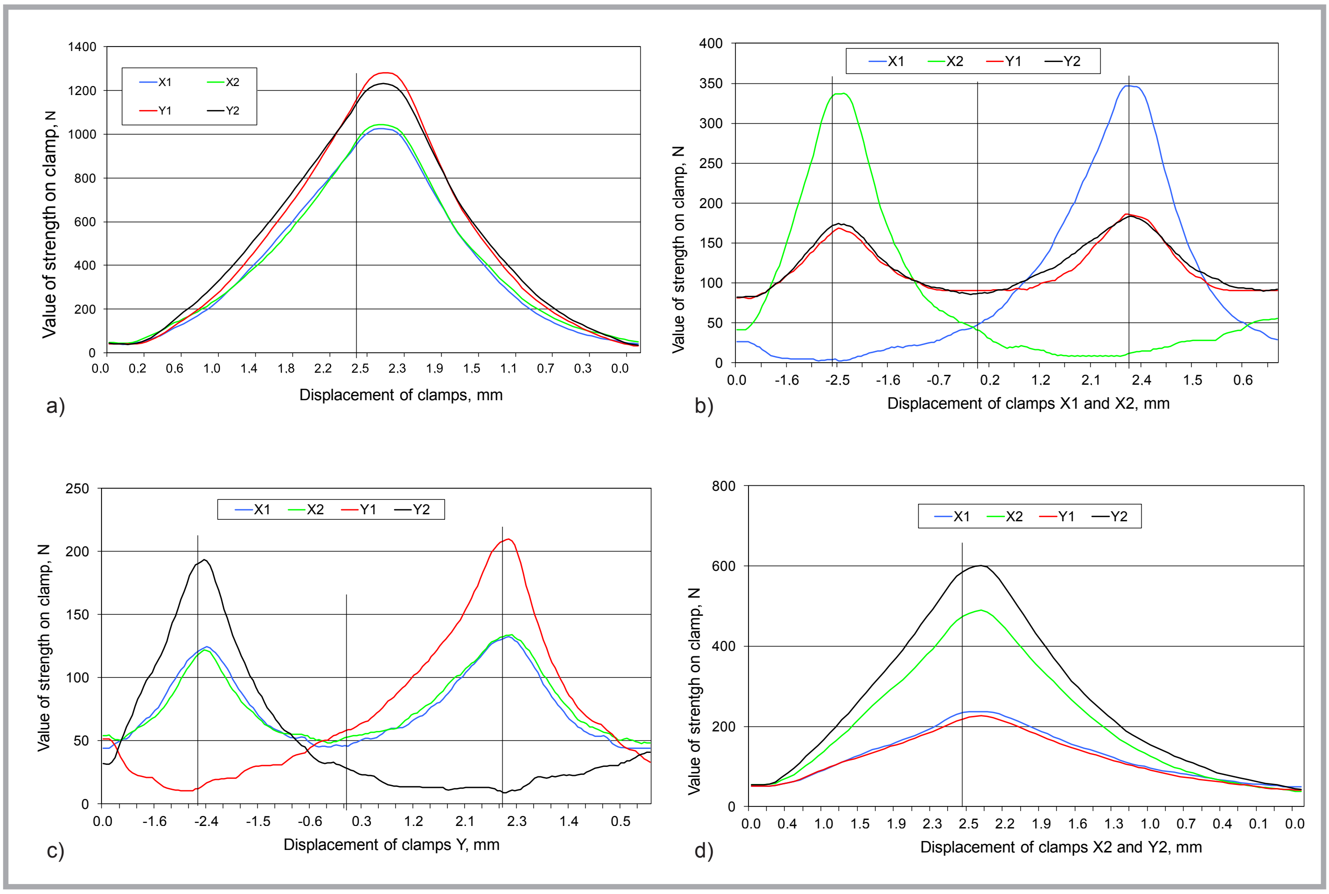

Figure 8. *Triaxial fabric; a) bi-directional stretching, b) oscillation towards X, c) oscillation towards Y, d) stretching with shear.*

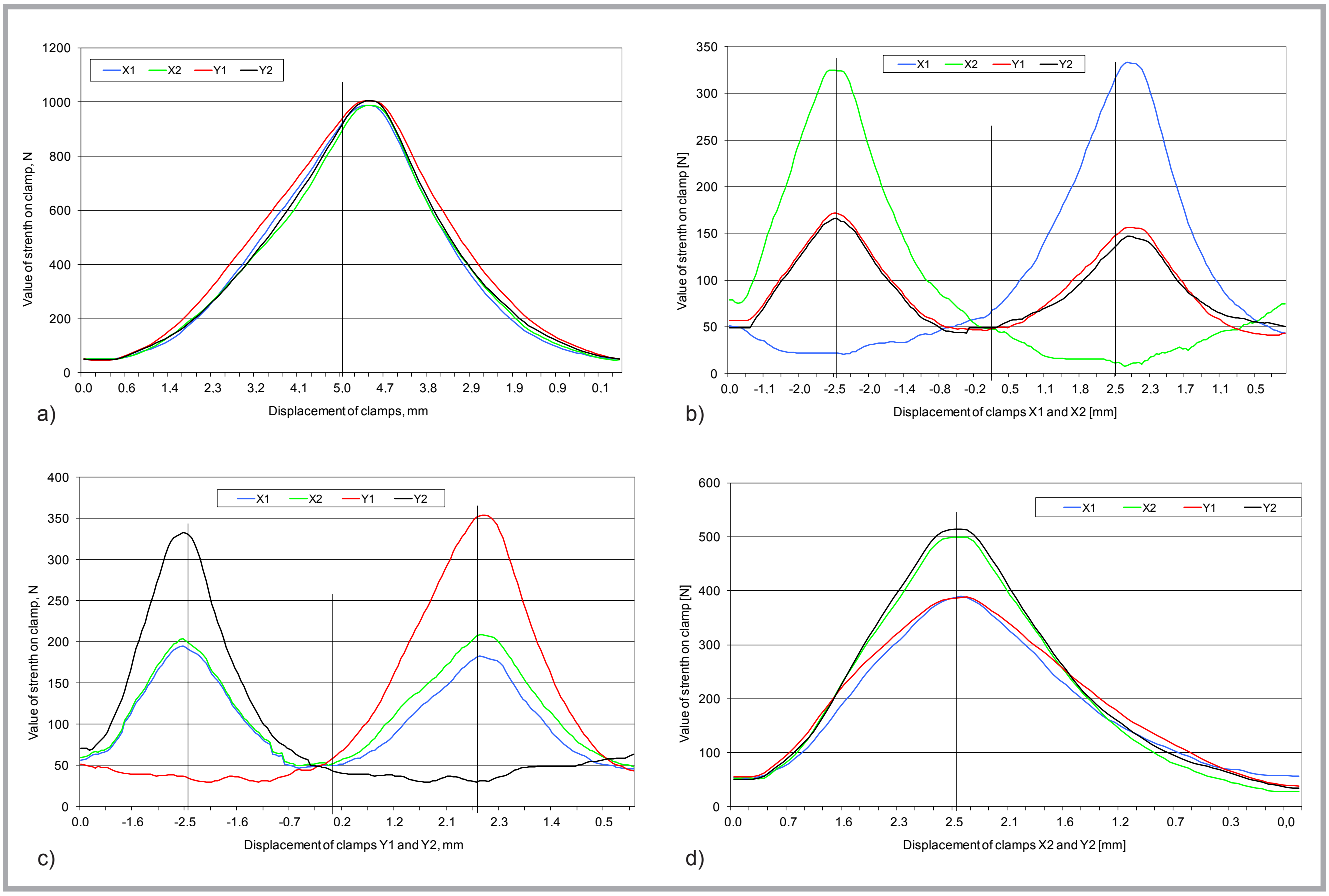

Figure 9. *Fouraxial NP fabric; a) bi-directional stretching, b) oscillation towards X, c) oscillation towards Y, d) stretching with shear.*

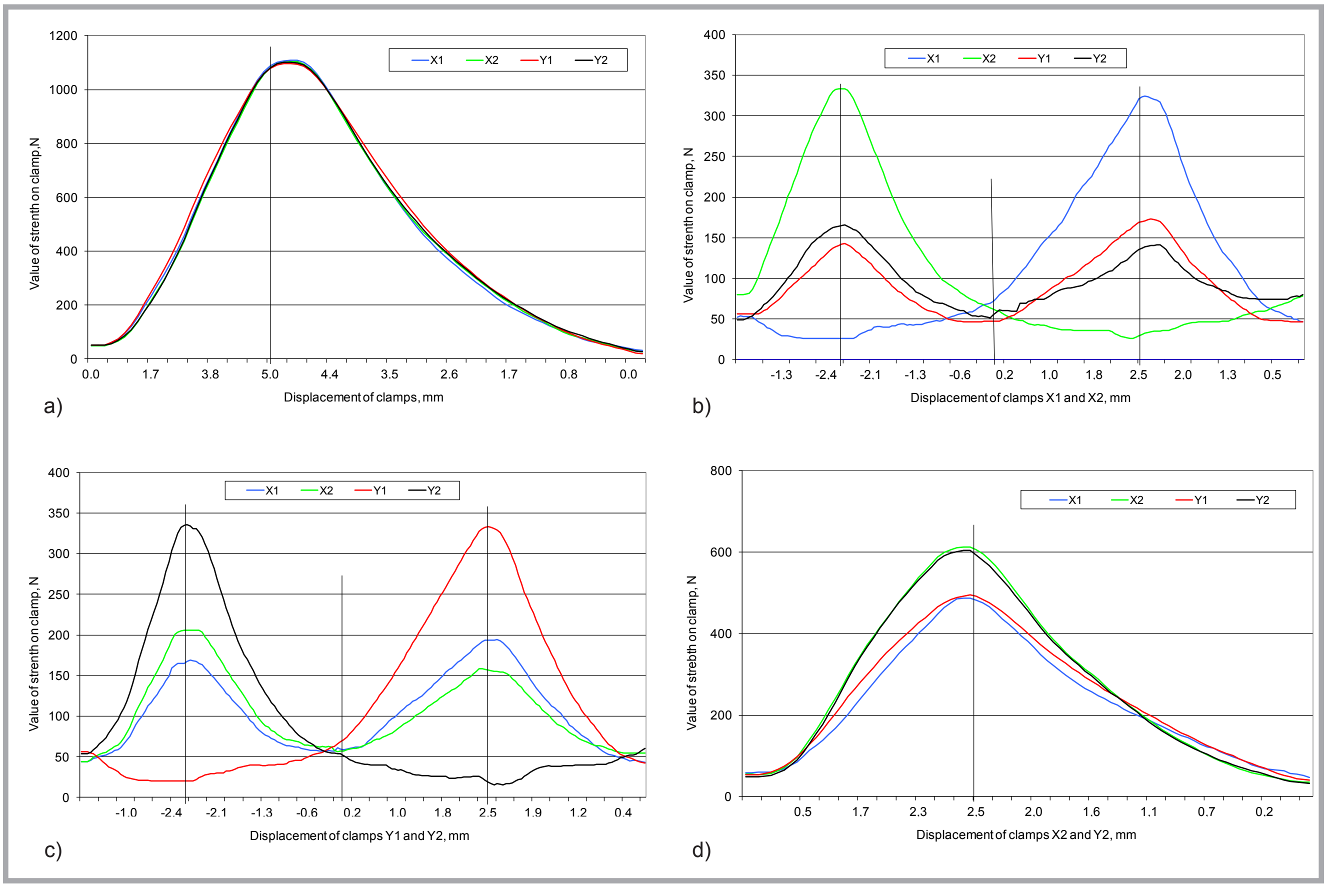

Figure 10. *Fouraxial NO/PO fabric; a) bi-directional stretching, b) oscillation towards X, c) oscillation towards Y, d) stretching with shear.*

The test was carried out with a switched-off rupture discriminator so that it was not stopped when a decline in the force value was recorded. Thus it was possible to analyse the entire process of sample destruction.

Results and discussion

1. Orthogonal fabric

Figure 7 (see page 46) presents the course of force changes occuring on the clamps while testing an orthogonal fabric.

The process of stretching an orthogonal fabric in two directions simultaneously indicates the symmetry of the fabric properties. This characteristic is confirmed by the graphs of forces occurring on the clamps during synchronous movements of clamps X while Y clamps stay motionless (***Figure 7.b***), and during synchronous movements of Y clamps with X ones being motionless (***Figure 7.c***). In both cases the fabric behaves in the same way i.e. the system perpendicular to the loaded one responds with a minimum stress increase, resulting from internal friction between the tapes forming the warp and weft arrangements in the fabric. The confirmation of this phenomenon is an increase in force on the pulling clamp. For example, in ***Figure 7.b*** it can be seen that the fabric is pulled by the X2 clamp first (when both clamps X1 and X2 move right synchronously), and then by clamp X1 (when both X1 and X2 clamps move synchronously to the left). Internal friction prevents the weft from moving along with the clamps of the load testing machine, hence the warp tapes try to move crosswise, which is manifested by a synchronous increase in forces registered on clamps Y1 and Y2, ***Figure 7.b***. An identical phenomenon of almost exactly the same intensity occurs when the force comes from the relocated warp system, ***Figure 7.c***. The phenomena registered and documented in ***Figures 7.b*** and ***7.c*** ultimately disqualify orthogonal fabric structures as a single-layer reinforcement for composites. The research demonstrates the mechanism of shear forces in the plane of the future composite reinforcement, and confirms the importance of precise supersaturation of such a fabric with resin. The lack of a clear response in the perpendicular direction confirms the low sensitivity of orthogonal structures to shear in the plane of the fabric. It was clearly shown by the next test based on oblique stretching of the fabric with clamps X2 and Y2, while clamps X1 and Y1 stayed motionless. ***Figure 7.d*** shows that the fabric responds almost exclusively to stretching since the maximum value of the forces corresponds to it. In this case only one X and one Y clamp move, so that the fabric is stretched by 2.5 mm, and not by 5 mm as in case of stretching with all four clamps. The value of the response in the form of stress corresponds to the stress state observed in the case of the displacement of all four clamps by 1.25 mm, see ***Figure 7.a***.

2. Triaxial fabric

Figure 8 (see page 46) presents the course of force changes registered on the clamps while testing a triaxial fabric.

The process of stretching a triaxial fabric simultaneously in two directions indicates a certain (about 18%) asymmetry of the fabric's directional properties. This characteristic is confirmed by the charts of to-and-fro movement with clamps X and Y. In both cases the fabric behaves significantly differently. At the same time, in a triaxial fabric a reaction perpendicular to the oscillation can be clearly seen, which is typical. It confirms the sensitivity of the triaxial structure to oblique loads in the plane of the fabric, coming from the tapes positioned diagonally between the clamps in the X and Y directions. The attempt to stretch the fabric by moving clamps X2 and Y2, which causes oblique stress and shear in the plane of the triaxial fabric, clearly illustrates this sensitivity. ***Figure 8.b*** shows that the fabric responds with greater stress while being stretched in the X direction than in the case of stretching in the Y direction, ***Figure 8.c***. Such a behavior of triaxial fabric is obvious and results from its structure and orientation of tapes with respect to the X and Y directions, see the description of sample orientation during the test included at the beginning of the chapter "Research Methodology". The research results presented confirm that in the case of using this type of structure for reinforcing composites, the directions incompatible with the main axes of the tapes will also be strengthened

3. Fouraxial fabric of NP structure

Figure 9 (see page 47) presents the course of force changes registered on the clamps while testing a fouraxial NP fabric.

The course of stretching a fouraxial fabric of NP structure simultaneously in two directions indicates an asymmetry of the fabric directional properties smaller than in the case of the triaxial fabric (about 12%). This characteristic is confirmed by oscillation charts with clamps X and Y (***Figures 9.b*** and ***9.c***). However, contrary to triaxial fabric, the fouraxial fabric of NP structure behaves similarly in both tests. Just like in the case of triaxial fabric, the reaction perpendicular to the oscillation can be clearly seen here. The result of the test confirms the greater and more uniform sensitivity of the fouraxial structure to an oblique load in the plane of the fabric, induced by the oblique (between clamps in the X and Y directions) position of the tapes. In all directions in the fabric there is the same number of tapes. ***Figure 9.d*** precisely illustrates this sensitivity by showing the result of stretching the fabric by moving clamps X2 and Y2, which induces oblique- shear stress in the plane of the fabric, asconfirmed by the similar courses of lines X2 and Y2 and those of lines X1 and Y1. The asymmetry of directional properties is in the case of a fouraxial fabric of NP structure significantly smaller than in that of a triaxial fabric, where the courses of lines X2 and Y2 are not that compatible. Such a behavior was expected when the fouraxial fabric structure was designed. When this type of structure is used for reinforcing composites, the directions which are incompatible with the main tape axes will also be strengthened much more effectively than in the case of a triaxial fabric

4. Fouraxial fabric of NO/PO structure

Figure 10 (see page 47) illustrates the course of force changes registered on the clamps while testing a fouraxial fabric of NO/PO structure.

The course of stretching a fouraxial NO/PO fabric simultaneously in two directions indicates better properties of the fouraxial in comparison to the NP fabric structure. The intention of modifying the structure of NP fabric was to "stiffen" it by reducing the difference in the take-ups of orthogonal fabrics interlaced together in a reciprocal turn of 45°. This effect was achieved, which is demonstrated by the higher stess value of NO/PO fabric compared to the stresses which arise in NP structures induced by the same displacements of the clamps of the load testing machine.

The comparison of test results shown in ***Figure 9.d*** and ***10.d*** shows an improvement of the symmetry of directional

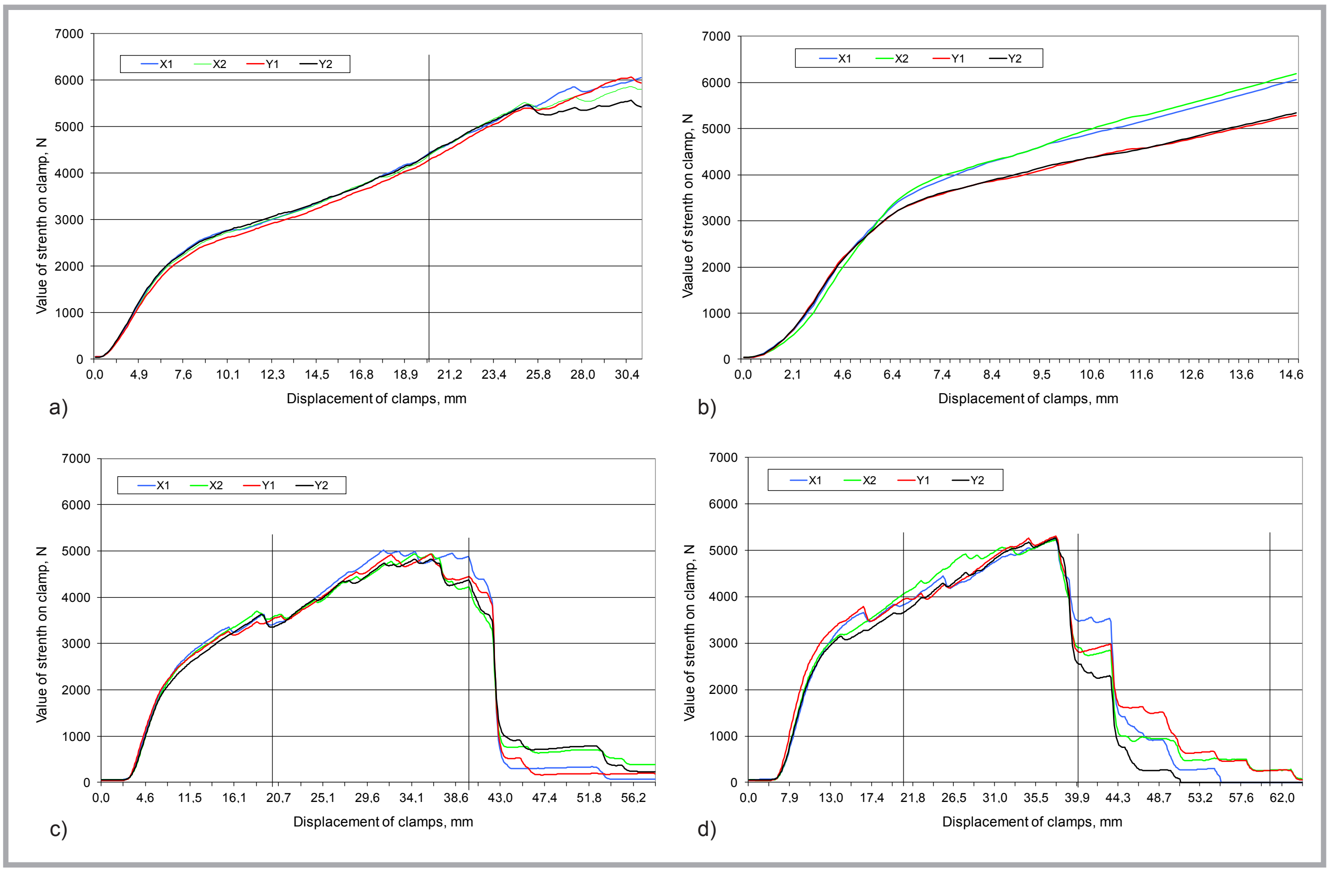

***Figure 11.** Stretching; a) orthogonal, b) triaxial, c) four-axial, d) fouraxial NO/PO fabric until distruction.*

properties of the fouraxial NO/PO fabric compared with the fouraxial fabric of NP structure.

Such characteristics of the fouraxial NO/PO fabric structure were expected when the structure was designed by introducing the interpenetration of two component orthogonal fabrics. When using this type of structure for reinforcing composites, the directions incompatible with the main axes of the tapes will also be strengthened much more effectively than in the case of a fouraxial NP fabric, made by braiding one orthogonal fabric with another one and rotating by 45°. More favorable conditions for cooperation with the composite matrix can also be expected, since the principle of the interpenetration of both component fabrics introduced provides "equal access to the matrix" for both fabrics.

5. Stretching the fabrics until destruction

Tests were carried out according to the procedures described in section 5 of the "Research methodology" (see ***Figure 11***).

The characteristics of stretching a classic orthogonal fabric (***Figure 11.a***) and triaxial fabric (***Figure 11.b***) are similar. In the classic fabric the first signs of destruction occurred under loading close to 5000 N, but within the working range of the load testing machine (security software stops the test when the force registered by one of the sensors exceeds 5800 N) no breakage was observed. Fouraxial fabrics (***Figure 11.c***) differ from one another in strength and susceptibility to deformation. Fabrics of NO/PO structure (***Figure 11.d***) are stiffer (less stretchy) and the first symptoms of destruction appear with a load of approximately 50% larger than in the case of fabrics of NP structure. The usefulness of applications in composites is determined by the Young modulus s = ΔF/ΔL calculated in the initial period of stretching, when the tensile curve has a rectilinear course, where ΔF – stands for a force increase, and ΔL means an increase in length. A higher value of the index defined in that way means a stiffer structure, which is less susceptible to deformation under the influence of tensile forces. For the fabrics tested, this index takes the following values: for an orthogonal fabric s_O = 289 N/mm, for a triaxial fabric s_{III} = 538 N/mm, for an NP fouraxial fabric s_{IVNP} = 280 N/mm and for a fouraxial NO/PO fabric $s_{IVN0/P0}$ = 414 N/mm. At the same time the analysis of the impact of the fouraxial fabric structure on the value of this index indicates how important the tape take-up ratio is in the case of fabrics used for the reinforcement of composites. Changing the method of mutual interlacing of orthogonal fabrics, rotated by 45° towards each other, from the NP to NO/PO arrangement increased the stiffness index by 48%. These research results suggest further directions of multiaxial fabric structure development in order to reduce the number of fabric layers necessary to ensure the required properties of composites used in conditions of multi- directional complex loading.

Conclusions

1. An orthogonal fabric possesses strong directional properties and therefore does not carry loads which are oblique to its main axes.
2. Any increase in the number of axes of the fabric results in improved directional properties and an increase in the degree of transfer of loads oblique to the main axes.
3. The bi-directional longitudinal rigidity of a multiaxial fabric – which is a desirable property in the reinforce-

ment of composites can be increased by changing the number of axes and reducing working-in of the tape in the fabric.
4. A multiaxial fabric may replace a package composed of many orthogonal fabrics when the reinforcement of a composite exposed to complex multidirectional loading is required.

The article presents fragments of research carried out at the Institute of Architecture of Textiles, Lodz University of Technology within project No. N507 454838, financed by the Polish National Science Center, entitled “Shaping mechanical properties of multiaxial woven structures designed for reinforcement of layered composites”

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