Textile & Leather Review

ISSN: 2623-6257 (Print) 2623-6281 (Online) Journal homepage: www.textile-leather.com Journal doi: 10.31881/TLR

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How to cite: Brnada S, Kovacevic S, Sabaric I, Drzaic L. Biaxial Cyclic Loading of Woven Fabrics. Textile & Leather Review. 2021; 4(3):149-159. https://doi.org/10.31881/TLR.2020.22

How to link: https://doi.org/10.31881/TLR.2020.22

Published: 7 September 2021

Biaxial Cyclic Loading of Woven Fabrics

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Article
UDC 677.024
DOI: 10.31881/TLR.2020.22
Received 18 December 2020; Accepted 31 March 2021; Published Online 14 April 2021; Published 7 September 2021

ABSTRACT

For the purpose of this paper, investigations were carried out on specifically designed fabrics with different structural parameters. The biaxial cyclic loading of fabrics and its consequences were investigated. The weave structures with the smallest weave units (plain weave, basket weave 2/2, rib weave 1/1 (2+2) and rib weave 2/2 (1+1) with the same warp and weft density (24 ends/cm and 24 picks/cm) were selected. Biaxial cyclic loadings of fabrics were performed on a newly developed patented device. The influence of the low level of cyclic loadings of fabrics on the change of tensile properties in warp and weft direction was investigated. The results showed that the low level of biaxial cyclic loading can lead to a permanent linear deformation of fabrics. Despite the fact that the forces that cyclically strain the fabric in two directions amount to 10% of the breaking elongation, after a certain number of cycles there is an irreversible deformation and reduction of breaking forces, but sometimes they can result in an increase in breaking forces. It was found that the tensile elongation of fabrics is affected both by thread crimping and by the structural properties of fabrics resulting from changes in the weave.

KEYWORDS

Biaxial cyclic loading of fabrics, Fabric deformation, Weave structures of fabrics, Tensile elongation of fabrics

INTRODUCTION

The market share of fabrics for technical purposes is increasing, as a substitute for many other materials such as steel, iron and generally components of massive constructions. In addition to their strength, resilience, durability and protection, they also feature other important properties, such as being the load-bearing component in composites, lightweight, pliable and breathable, all according to the targeted use. Fabrics used for technical purposes are exposed to extreme conditions, either weather conditions or various mechanical impacts. Multidirectional loading often occurs during the application of fabrics and can be long lasting and intense, such as in the application of fabrics in road construction, civil engineering, transport, industry, agriculture, protection, etc. Likewise, fabrics are often exposed to the low level of cyclical loading, such as in car seat covers, where deformation can occur after a certain time.

A fabric is an orthotropic material with two axes of symmetry (warp and weft direction) in which its mechanical properties are extreme (moduli, maximum breaking force, minimum elongation at break) [1,2]. The authors of the paper [3] performed an experiment on laminated fabric by subjecting it to uniaxial, uniaxial cyclic and biaxial cyclic loading to expose the detailed mechanical behaviours and determine proper elastic parameters for the laminated fabrics under specific stress states. They observed three degrees of tensile behaviour of the fabrics (crimp region, nonlinear transition region and yarn extension region). In order to be able to predict the behaviour of the fabric as a whole, more extensive research is needed regarding the low loads (up to 10% of the maximum breaking elongation) and a solution should be found when designing it. In their research [4], the authors divided the plain weave unit into small parts and applied a mechanical model to each of them in order to predict fatigue strength of a plain-woven fabric reinforced composite subjected to multiaxial cycling loads. They commented that the "agreement between the predicted and available experimental results is reasonable". The properties of fabrics, which depend on fibres, yarns and structures and their mutual contractions, have been investigated and presented in the literature [5-8].

For woven materials, there is a rule that the warp and weft run in the direction of the highest loading [9-11]. Due to the action of the external forces, the fabric is subjected to tensile loading. From the perspective of material behaviour, loading is the internal distribution of forces that creates an equilibrium in response to the loads impacting the fabric.

When the fabric is subjected to tensile and cyclic loading, its dimensional and mechanical properties change, and a material fatigue occurs [12,13]. Material fatigue should provide answers to very important questions, such as the expected number of cycles the material can withstand and that its mechanical properties are kept within the recommended areas of application. Most often these are low loads that occur in two or more directions. Fabrics exposed to these loads experience changes in properties, especially mechanical ones, which depend on two groups of factors:

a) The internal factors relating to the structure and the material, including fibres, yarn, fabric density, the mass and the weave structure.
b) The external factors relating to the test conditions, such as cycle duration, loading level and the number of cycles.

In their review, the authors discussed the results of experimental investigations under monotonic and cyclic loadings [14]. They noted that composite materials could exhibit complicated behaviour in the biaxial loading conditions that often exist in engineering practice. In conclusion, they indicate, among other things, that flat cruciform specimens are appropriate for a biaxial test, if the 'edge effects' can be overcome by introducing a central notch or deep-cut edge notches in the specimens. They also point out the simplicity of performing the biaxial test and interpreting the results.

In their paper [15], the authors investigated the fatigue of E-glass/polyester fabrics due to cyclic loading. They concluded that the fabric biaxial pre-stressing can extend the fatigue in the intermediate and low-stress regions of composites with woven fabric as reinforcement. Also, increased off-axis orientation is crucial for prolonging fatigue life. The aim of this paper is to examine the consequences of the low level of biaxial cyclic loading of fabrics of different structures, i.e., to investigate to what extent biaxial cyclic loading of fabrics affects tensile properties of fabrics.

In the study [16], uniaxial and biaxial tests were performed to analyse the biaxial cyclic behaviours with different stress ratios. The tests were performed on coated woven fabrics. They found that the material's tensile strength after cyclic loading remains almost unchanged, which may be related to the lower number of cycles and that the tensile behaviours under cyclic loading are mainly related to the stress amplitude, the temperature, and the structure of woven fabric.

In the paper [17], the authors stated that, although the uniaxial strength was studied extensively, it cannot properly characterize the real strength of the woven fabric composite due to the normal biaxial tensile state in operation service. They found that the biaxial strength equals the lower uniaxial strength multiplied by an amplification factor of 1.1–1.3 under a 1:1 stress ratio.

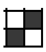
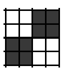
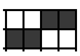
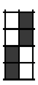
EXPERIMENTAL

Research was carried out on mechanical behaviour of fabrics that were subjected to conditions of biaxial cyclic loading in both warp and weft direction. The research was conducted on plain weave fabrics (P) and plain weave derivatives: basket weave 2/2 (B), rib weave 1/1 (2+2) (R1) and rib weave 2/2 (1+1) (R2). Due to their stable structure and loading resistance, these weaves are often used in the production of technical fabrics that will be subjected to cyclic loading during use (e.g., car covers, car seat covers, mobile buildings, road construction, civil engineering, etc.).

Materials

The basic parameters of warp and weft yarn are: 100% cotton, yarn count 36 tex, number of twists 505 twists/m, breaking force 4.26 N, elongation at break 6.4%, strength 11.8 cN/tex. The tests were carried out on fabrics of the same density in warp and weft (24 threads/cm) in four weaves. The samples were woven from the same lot of warp and weft on a Picanol air-jet weaving machine in the textile factory Čateks, Čakovec. Further fabric properties related to weave structures are listed in Table 1, which presents the design parameters of fabrics and their structural properties. The breaking forces and elongation at break are shown in Table 2.
The plain weave fabric has the highest mass per unit area, the smallest thickness, but also the greatest weft crimp (Table 1).

Table 1. Basic properties of fabrics related to weave structures

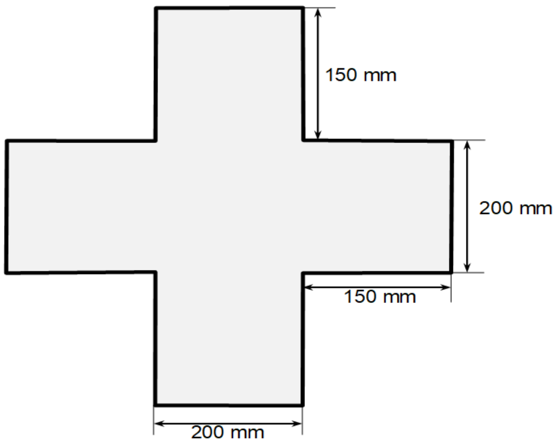
Weave	Designation	$\bar{X}$ / CV	Mass per unit area (g/m^2)	Thickness (mm)	Density (threads/cm)		Crimp (%)	
					Warp	Weft	Warp	Weft
Plain 	P	$\bar{X}$	186,7	0,332	24,2	24,0	7,9	8,2
		CV (%)	0,1	1,061	1,7	0	5,7	8,1
Basket 	B	$\bar{X}$	178,8	0,379	24,3	23,7	3,6	9,0
		CV (%)	0,6	0,949	2,0	2,0	4,2	6,4
Rib 1/1 	R1	$\bar{X}$	177,1	0,377	24,5	24,0	6,3	5,6
		CV (%)	0,7	0,886	2,2	3,4	5,1	5,3
Rib 2/2 	R2	$\bar{X}$	178,1	0,376	24,4	24,3	1,8	9,8
		CV (%)	0,9	1,152	2,1	2,0	6,8	5,5

Working methods and test equipment

The basic parameters of the fabric structure were calculated as follows: determination of mass per unit area was determined in accordance with the ISO 3801:1977, thickness of the woven samples was determined in accordance with the ISO 5084:1996, number of warp and weft threads per unit was determined in accordance with the HRN EN 1049-2:2003, and the determination of crimp of yarn in woven samples was conducted in accordance with the ISO 7211-3:1984, where warp and weft crimp are expressed in % as a length difference between the yarn woven in fabric and the straightened yarn in relation to the length of yarn in the fabric [18-21].

The testing of fabric tensile properties was carried out on the Textechno Statimat M tensile tester in accordance with the standard test method HRN EN ISO 13934-1:2008 [22]. The fabric samples were tested in warp and weft direction before and after cyclic loading. The device for samples preparation for measuring the resistance of technical textile materials to biaxial cyclic stress was patented under the patent number HR P20150735 A2. The number of loading cycles was 30,000 cycles and frequency was 80 cycles/min. The shape of the prepared sample is in a cross form (Figure 1b), with the dimensions of 500x500 mm, while the centre surface of the cruciform is 200×200 mm. The cyclic stress of the material is achieved by the vertical movement of a metal plate (floor), with the dimensions of 200×200 mm, with side rollers, which is acted upon by a force perpendicular to the surface of the sample from below. The force acting on the sample of the tested material is variable but could be calculated through the stiffness of the spring and the height of the floor at the current moment. After the cyclic loading, the tensile properties of the fabrics were tested in accordance with the modified ISO 13934 on three testing strips per sample direction. The dimensions of the mono-axial test specimens were 200x50 mm, wherein the longer side was subjected to the tensile loading. The force at constant elongation and the maximum force and elongation of the samples were recorded. Elongation was calculated as the ratio of the elongation of the test specimen from the initial length, expressed as a percentage.

a)



b)

Figure 1. (a) Biaxial loading apparatus for fabrics; (b) Sample dimension

RESULTS

Figures 2-5 show scattered diagrams of force-elongation point pairs for fabric samples. Point clouds were approximated by sigmoid curves, dose-response functions, and the area between the curves before and after cyclic preloading was calculated in order to determine the difference in mechanical behaviour of fabrics. Sigmoid dose-response function, or S curve approximates the data (stress or force/strain) for tensile mechanical behaviour of the woven fabric with very high accuracy.

The comparison of fabric breaking forces before and after cyclic loading with error intervals is shown in Figure 6, and regression lines and regression coefficients in Figure 7.

By examining the fabrics before and after the cyclic loading depending on the weave structure, their differences can be determined, even though they are woven from the same yarn on the same loom and under the same conditions.

Basket weave has the greatest thickness, transverse rib weave (R2) has the lowest warp crimp, but the highest weft crimp. Despite the fact that all samples were woven under the same conditions, there were large crimp differences in the warp direction (1.8% (R2) to 7.9% (P)) and in the weft direction (5.6% (R2) to 9.8% (R2)).

The breaking forces before and after cyclic loading per specimens and test directions differ and do not follow the course of changes in other parameters, indicating that the breaking forces are mainly affected by the weave structure (Table 2). Rib weave (R2) has the highest breaking force in the warp direction before and after the cyclic testing (484/482 N), while plain weave has the highest breaking force in the weft direction (535/533 N). Basket weave (B) has mostly the lowest breaking force in warp and weft direction (warp 449/481, weft 440/431). Plain weave (P) has the highest elongation at break in the warp direction (16/14%), while basket and rib weaves have the highest elongation at break in the weft direction.

Table 2. Basic properties of fabrics related to weave structures

Test conditions	Weave designation	Test direction	Breaking forces		Elongation at break	
			$\bar{X}$ (N)	CV (%)	$\bar{X}$ (%)	CV (%)
Before cyclic loading	P	Warp	476	3,2	16	2,7
		Weft	535	8,0	18	1,9
	B	Warp	449	5,9	9	3,4
		Weft	440	4,1	19	3,0
	R1	Warp	478	2,2	14	3,1
		Weft	449	1,8	13	3,0
	R2	Warp	484	1,9	9	1,4
		Weft	490	2,9	19	0,2
After cyclic loading	P	Warp	452	8,0	14	15,7
		Weft	533	1,9	15	4,0
	B	Warp	481	0,9	7	5,8
		Weft	431	8,4	14	1,0
	R1	Warp	467	1,6	11	6,3
		Weft	444	2,6	10	2,3
	R2	Warp	482	1,8	8	1,5
		Weft	484	1,9	13	3,6

The difference in breaking forces of the specimens that are subjected to cyclic loading, compared to the ones that were not, is very small, although the consistency of slightly lower breaking forces for the samples that were subjected to cyclic loading is evident. The reason for the small deviations are the already mentioned relatively low cyclic loads at which the fabric slightly deforms (level of crimp straightening). An exception, however, is the basket weave in the warp direction, where the breaking forces in the cyclically loaded specimens are higher even after repeated measurements. The threads within the basket weave are looser, which allows them to interact, they are stretched at low loads, the fibres inside the yarn approach each other and are, therefore, more resistant. In materials with a fibrous structure, the load acts in the direction of the fibres, and if it is small enough, it can act in such a way that it is further adjusted by stretching the structures, bringing the fibres closer together in a yarn, which then becomes more compact and stronger. The elongation at break was reduced by cyclic loading in all specimens in both test directions. The reason for this is the occurrence of the linear deformation, i.e., an extremely small elongation in the elongation direction, which could not be determined with statistical certainty. A comparison of crimp and mechanical parameters shows the correlation between elongation at break and crimping, whereby higher thread crimping in the fabric leads to higher elongation at break.

Figures 2 to 5 show the tensile stress diagrams per weave structures in the warp and weft direction before and after cyclic loading.

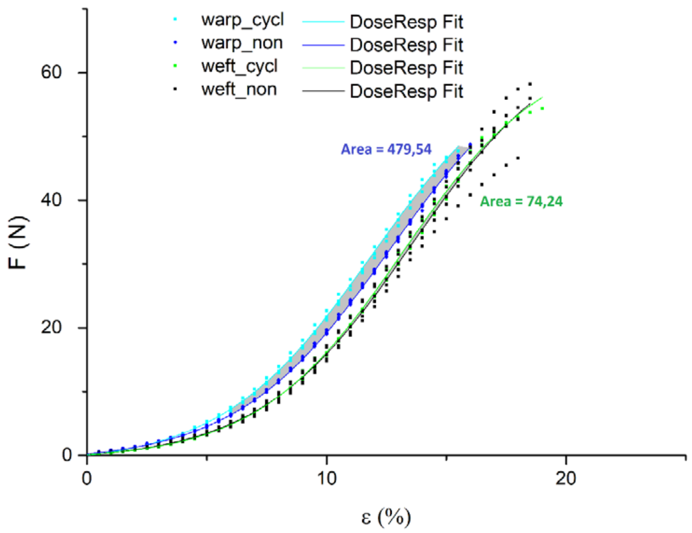


Figure 2. Tensile behaviour of the plain weave fabric before and after cyclic loading; where: warp_cycl – warp direction after cyclic loading, warp_non - warp direction before cyclic loading, weft_cycl – weft direction after cyclic loading, weft_non – weft direction before cyclic loading

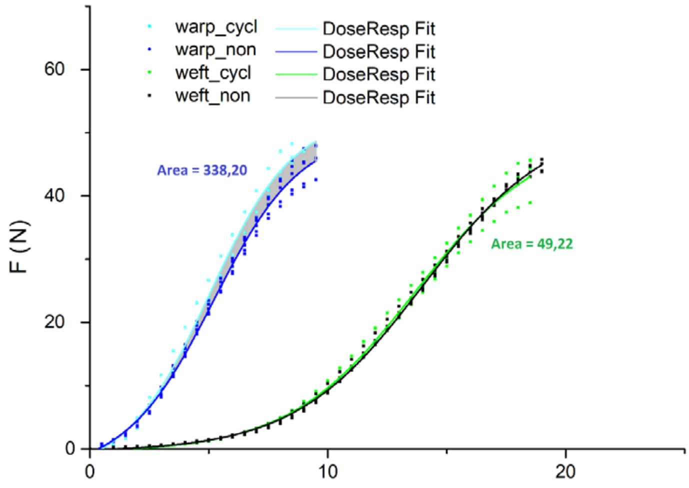


Figure 3. Tensile behaviour of the basket weave fabric before and after cyclic loading

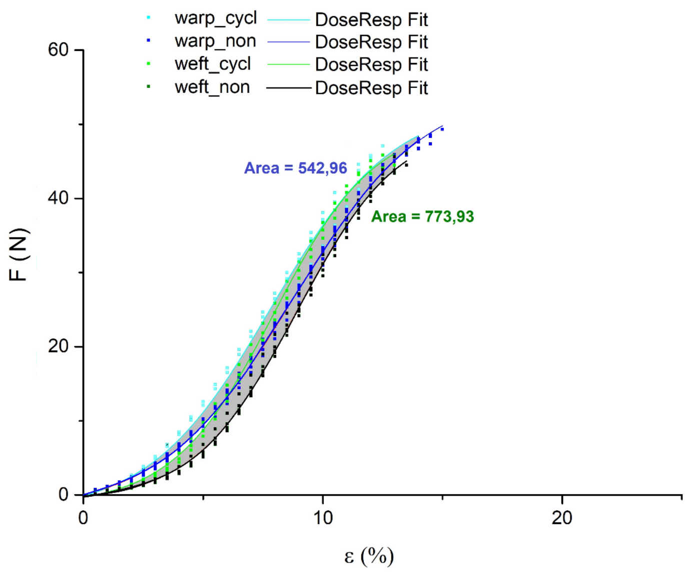


Figure 4. Tensile behaviour of the longitudinal rib weave fabric (R1) before and after cyclic loading

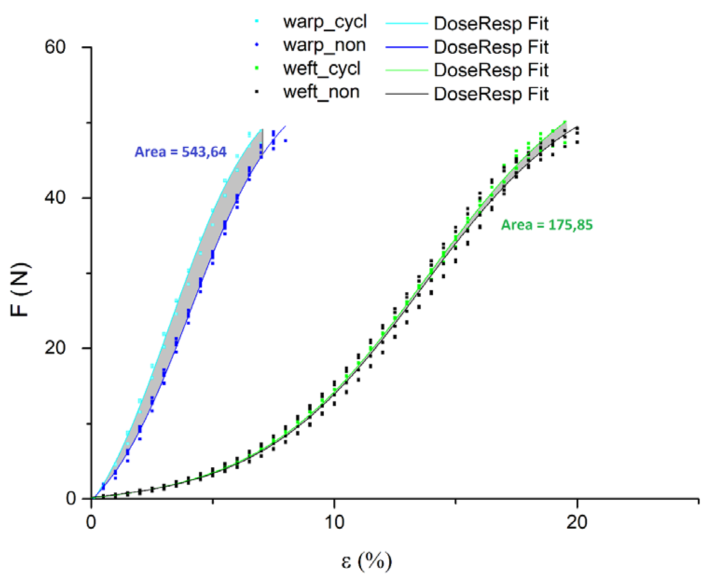


Figure 5. Tensile behaviour of the transversal rib weave fabric (R2) before and after cyclic loading

The results of the tensile test are shown by a scatter diagram, and the pairs of force-elongation points are approximated by the sigmoid curve, dose response. By integrating the curves in the tensile area (until break) and adjusting the base curve of the unloaded specimen, the area under the curves of the cyclically loaded and unloaded specimen is highlighted for each weave and direction. The obtained surfaces represent the difference in the work of rupture, i.e., the energy required to break the material. From the resulting curves it is apparent that the biggest difference in energy required to break the material was in the transverse rib weave, in both directions (warp direction 542.96x10^{-5}J and weft direction 773.93x10^{-5}J). In other samples, the differences in the warp direction were greater than in the weft direction. The reason for this is a greater elongation of the samples in the weft direction relative to the direction of the warp, which has a higher tensile stiffness, i.e., higher stress. In all cases, the non-linear behaviour of the stress-strain curves graphically displayed in the coordinate system, which were subjected to tensile loading until they break, is obvious. At the beginning of the elongation process, the yarn system was elongated for a longer period of time at low loads, especially in the weft direction. Thus, in the first part of the curve the length of the nonlinear part of the stress curve depended on the crimping of the longitudinal thread system. Higher crimping resulted in a longer length of the nonlinear part of the curve. During the tensile elongation of the fabric on the tensile strength tester, the longitudinal threads were stressed and lied close to each other, while the transverse threads were free and wrapped more and more around the longitudinal threads. In this part of the diagram, energy differences are visible for all the samples, which increase as the elongation progresses.

The resistance created by the longitudinal threads directly affects the breaking force (Fig. 6). The percentage of change was calculated as the difference of the breaking force of the samples before and after the cyclic load in relation to the breaking force of the samples before the cyclic load. The percentage of change was more significant in the direction of the warp, with smaller values of crimp, especially in the case of the samples of plain and basket weave.

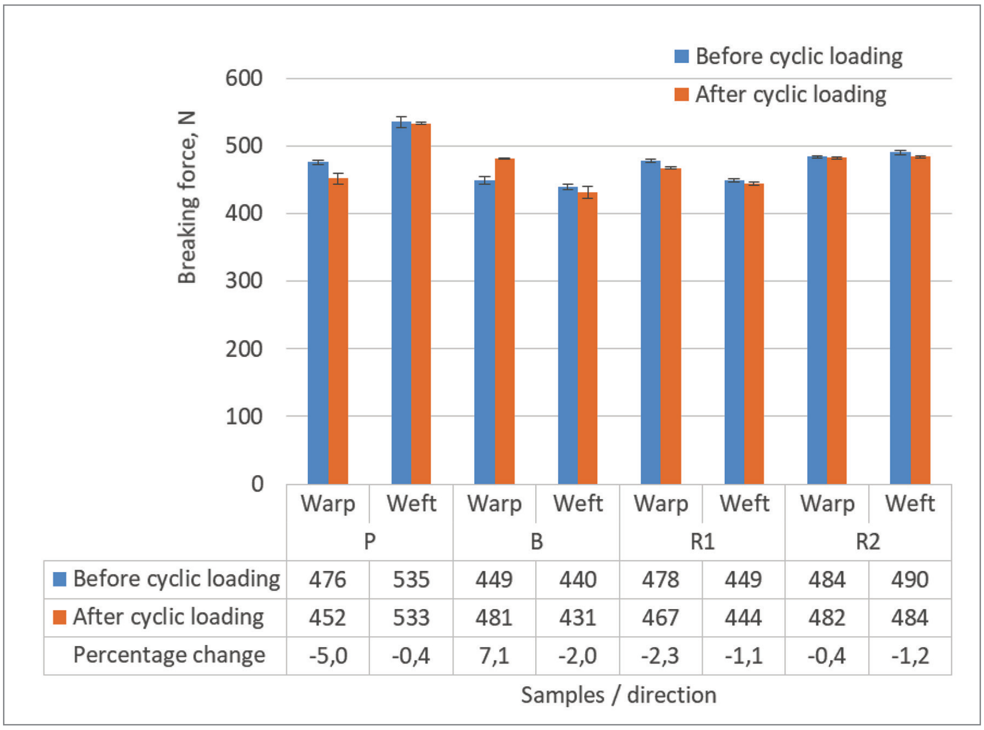


Figure 6. Breaking forces of the fabrics before and after cyclic loading with error intervals

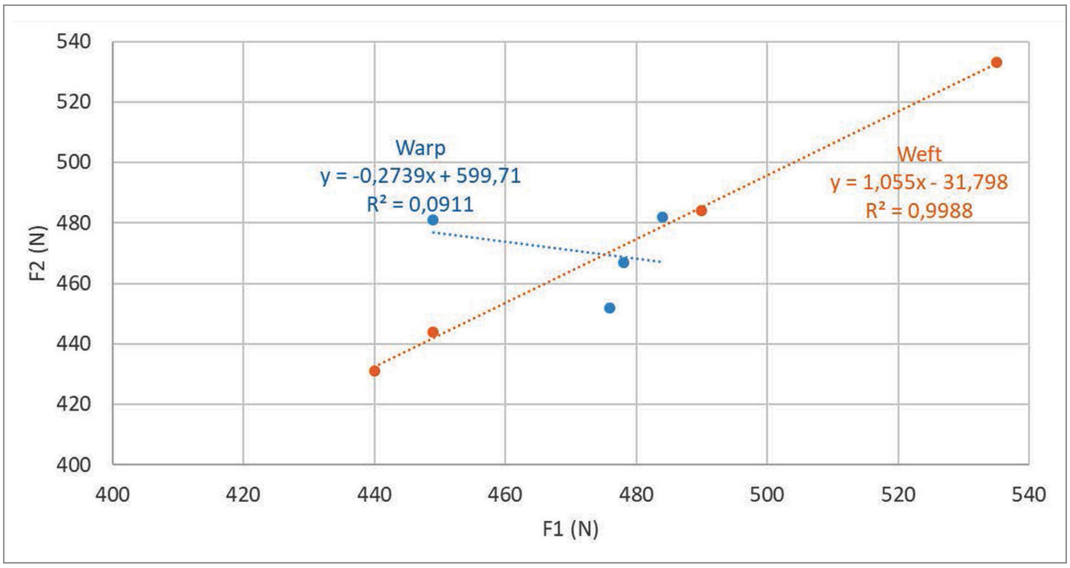


Figure 7. Regression lines and regression coefficients for the forces at break before and after cyclic loading; F1 – breaking forces before cyclic loading (N), F2 – breaking forces after cyclic loading (N)

Scattering points are significantly different between warp and weft (Fig. 7). The scattering values of the breaking forces before and after cyclic loading in the warp direction are significantly lower than in the weft direction, but further away from the approximate regression line, resulting in a lower regression coefficient (R^2=0.0911). The weft direction has more scattered values, but closer to the approximated line, so the regression coefficient is higher and amounts to R^2=0.9988.

CONCLUSION

The following conclusions can be drawn from the analysis of the results obtained:

- Fabric weave has a considerable influence on the mechanical properties of a fabric, especially the breaking forces before and after cyclic loading in warp and weft direction.
- Lower crimp leads to greater changes in the tensile mechanical behaviour of woven fabrics subjected to cyclic preload in the observed direction, due to higher tensile stiffness.
- Biaxial cyclic preloading at low loads has different effects on the deformation of the fabrics in warp and weft direction, which depends on the crimp that affects the rate of change of tensile stiffness during stretching. In all the samples, the values of elongation at break is lower after cyclic loads compared to before, which results in an increase in the tensile stiffness. The percentage of changes of elongation at break for the samples subjected to the cyclic load relative to the ones before, in warp directions, ranges from 11,1 to 22,2%, and in the weft direction from 16,7 to 31,6%.
- Biaxial cyclic loading at low loads compensates for forces in the threads, which can sometimes lead to an increase in the breaking forces (e.g., basket weave in the warp direction), but at the same time to a lower elongation of the fabric.
- Woven fabric in plain weave has the highest values of the breaking force, but it is simultaneously the one most affected by the cyclic loading. Due to the compactness of the structure, the resistance to tensile deformation (tensile stiffness) of the plain weave fabric is the highest (in relation to its derivatives), which is why it endures the greatest stress. In these conditions, the cyclic stress causes greater fatigue of the material, which is manifested in reduced mechanical properties.

This paper makes contribution to the study of fabrics woven in different weaves at the low level of biaxial cyclic loads (less than 10% of elongation at break).

Author Contributions

Conceptualization – S.K. and S.B.; methodology – S.B.; formal analysis – S.K., L.D. and S.B; investigation – L.D. and S.B; resources – L.D. and S.B; writing-original draft preparation – S.K. and S.B; writing-review and editing – S.B.; visualization – S.K., S.B. and I.S.; supervision – S.K. and S.B. All authors have read and agreed to the published version of the manuscript.

Funding

„This work has been fully supported by the Croatian Science Foundation under the project number IP-2018-01-3170”

Conflicts of Interest

The authors declare no conflict of interest.

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