Mir Reza Taheri Otaghsara,
***Ali A.A. Jeddi,**
****Jamshid Aghazedeh Mohandesi**

Department of Textile Engineering, Amirkabir University of Technology,
Tehran 15914-Iran.
E-mail: mtaheri@jdcord.jd.ac.ir

***Department of Textile Engineering, Amirkabir University of Technology,**
Tehran 15914-Iran
Corresponding author, e-mail: ajeddi@aut.ac.ir

****Department of Mining and Metallurgical Engineering, Amirkabir University of Technology,**
Tehran 15914-Iran.
E-mail: agazad@yahoo.com

Tensile Property and Fatigue Behaviour of Warp Knitted Fabrics

Abstract
Several two fully threaded guide bar warp knitted structures with three different course densities (cpc) were knitted from polyester textured yarns, and their tensile properties and fatigue behavior were investigated. Tensile tests were applied to determine the tensile behaviour of the fabrics and obtain the parameters controlling fatigue behaviour. A number of cycle amplitudes, such as 2, 4, 6, 8, 10 and 12 mm, were applied in fatigue tests. The existence space for yarn movement and the length of the underlaps were considered as structural parameters influencing the corresponding mechanical behaviour. The results show that with an increase in the underlap length, the breaking strain decreases, and the breaking strain in fabrics with a longer underlap in the front guide bar is more than those with the same underlap length in the back guide bar. There is no meaningful relationship between cpc and breaking stress. Repeated extension causes stress relaxation and secondary creep and subsequent strain softening in warp knitted structures. The cyclically stabilised stress of fabrics was increased by raising the amplitude of extension and/or by increasing the length of the underlap. Also the cyclic stabilised stress of fabrics with a longer underlap in the back guide bar was higher than those with the same length of the underlap in the front guide bar. There is no distinguished trend between the cyclic stabilised stress and cpc of fabrics.

Key words: *warp knitted fabrics, cyclic loading, fatigue, tensile, stabilised load, strain softening, fabric density.*

Introduction

The fatigue behaviour of warp knitted fabrics is important, since during use as apparel or industrial textiles, they are more likely to undergo repeated rather than static loading. Hence, under a cyclic tension the mechanical properties of a fabric tend to decay more than in the application of a static tension. This phenomenon can be attributed to the fatigue behaviour of fabrics, because fatigue is the failure or decay of the mechanical properties of a material after the application of repeated stress or strain. The structural parameters and condition of cyclic loading play a basic role in the fatigue behaviour of textile materials. The effects of loading parameters and structural specifications on the fatigue properties of textile fibres have been investigated by several researchers [1 - 7]. Narisava et al. [8] investigated the fatigue of nylon fibres at a fixed extension stroke without the take up of non-recoverable elongation. They observed that the stress amplitude gradually decreased to a stationary value with an increasing number of fatigue cycles.

Frank and Singleton [9] observed that the endurance of Nylon, Polyester, and Viscose rayon filament yarns against cyclic extension depends on the structure and physical properties (regain and thermoplastic property) of these yarns. Jeddi et al. [10] reported that fibre elongation, fibre slippage and yarn decrimping are factors that influence the fatigue life of cotton-polyester blended spun yarns. Also, they showed that the Polyester component in these yarns results in a significant improvement in fatigue resistance under tensile cyclic loading.

Kobliakov et al. [11] investigated the tensile fatigue behaviour of woven and weft knitted fabrics under different strokes and frequencies of cyclic straining. They showed that by increasing the stroke, deformation (i.e. the ratio of non-recoverable elongation to the initial length of the fabric specimen) increases; however, they concluded that by increasing the frequency of cyclic loading, this deformation decreases. Jeddi et al. [12] investigated the fatigue behaviour of warp knitted fabrics. They attributed the fatigue behaviour of fabrics to their structure and showed that the final deformation and tensile modulus of fabrics increases as the number of fatigue cycles rises, during which the tensile breaking extension decreases.

Ben Abdessalem et al. [13] studied the behaviour of plain cotton knitted fabrics under a large number of cyclic elonga-

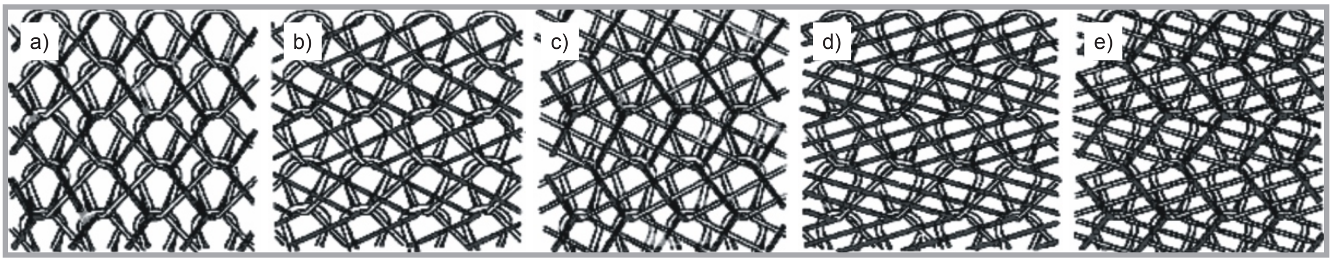

Figure 1. *Double guide bar warp knitted fabrics: a) Tricot; b) Locknit; c) Reverse Locknit; d) Three needle Satin; e) Three needle Sharkskin.*

tions. In this investigation the fatigue test applied to fabrics involved a variation in fabric dimensions, and a permanent deformation that persists after relaxation.

The objectives of this study are to investigate the tensile and fatigue behaviour of warp knitted structures and the effects of fabric structure, course density (cpc) and the amplitude of cyclic extension on the fatigue behaviour of such fabrics by on line data acquisition using a standard fatigue testing machine.

Material and methods

In this study, two fully threaded warp knitted fabrics with guide bars were produced from polyester textured filament yarn with a count of 11.2 tex (100 den). The fabric structures were Tricot, Locknit, Reverse Locknit, three needle Satin, four needle Satin, three needle Sharkskin and four needle Sharkskin. Each of these structures was knitted at three different course densities (15, 20 and 25 course per centimeter "cpc"). The fabric structures are shown in ***Figure 1***. The fabric samples were knitted on a Karle Mayer Ketten KH2 machine, with gauge 28 (28 needles per inch). All the fabrics were washed after the knitting process to remove spin finish and industrial oil contaminants, and then heat set. The dimensions of the fabric samples changed slightly after the washing and heat set processes. ***Table 1*** shows the fabrics' characteristics.

Table 1. *Characteristics of knitted fabrics; FB - front guide bar; BB - back guide bar; cpc - course per cm; wpc - wale per cm.*

Fabric Structure, Number of underlaps		Nominal cpc	Fabric code	Run-in, cm		Fabric density, cm^{-1}	
FB*	BB*			FB	BB	cpc	wpc
Tricot		15	T_1	163.3	153	20.2	12.1
		20	T_2	142.7	138.7	23	13.5
1	1	25	T_3	135.7	127	25.2	14.7
Locknit		15	L_1	208	156.4	18	14.8
		20	L_2	190	135	21.1	15.9
2	1	25	L_3	176.7	126	23.1	16.8
Reverse Locknit		15	RL_1	168.5	196	18.1	13.1
		20	RL_2	153	177.5	21.7	13.8
1	2	25	RL_3	143.4	168.7	25.2	13.7
Three needle Satin		15	ST_1	250.5	155	16.8	15.8
		20	ST_2	231	127	20.5	16.5
3	1	25	ST_3	216	121.5	22.7	16.8
Four needle Satin		15	SF_1	289	155	16.4	16.2
		20	SF_2	271.5	129	20.5	16.9
4	1	25	SF_3	259.4	22.4	23	16.8
Three needle Sharkskin		15	SHT_1	171.5	234.5	17.5	13.1
		20	SHT_2	153	221.5	21.7	13.7
1	3	25	SHT_3	150	207.1	23.5	13.7
Four needle Sharkskin		15	SHF_1	170.5	279	17.7	13
		20	SHF_2	148	274.5	21.3	2.6
1	4	25	SHF_3	148	267.5	22.6	12.5

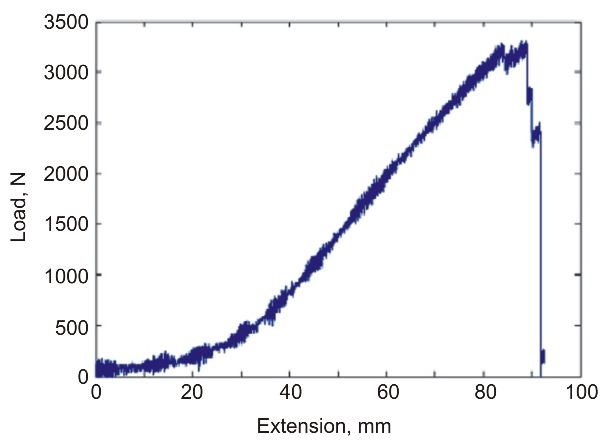

Figure 2. *Typical load-extension diagram of fabric T2.*

Tensile tests

In order to study the tensile properties of the fabric samples and obtain the parameters of cyclic tests, the fabric samples were tested on an Instron 8502 servo-hydraulic testing machine. Because of the high load capacity (± 500 kN) of the testing machine, specimens of 50 cm width were eight folded to increase the accuracy of measurements. For each fabric structure five specimens of 50 mm gauge length were tested in the course direction. The reason for choosing the 50 mm gauge length is the limitation of the movement course of the testing machine's moving clamp. A typical load-extension diagram (T2) is shown in ***Figure 2***.The diagram of load-extension for all the fabrics has two slopes. The angle of the first slope is closer than the second one and is separated by a knee, which was taken into consideration as a criterion for obtaining the amplitude of cyclic extension in fatigue tests.

Fatigue tests

The hysteresis loops of a material generally stabilises after cycling for a relatively short duration, and the material achieves equilibrium conditions under the strain limits imposed [14]. In such a case the cyclic stress-strain response of the material may be quite different from the initial monotonic response. Cyclical stress-strain curves may be obtained by several methods [14]. **I)** A series of companion samples may be cycled within various strain limits until the respective hysteresis loops become stabilised. The cyclic stress-strain curve is then determined by fitting a curve through the tips of the various superimposed hysteresis loops. **II)** A faster method for obtaining cyclic stress-strain curves is by multiple step testing, wherein the same sample is subjected to a series of alternating strains of increasing magnitude. In this manner one specimen yields to several hysteresis loops, which may be used to construct the stress-strain curve. **III)** An even quicker technique involving only one sample has been found to provide excellent results and is used extensively in current cyclic strain testing experiments. In this method the specimen is subjected to a series of blocks of gradually increasing and subsequent decreasing strain excursion. In the present investigation the first method was used to achieve more accuracy in the fatigue tests.

An Instron 8502 servo hydraulic testing machine –similar to that used in the tensile test- was used for the fatigue tests. The specimens prepared for the fatigue tests were similar to those in the tensile tests. A gauge length of 50 mm was selected, based on the suggestion of the Instron Company, for cyclic frequency limitation in the testing machine. The amplitude of cycling was selected as 2, 4, 6, 8, 10 and 12 mm, thus cyclic loadings were carried out in the second slope region of the load-extension diagram of the fabric samples. The frequency of the cycling was set at 0.5 HZ, and the data sampling rate at 2 HZ. One sample was tested for each amplitude of extension. All the fatigue tests were carried out under a preload of 500 N. This preload caused an extension, which is settled down in the second slope of the load-extension diagram for all the fabric samples. In the present study FLAPS (Fatigue Life Analysis System) software was applied to run the fatigue tests and data acquisition. Data from all samples was obtained during 500 cycles.

Due to the difference between the fabric course densities, the stress imposed on the fabric samples (σ) was calculated according to the *cN*/course (*cN/c*):

$$\sigma = 100 \times \frac{Load}{W \times CPC}$$

Where *W* is the sample width (50 cm) and *CPC* is the course density (course cm $^{-1}$).

Results and discussion

The amplitude of slippage and movement of the components over each other due to tensile tension is one of the important factors influencing the elastic behaviour of materials. In warp knitted fabrics two structural parameters have important roles in fabric elasticity [12]:

I) ***the space available for yarn movement;*** this space allows yarn movement over each other inside the fabric structure. It is formed between the overlaps and the front guide bar underlap. If sufficiently large, the back guide bar underlap can move easily.

II) ***The length of the underlap***; with an increase in the length of the underlap, the strain in the course direction may decrease, while in the wale direction it increases.

As regards the elasticity of warp knitted fabrics, the space available for yarn movement plays the main role rather than the length of the underlap. These two parameters have an apposite effect on fabric elasticity.

Tensile properties

Tensile properties of the fabrics studied are shown in ***Table 2. Figure 3*** shows graphically the average breaking elongating of the fabrics used in the tensile tests. As shown in ***Figure 3***, the breaking strain in fabrics with a longer underlap in the front guide bar is more than those with the same length of underlap in the back guide bar (L > RL, ST > SHT and SF > SHF). This is due to the first parameter, which means a larger space available for the back guide bar underlap in fabrics L, ST and SF, as was explained in our previous work [12]. This larger space causes an increase in the yarn movement of these fabrics. Also, ***Figure 3*** shows that by increasing the underlap length, the breaking strain decreases (SF < ST < L < T and SHF < SHT < RL < T); this phenomenon can be attributed to the latter parameter, i.e. the length of the underlap in the front guide bar increased from T to L, ST and SF, and the length of the underlap in the back guide bar increased from T to RL, SHT and SHF.

It can be seen from ***Figure 3*** that with an increase in cpc, the breaking strain decreases. This phenomenon is the result of the closer angle between the underlaps and the direction of the tensile load in fabrics with a higher cpc ($T_3 < T_2 < T_1$, $L_3 < L_2 < L_1$, $RL_3 < RL_2 < RL_1$ and …). The tenacity of fabrics rises by increasing the cpc (***Table 2***). The main reason for this behaviour is the presence of more courses in samples of higher cpc. As was expected, with an increase in cpc in fabrics RL, SHT and SHF, the breaking stress increased. However, it is interesting that fabrics T, L, ST and SF had a quite opposite result, i.e. with an increase in cpc, the breaking stress decreased, during which the tenacity increased

Table2. *Tensile properties of studied fabrics.*

Fabric code	Breaking strain, %	Tenacity, N	Breaking stress, cN/c
T_1	170.8	3072	304.2
T_2	167.2	3277	285
T_3	163.7	3509	278.6
L_1	147.5	3142	349.2
L_2	144.2	3344	317
L_3	143.1	3898	337.6
RL_1	150.3	3635	401.6
RL_2	131.3	4710	434.2
RL_3	113.6	5743	455.8
ST_1	119	3968	472.4
ST_2	114.4	4154	405.2
ST_3	110.6	4323	380.8
SF_1	114.6	5873	716.2
SF_2	109	6278	612.4
SF_3	102.6	6636	577
SHT_1	106.6	5340	610.2
SHT_2	93.6	7075	652
SHT_3	84.7	7767	661
SHF_1	92.2	7956	899
SHF_2	77.6	9643	905.4
SHF_3	74.5	10350	916

Figure 4 shows the relationship between the fabric structure and breaking stress for the fabric samples with nominal cpc 20. This figure shows that the breaking stress of fabrics with a longer underlap in the front guide bar is higher than those with shorter a underlap (SF > ST > L > T), also the breaking stress of fabrics with a longer underlap in the back guide bar

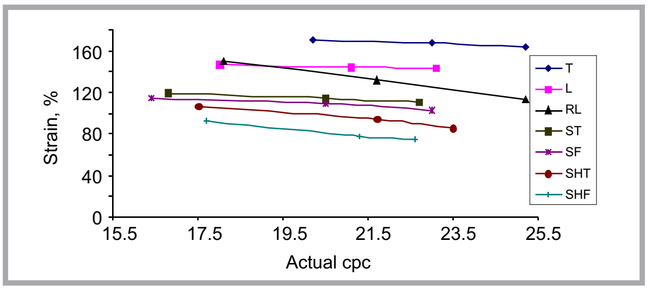

Figure 3. *Breaking strain of fabrics of different actual cpc.*

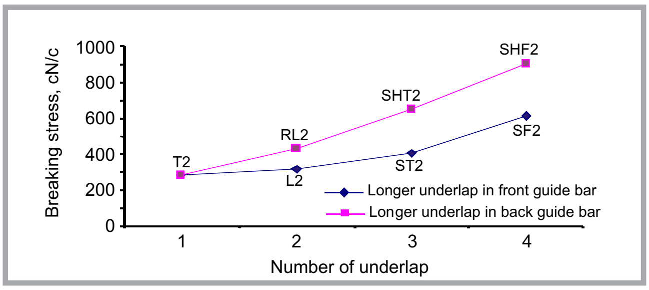

Figure4. *Breaking stress of the fabric samples with nominal cpc 20.*

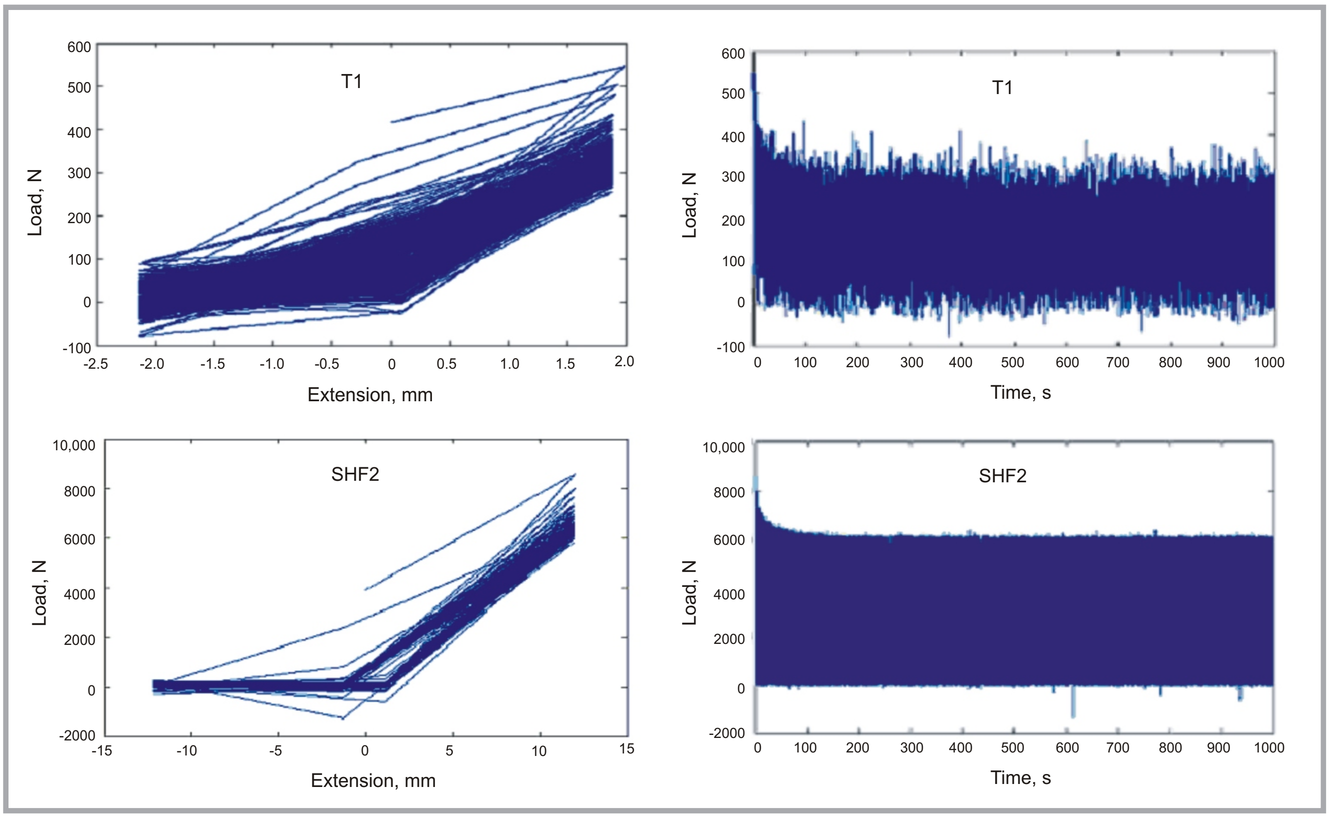

Figure 5. Typical diagram of load – extension and load – time of samples T_1 (amplitude of cycling = 2 mm) and SHF_2 (amplitude of cycling = 12 mm).

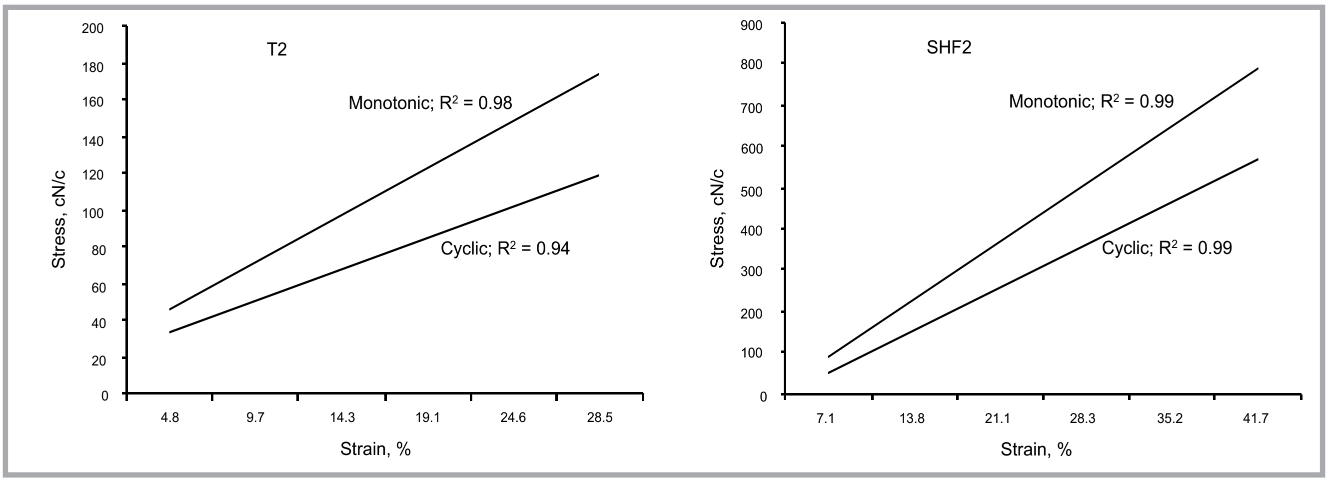

Figure 6. *Monotonic and cyclically stabilised stress-strain curves for fabric samplesT2 and SHF2.*

is higher than those with a shorter underlap (SHF > SHT > RL > T). This phenomenon can be attributed to the second structural parameter of warp knitted fabrics. In addition, there are more yarns between the two adjacent courses and wales of fabrics with a higher number of underlaps. It can be seen from ***Figure 4*** that the breaking stress of fabrics with a longer underlap in the back guide bar is higher than those with the same length of underlap in the front guide bar (RL > L, SHT > ST and SHF > SF). This is due to the first structural parameter, i.e. less available space for the movement of the back guide bar underlap in fabrics with longer back guide bar underlaps. The placing of the back guide bar underlap between the front guide bar underlap and overlaps causes the limited movement of the back guide bar underlap.

Fatigue properties

Figure 5 shows a typical diagram of the load – extension and load – time for samples T1 and SHF2 in the cyclic test. It can be seen from this figure that the maximum load gradually decreases in subsequentcycles, and there is a hysteresis loop where its width decreases gradually. The trend of maximum load variation in successive cycles shows that this load will reach a constant amount as a cyclically stabilised load, and the fabric samples achieve an equilibrium condition for the corresponding strain imposed . In this study, the stress in the first cycle was taken into consideration as monotonic stress for the given strain. The pre-extension of fabrics for a 500N preload (PE), the amplitude of the cycling (AC), the maximum stress in the first cycle (σ_1), and the maximum stress at stabilisation (σ_2) are tabulated in ***Table 3***.

Figure 6 shows typical monotonic and cyclically stabilised stress-strain regression curves for Tricot (T2) and four needle Sharkskin (SHF2) structures with nominal cpc 20. It can be seen that a cyclically stabilised stress-strain curve is placed under the monotonic stress-strain curve, which means that the fatigue process causes strain softening in fabrics [14]. This phenomenon can be explained as:

1. The application of a load on the fabric causes yarn straightening and loop deformation [13] in the direction of the load applied. These yarn deformations do not recover immediately but rather progressively with time. This factor causes stress relaxation in the yarn with time.
2. The preload and cyclic extension applied to fabrics during cyclic extension causes the stress relaxation of yarn in the fabric structure. This factor causes some secondary creep (non- recoverable time dependent extension) in the fabric as the tests proceed [6 - 10, 12, 13 and 15].

The linear regression plot of the relationship between the cyclically stabilised stress and amplitude for the cycling of all the fabric structures with nominal cpc 20 is demonstrated in ***Figure 7***. The coefficient of correlation (R^2) in all the regressions is above 0.95. As is expected, by increasing the cyclic amplitude, the cyclically stabilised stress increase. This figure shows that the cyclically stabilised stress increases with an increase in the length of the underlap (SHF2 > SHT2 > RL2 > T2 and SF2 > ST2 > L2 > T2). This seems to be due to the presence of more yarns between the two adjacent courses and wales of fabrics with a higher number of underlaps. Also it can be seen from ***Figure 7*** that the cyclically stabilised stress of fabrics with a longer underlap in the back guide bar is higher than those with the same underlap length in the front guide bar (SHF2 > SF2, SHT2 > ST2 and RL2 > L2). This can be attributed to the less space available for the movement of the back guide bar underlap in fabrics with a longer back guide bar underlap. Moreover, the placing of the back guide bar underlap between the front guide bar underlap and the overlaps causes the limited movement of the back guide bar underlap in fabrics with a shorter underlap in the front guide bar.

Conclusion

In the present study, the tensile and fatigue behaviour of different structures of warp knitted fabrics of different course density (cpc) was investigated. The results show that structural parameters have an influence on the tensile and fatigue properties of warp knitted fabrics. It seems that the mechanism of fatigue failure and a cyclic stabilised stress similar to tensile behaviour can be controlled by means of the structural parameters of warp knitted fabrics i.e.: a) the space available for yarn movement in the fabric structure, and b) the length of the underlap.

The breaking strain of the fabrics reduced with an increase in the underlap length, and the breaking strain in fabrics with a longer underlap in the back guide bars was lower than those with the same underlap length in the front guide bars. The tenacity of the fabrics was increased by increasing the length of the underlap, and the tenacity of fabrics with a longer underlap in the front guide bar was lower than those with the same underlap length in the back guide bar. Although the tenacity was increased by increasing the course density (cpc), no considerable difference was observed for the breaking stress due to cpc.

Repeated straining causes stres*s* relaxation in warp knitted fabrics, and the maximum stress in each cycle decreased as the number of cycles increased, and the maximum stress in the given amplitude of extension reached a constant amount, which was termed "cyclically stabilised stress". The results show that cyclic extension causes strain softening in warp knitted fabrics. The cyclically stabilised stress of the fabrics was increased by increasing the amplitude of extension and/or by increasing the length of the underlap. Also the cyclic stabilised stress of fabrics with a longer underlap in the back guide bar was higher than those with the same underlap length in the front guide bar. Although the load in a stabilised state was increased by increasing the cpc, there seems to be no distinguishable trend between the cyclic stabilised stress and the cpc of the fabrics.

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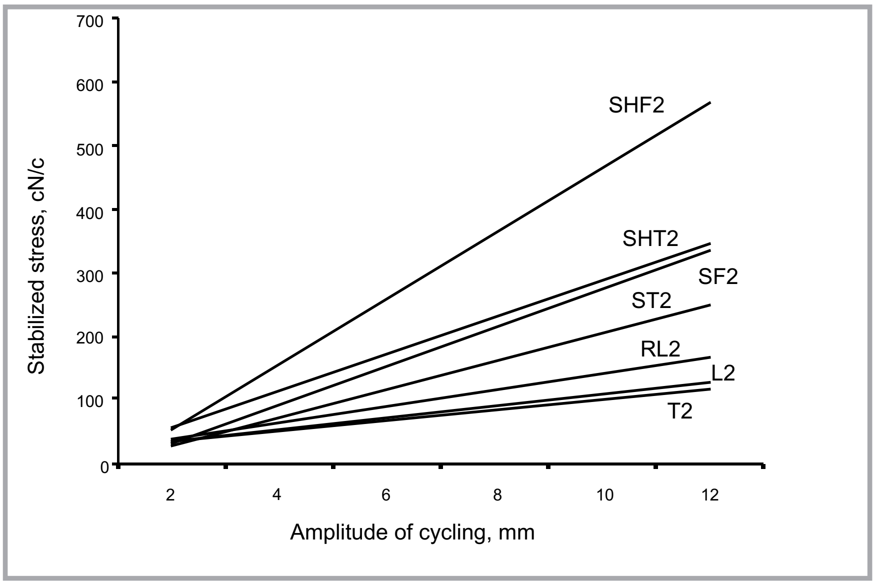

Figure 7. *Cyclically stabilised stress of the fabric samples with nominal cpc 20.*

Table 3. *Parameters of tests and maximum stress in the first cycle and in a stabilised state in the fatigue tests; PE: Pre-extension of fabric for 500N preload; AC: amplitude of cycling; σ_1: maximum stress at first cycle; $\sigma 2$: maximum stress at stabilization.*

Sample code	PE, mm	AC, mm	σ_1, cN/c	σ_2, cN/c	Sample code	PE, mm	AC, mm	σ_1, cN/c	σ_2, cN/c	Sample code	PE, mm	AC, mm	σ_1, cN/c	σ_2, cN/c
T_1	47.05	2	54	30.9	T_2	33.34	2	47.7	39.9	T_3	29.76	2	46.8	31.8
T_1	43.97	4	77.2	44.5	T_2	32.36	4	77.9	50.6	T_3	26.62	4	61.3	41
T_1	44.65	6	98.4	57.7	T_2	33.97	6	94.1	62.4	T_3	28.41	6	80	55.6
T_1	43.95	8	118.8	72.4	T_2	33.85	8	112.2	75.9	T_3	25.85	8	100.8	70.9
T_1	44.11	10	144.5	89.3	T_2	31.27	10	145.2	95.6	T_3	26.5	10	121.9	89.5
T_1	44.15	12	153.4	92.3	T_2	34.26	12	183	130.4	T_3	29.04	12	147.1	102.4
L_1	36.6	2	59.8	54.7	L_2	32.02	2	63	43.2	L_3	25.9	2	66	41.2
L_1	33.8	4	81.4	53.9	L_2	29.25	4	71.8	50	L_3	26.81	4	93.4	62.1
L_1	33.6	6	105.8	65.8	L_2	26.62	6	97.7	62.3	L_3	23.04	6	121.3	79.8
L_1	35.8	8	130.2	83.2	L_2	28.95	8	129.7	87	L_3	26.53	8	164.4	114.1
L_1	35.15	10	160.5	104.1	L_2	30.14	10	163.8	111.3	L_3	25.27	10	199.6	135.4
L_1	36.15	12	193.6	127.7	L_2	27.67	12	192	134.9	L_3	21.93	12	219.1	151.5
RL_1	25.68	2	71.3	41.6	RL_2	20.27	2	65.1	41.3	RL_3	16.89	2	68.9	41.8
RL_1	27.19	4	94.7	61	RL_2	18.48	4	101.6	61	RL_3	14.44	4	104.6	69.6
RL_1	25.57	6	125.8	74.5	RL_2	20.7	6	141.9	91.3	RL_3	15.33	6	155.6	115.6
RL_1	25.35	8	155	93.1	RL_2	21.22	8	176.1	118.9	RL_3	15.6	8	206.4	146.8
RL_1	25.1	10	178.5	119	RL_2	19.81	10	210.8	137.8	RL_3	14.92	10	251.8	178.5
RL_1	25.15	12	210	140.7	RL_2	21.17	12	247	170.1	RL_3	13.41	12	292.5	204.2
ST_1	33.4	2	85.7	41.6	ST_2	23.55	2	67	41.1	ST_3	21.09	2	81	48.8
ST_1	34.79	4	123.3	66.4	ST_2	24.03	4	101.2	65.6	ST_3	19.68	4	107.8	72.2
ST_1	32.73	6	161.3	93.8	ST_2	25.16	6	148.5	94.5	ST_3	20.62	6	151.6	101.9
ST_1	30.16	8	229.6	137.1	ST_2	22.13	8	234.3	155.7	ST_3	20.51	8	216	141.2
ST_1	29.34	10	297.2	185.6	ST_2	21.14	10	324.6	221.5	ST_3	19.27	10	282.6	194
ST_1	30.48	12	343.6	224.87	ST_2	22.19	12	353.7	244.4	ST_3	20.02	12	351.2	247.6
SF_1	27.18	2	88.6	48.1	SF_2	20.69	2	81.4	53.5	SF_3	19.12	2	85	51.8
SF_1	26.19	4	143.6	77.1	SF_2	19.61	4	116.5	73.2	SF_3	22.17	4	155.83	94.8
SF_1	26.04	6	213.2	119.4	SF_2	20.01	6	225.8	143.5	SF_3	18.9	6	227.8	147.6
SF_1	25.93	8	284.5	191.9	SF_2	20.65	8	317.1	212.7	SF_3	19.86	8	363.3	245
SF_1	25.88	10	361.4	224.3	SF_2	20.49	10	369.6	256.5	SF_3	21.66	10	423.3	280.2
SF_1	25.16	12	473.5	303.3	SF_2	18.55	12	509.1	353.7	SF_3	18.4	12	446.1	307.2
SHT_1	20.07	2	100.9	52.3	SHT_2	11.23	2	84.3	53.8	SHT_3	10.87	2	113	75.6
SHT_1	20.26	4	175.1	92.7	SHT_2	11.93	4	163.9	106.5	SHT_3	9.58	4	184.2	123.1
SHT_1	19.37	6	240.2	144.2	SHT_2	11.44	6	247.6	149.8	SHT_3	11.69	6	297.7	203.1
SHT_1	18.79	8	290.2	184.5	SHT_2	12.48	8	385	265.4	SHT_3	10.06	8	375.3	261.5
SHT_1	18.04	10	364.2	243.2	SHT_2	10.82	10	434.6	306.8	SHT_3	9.46	10	458.7	328.3
SHT_1	19	12	432.8	289.9	SHT_2	10.79	12	457.8	316.5	SHT_3	9.17	12	539.9	386.6
SHF_1	12.6	2	110.4	68.7	SHF_2	6.62	2	110.3	68.6	SHF_3	7.31	2	103.7	63.2
SHF_1	11.68	4	222.4	130.4	SHF_2	7.78	4	190.5	124.7	SHF_3	7.02	4	230.1	146.6
SHF_1	12.2	6	372	239.7	SHF_2	6.8	6	378.4	263.1	SHF_3	6.32	6	373.5	259.2
SHF_1	11.27	8	486	329.1	SHF_2	6.59	8	527.6	379.8	SHF_3	6.63	8	500.9	352.8
SHF_1	11	10	630.5	431.6	SHF_2	6.86	10	619	442.6	SHF_3	6.76	10	627.8	441.6
SHF_1	10.95	12	726.4	502	SHF_2	7.56	12	807	578.6	SHF_3	6.61	12	738.2	512.1

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Received 25.06.2007 Reviewed 02.12.2008