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Investigation and Modelling of Stress Relaxation on Cylindrical Shell Woven Fabrics: Effect of Experimental Speed

Abstract
This paper evaluates the effects of experimental speeds (22, 24 and 26 m/min) on woven fabrics' stress relaxation behaviour in a cylindrical form under constant torsional strain. Worsted woven fabrics were put under experimentation with identical specifications along the warp direction such as yarn density, fabric construction and fibre content, However the structural parameters were somewhat different in the weft direction. The experiments were conducted using the method established by Hezavehei, et.al (2011) and the stress relaxation behaviour of specimens at three speeds of a spiral shaft which can hold samples tightly in a cylindrical form and automatically rotate were investigated. According to the results obtained, with increasing the speed of fabric rotation around the main shaft, the quantity of stress relaxation percent decreases. The effect of experimental speed on the stress relaxation behaviour is differently reported for the warp and weft directions due to the variety of structures along each individual direction. Regarding this, the reduction in the torsional strain recovery of samples in the weft direction is significantly more than that in the warp direction. In fact, the stress relaxation behaviour is likely to be related to the physical and viscoelastic properties of fibre, yarn and fabric. Hence the experimental data were fitted with two well known viscoelastic models such as an ordinary Maxwell's and three component Maxwell's model with a parallel connected nonlinear spring. The results were fairly justified by curve fitting of experimental data with the three component Maxwell's model including a parallel connected nonlinear spring. Furthermore non-linear behaviour was observed from experimental validation with a remarkable correlation coefficient.

Key words: *stress relaxation, constant torsional strain, woven fabric, Maxwell's model, three component Maxwell's model, experimental speed.*

Introduction

Stress relaxation is one of the principal mechanical behaviours of material which explains structural responses against stresses. It could be addressed for a diversity of structures progressively for fabrics and textiles. Furthermore time is defined fundamentally as a main element according to the nature of viscoelastic mediums. In terms of the stress relaxation variation of fabric, as well as time, some elements are likely to be more superior such as the weave, fabric density, material content, yarn density and so on. If stresses and strains appear over a garment for a period of time, residual stresses will show a decline when the strain is kept constant. In fact, the mechanical properties and shapes of the structure usually suffer from stresses and strains either in the manufacturing process (when the fabric is being tailored) or throughout the period of its application. Besides, two common elements dominate the initial structural deformation of fabrics after loading called recoverable and unrecoverable which are usually ascribed as elastic and plastic deformation, respectively [1]. The imperfections might be unveiled as unrecoverable deformation while garment is subjected to high tension processes due to inexorable strains. Accordingly the fabric's capability to be consistent in demand could be significantly reduced [2, 3]. However, understanding the behaviour of the structure from a mechanical view point becomes predominantly definitive when the structure is required to present desirable properties for a long period of time [1].

Several interesting points have attracted quite a few researches to evaluate the stress relaxation of fabrics, yarns and polymeric materials [4 - 10] accompanied by developing viscoelastic models [11 - 16]. In some studies previously performed correlations between the mechanical properties and behaviour of fabrics were conducted. Estimation of fabric behavior was made in the manufacturing process against operational stress such as tensile, compression, sheer and bending. Owing to this experiment the mechanical properties were found to be significant parameters in describing and predicting the behaviour of fabrics [17]. When the elasticity of the constituents increasingly changes, for instance, in fabric containing elastane fibres, the longest relaxation time should be given to the structure for recovering the deformation [14]. It shows that the elasticity of the garment may also play a considerable role in ultimate stress relaxation behaviour. Furthermore it was demonstrated that Maxwell's model is unable to explain the behaviour of fabric under constant deformation. Hence this model was appropriately employed either for explaining relaxation phenomena in the fabric or changes of stresses inside a fabric roll [11, 12]. For knitted fabrics the elasticity of the structure usually exhibits a different trend based on the knitted structure; the stress relaxation might dissimilarly be changed from each direction of the component due to acting as an anisotropic body. In order to justify this dependency uniaxial and biaxial strain was employed through the elastic and viscoelastic structures. As a consequence, it was demonstrated that the stress relaxation under biaxial strain is in coordination with rotation around angle of the knit [15].

To simplify the viscoelastic behaviour of fabrics, further different derivations of the dashpot and spring model have been abundantly developed. For the purpose of having a reliable and convenient prediction of fabric behavior, the mechanical values were mathematically fitted with some viscoelastic models such as the generalized Maxwell's [11 - 14] and modified standard linear solid models [14], the four element model with two springs and two dashpots [15], and the two and three component Maxwell's model [16]. These pointed out that the linear or non-linear viscoelastic behaviour of the textile structure as a presumption could be confirmed. On the other hand, a rheological model for the crease of fabrics was presented earlier [18]. Furthermore woven and knitted fabrics' crease and relaxation shrinkage behaviour was examined, where the shrinkage of the yarn constituent seemed to be a main influential factor [19]. The mechanics of deformation as well as analysing large shear strain in woolen fabrics were investigated along different shear angles [20]. The generalised linear viscoelastic model developed led to low strain deformation. Although an independent variation in the shear stress relaxation rate was observed with increasing the maximum shear angle up to 16º, the results were in good agreement with the model presented. Because of the higher pressure at the yarn cross-over points at higher shear strains, the inter-fibre frictional stress increased exponentially with an increasing shear strain. Owing to this fact, when a high level of strain was experienced by fibres, the later results became enormously important for predicting the recovery behaviour of the fabric from deformation such as wrinkling and creasing [20]. The stress relaxation of three-ply breathable-coated fabric was scrutinised last decade which was constructed from an outer polyester woven fabric, an inside polytetrafluoroethylene micropore film and a linear polyester knitted fabric [21]. The different directions of the structures such as weft, warp and through a 45º angle were subjected to tensile stresses. As a result of this study, stress relaxation of the fabrics was attributed to the fabric and film properties, which are completely dissimilar along the weft and warp directions even though the tensile properties were reported similar for all of the directions.

Although extensive researches have been carried out on the stress relaxation behaviour of fabrics, only a few cover the whole of the concept in terms of the real condition of the experiment. Recently a new experimental method for measuring the stress relaxation of worsted fabric has been successfully proposed [22]. There is much convincing evidence regarding the expression of stress relaxation and recovery of worsted fabric with varying structural properties. The process was assumed to be more similar to the real situation of fabrics under regular operation and consumption. It was illustrated that with increasing polyester content in woven fabrics the stress relaxation percentage decreases. Also by employing the same method behaviour of stress relaxation of polyester blended fabric under constant torsional strain was evaluated [23]. Based on the result of this study, the stress relaxation behaviour of worsted fabrics was found to be attributed to the viscoelastic properties of fibres, and such other properties of fabrics as thickness and weight. In the mean time, the decreasing trend of stress relaxation was observed with an increment of thickness and weight of the fabrics. The viscoelastic behaviour of the fabrics and their stress relaxation curve were in agreement with Maxwell's model [22]. The later experimental method is quite new in this particular field of study. Hence a much more systematic study would identify how the stress relaxation behaviour of textile structures, especially worsted fabrics, interacts with other variables.

This paper mainly focuses on developing the system which is summarised above. The stress relaxation behaviour of worsted fabric was considered with slight changes in the experimental instrument throughout the study. Meanwhile the physical and structural properties of the fabrics and their effect on the stress relaxation behaviour in both the weft and warp directions were considered. Beside this statistical evaluations as well as mathematical modelling of stress relaxation based on the linear and non-linear viscoelastic models are also presented.

Experimental

Materials

In order to establish an understanding of what is involved in the stress relaxation behaviour of worsted fabrics, 9 different samples were prepared with similar properties along the warp direction, such as 29 end per cm and a 50 tex warp count. However, specifications in the weft direction were completely different in woven fabrics, which are presented in ***Table 1***.

From the table above fabric codes from A to G were made with a Twill fabric construction; however, the construction for the last two fabrics (H and I) are Plain and Hopsack. The differences between Twill fabrics were such structural variations as yarn count in tex, fabric density in pick per cm, weight in g·m^{-2}, thickness in mm and fibre content in %. Except for the fabric construction variation between samples H and I, there is no significant difference in their linear density (yarn count), fabric density, and fibre content.

Fabric stress relaxation tester

For the purpose of stress relaxation determination of woven fabrics, the method already established by Hezavehie et.al was used [22]. On this instrument, rectangular fabric specimens (with dimensions of 290×160 mm) were formed into a cylinder shape and then mounted between two circular rings with a 90 mm diameter. The upper ring, which is automatically controlled by the software,

Table 1. *Structural properties of woven fabrics along weft direction;* ***Notes****:* w: wool; p: polyester.*

Fabric code	Linear density, tex	Fabric density, pick per cm	Weights, g/m^2	Thickness, mm	Fabric construction	Fibre content, %
A	50	24	257	0.94	Twill 2/2	45w-55p*
B	38		236	0.92		
C	50		264	0.93		35w-65p
D			258			10w-90p
E		18	235			35w-65p
F		20	246			
G	45	19	226	0.90		45w-55p
H			224	0.91	Plain 1/1	
I			223	0.88	Hopsack 2/2	

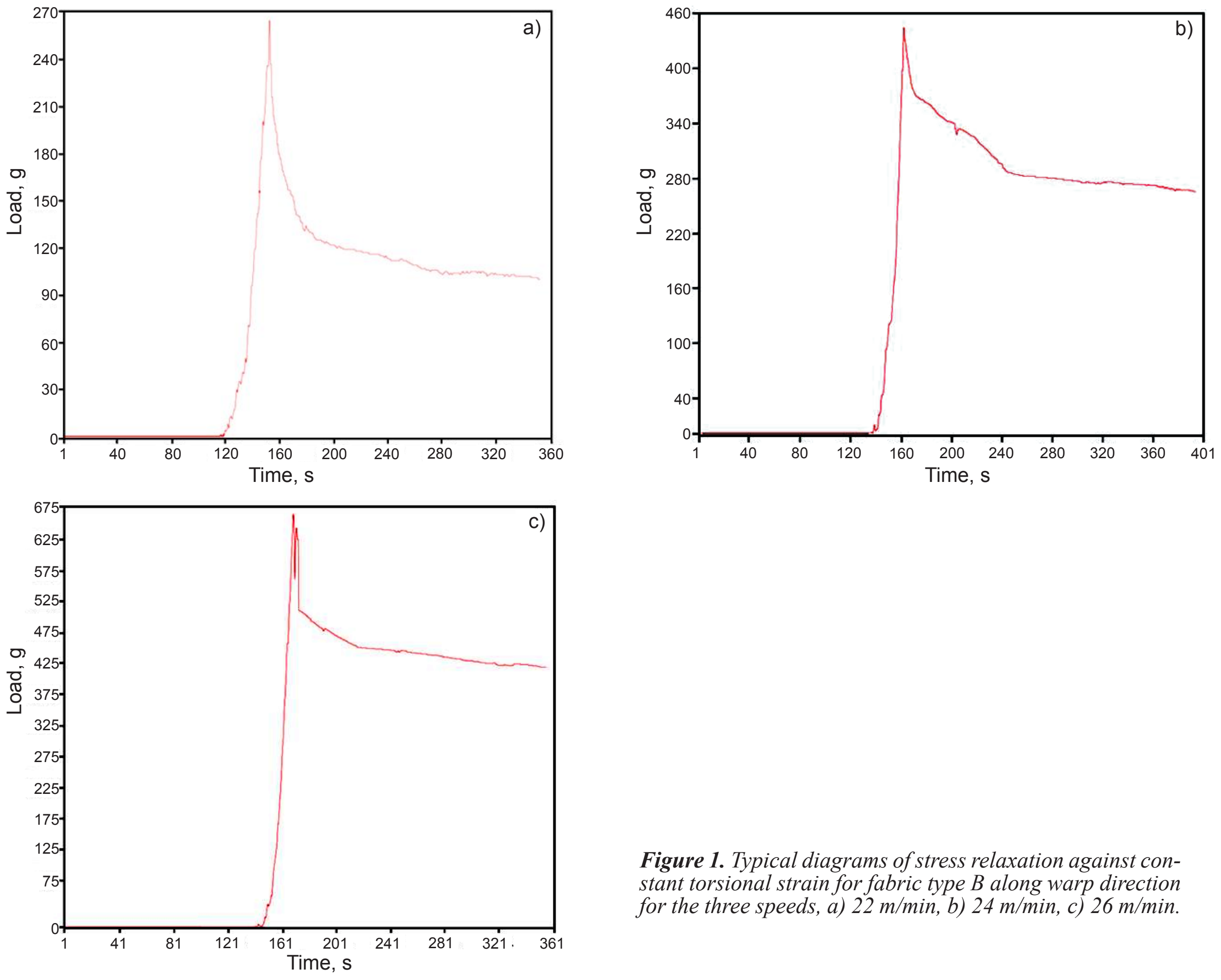

***Figure 1.** Typical diagrams of stress relaxation against constant torsional strain for fabric type B along warp direction for the three speeds, a) 22 m/min, b) 24 m/min, c) 26 m/min.*

can gently rotate and move downwards around the spiral shaft over intermediate gears equipped with a stepper motor (Model Sanyo Denki, Type 103H 89222-6341, 22 kg·cm). The speed of the stepper motor in this study varied in three levels for each run of the experiment in a clockwise rotational direction. These parameters were adjusted and controlled through the electronically intermediate board using Labview software Ver. 6 (National Instrument Co.) [22]. Standard conditions of 22 ± 2 ºC and 65 ± 2 percent r.h. were retained throughout the experiments. Typical diagrams of stress relaxation versus constant torsional strain for sample B are shown in ***Figure 1***.

***Table 2.** Results of stress relaxation at three speeds at 300 seconds; **Note**: Mean value; Numbers in parentheses are the standard deviation.*

Fabric code	Stress relaxation (%) at different speeds of the spiral shaft (m/min)					
	22		24		26	
	warp	weft	warp	weft	warp	weft
A	74.89 (1.86)	100 (0)	76.10 (4.2)	42.03 (3.64)	37.27 (3.36)	37.31 (3.4)
B	61.98 (2.1)	71.30 (2.58)	33.57 (4.11)	92.22 (4.36)	36.11 (4.49)	66.36 (3.36)
C	51.12 (1.7)	52.30 (2.61)	38.33 (4.9)	75.23 (3.53)	21.04 (3.61)	26.21 (4.06)
D	46.52 (1.66)	66.08 (2.29)	42.49 (3.87)	42.86 (3.94)	28.15 (3.89)	30.28 (3.15)
E	71.5 (2.29)0	87.19 (1.9)	55.37 (3.94)	100 (0)	35.17 (3.49)	81.70 (3.63)
F	55.48 (2.36)	100 (0)	54.79 (3.83)	89.10 (4.57)	23.48 (3.21)	37.30 (3.79)
G	89.28 (1.78)	100 (0)	93.02 (4.27)	96.07 (3.57)	40.95 (4.09)	32.48 (3.85)
H	51.43 (2.9)	72.38 (2.87)	85.53 (3.58)	100 (0)	34.38 (3.2)	35.94 (3.79)
I	100 (0)	100 (0)	100 (0)	81.63 (3.67)	68.71 (4.12)	61.29 (3.41)

Values of the torsional force were continuously measured along each direction of the samples individually, making use of the load cell (Model BONGSHIN, Type DBBP-S-Beam, 20 kg, South Korea) which is attached to the bottom disk. The maximum torsional force was recorded at a point where the fabric was completely rolled around the main shaft and loading was ceased, after which the sample was left to relax for an appropriate time (see ***Figure 1***). The minimum torsional force was recorded at a later point where the fabric had mostly recovered from the torsional strains and the trend had leveled off, as shown in ***Figure 1***. The stress relaxation behaviour of the fabrics was calculated differently for samples strained by employing three speed of the spiral shaft (22, 24 and 26 m/min) at 300 seconds. ***Equations 1*** and ***2*** were developed for measuring the stress relaxation percentages and ultimate stresses, respectively [22]:

$$Stress\ relaxation = $$

$$= \frac{Stress_{Max} - Stress_{Min}}{Stress_{Max}} \times 100,\ \% \quad (1)$$

Where the stress can be measured as below:

$$Stress = \frac{T}{2\pi rt} \quad (2)$$

where T is the torsional force in N, r denotes the radius in mm, and t the thickness in mm. 54 tests were carried out with nine fabrics and three speeds of the spiral shaft in different directions of the samples. Each test was repeated 5 times and the average along with the standard deviation were reported. The experimental results are expressed as a percentage set at any time for fabric stress relaxation in the warp and weft directions. ***Table 2*** summarises the numerical values calculated for the recovery of each individual specimen.

The table above draws attention to the fact that the stress relaxation behaviour of the samples showed different trends in each condition. The experimental work which was carried out to establish the time-dependant behaviour of worsted fabrics associated with either structural properties or the speed of the spiral shaft from the instrument (experimental speed effect) will be comprehensively discussed in detail in the following sections.

Result and discussion

The results of stress relaxation measurement under constant torsional strain at three different speeds of the spiral shaft are discussed herein. As first step the time-dependant strain recovery of the samples were examined only in relation to fabric type.

Stress relaxation mechanism

Statistical evaluation was performed on the fabric type's effect on fabric stress relaxation by means of the one way analysis of variance (ANOVA) test method. ***Table 3*** lists ANOVA statistical analysis results for stress relaxation in each direction of samples at a 5% confidence limit. As shown in this table, stress relaxation along the warp and weft directions at the three speeds was significantly influenced by the fabric types, meaning that when considering the different types of woven fabrics, due to the tightness or looseness of the structure, various stress relaxation could be observed even for slightly dissimilar fabrics.

This table also table shows the effect of fabric types on the strain recovery of the samples regardless of speed influences. The following parts will discuss the structural behaviour of samples under torsional strain for each speed of the spiral shaft.

Stress relaxation at the minimum speed (22 m/min)

The relationship between structural properties with a capability of strain recovery in worsted fabrics can be found by referencing the classifications of ***Figure 2***. The stress relaxation amounts were calculated for both directions of warp and weft, which are visually shown below.

As is clearly shown in ***Figure 2***, the percentage of stress relaxation in the weft direction for each sample is comparatively higher than that for the warp direction. Furthermore analysis of results from the figure below for relaxation phenomena indicates that with increasing the wool content, for example, in sample A the stress relaxation shows considerable improvement along both principle directions. According to the woven structure of the current sample, it could be stated that the inter-fibre frictional stresses can have the possibility to dominate the structure resulting in real strain recovery [20]. In addition, the slippage and rotation of cross-over yarns that form the fabric could start when the force enacted on the fabric becomes larger than the frictional restraint. Even so, this observation was not consistently made for the other specimens with the same content of wool and polyester, such as B and G. There seems to be other predominant parameters that have a significant influence on the stress relaxation of the later samples. In view of this fact, the deviation from rational stress relaxation behavior might occur due to the difference between yarn count and pick per cm along the weft direction of these specimens. On the other hand, for samples C and D the time-dependant behaviour was reported to be lower by about at least 50%, which could be associated with the higher deformation and restrictive elasticity of the polyester fibres versus the constant torsional strain, meaning that plastic deformation took place while the maximum torsional process was being recorded. The highest quantity of recovery after unloading the fabric was obtained for the sample with a Hopsack fabric design . Since the fabric structure is an influential parameter in

***Table 3. Summary** of ANOVA statistical analysis results for woven fabrics' stress relaxation at 22, 24 and 26 m/min; **Notes**: +: significance between data.*

Experimental speed	Stress relaxation	
	warp	weft
Minimum speed at 22 m/min	+	+
Medium speed at 24 m/min	+	+
Maximum speed at 26 m/min	+	+

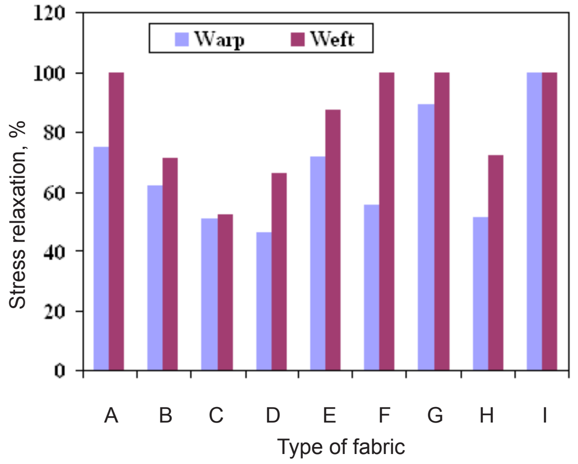

Figure 2. *Stress relaxation along warp and weft directions at 22 m/min.*

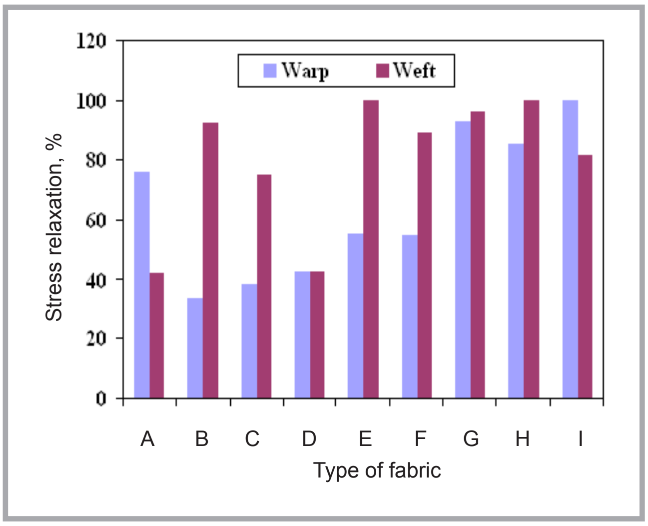

Figure 3. *Stress relaxation along warp and weft directions at 24 m/min.*

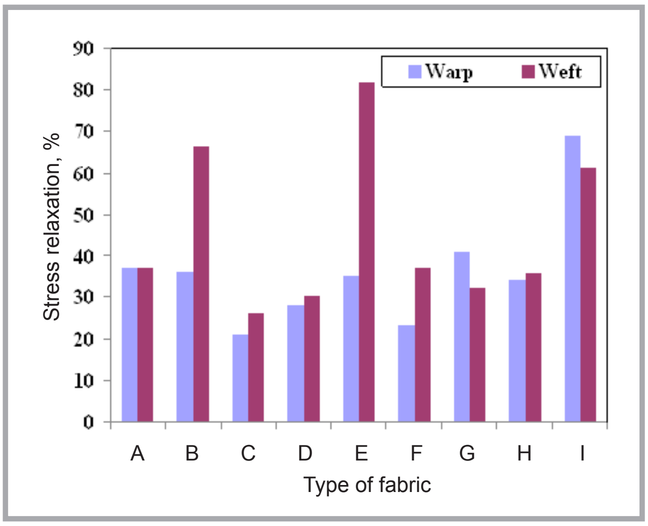

Figure 4. *Stress relaxation along warp and weft directions at 26 m/min.*

itself, the role of the thickness and fabric weight, which intrinsically present the significant interaction of fibres within the structure, could not be neglected. Therefore fabrics with a lower amount of thickness and weight also indicate a faster recovery process. The result agrees reasonably well with previous works [22, 23].

Stress relaxation at the medium speed (24 m/min)

In this part the stress relaxation of specimens with the same specification was measured when the pace of the spiral shaft in the stress-relaxation tester was increased by 2 m/min. Since the rotation around the main axis took place more quickly, torsional stresses acted comparatively higher than in the last experiment, which is likely to be the overreacting of samples in order to sustain further torsional strain. Results obtained dealing with the parameters of fabrics subjected to higher strain rates are presented in ***Figure 3***.

Fabrics were exposed to a higher stress rate and it was expected that their behavior could be more precisely predicted through the broad stress relaxation domain. Comparing ***Figures 2*** and ***3***, the relaxation percent of samples under lower loading shows less splitting averages. However, stress relaxation for the specimens under larger strain rates had wider averages especially along the warp direction (***Figure 3***). Primarily it was the logical presumption that the ability of strain recovery of the samples could be reduced with increasing the torsional stress around and over the yield point. Moreover below this area, with increasing the torsional loads, a higher stress relaxation percentage could be observed; however, some occasional deviations from the fundamental viscoelastic behaviour occur caused by the structural properties of woven fabrics. A noticeable factor from ***Figure 3*** is the minimum stress relaxation percent observed for fabrics B, C and D in the warp direction; although the maximum amount is still shown from sample I. In addition to that, it should be pointed out that the dominant factor for the stress relaxation trend of those samples with a Twill fabric construction was the weft direction instead of the warp . Whereas along the weft direction sample D still shows lower stress relaxation, the story for sample A changed in comparison with the result from ***Figure 2***. The highest stress relaxation percent was already obtained while the speed of the spiral shaft was 22 m/min, whereas the lowest stress relaxation was observed with an increase in speed. With increasing the torsional loads, permanent deformation began, presumably due to either variation in behaviour from elastic to plastic deformation of constituents or the internal complexity of the structure, which is attributed to the thickness, fabric density and yarn count. As mentioned earlier the role of the inter-fibre friction of yarns cannot be negligible, since its influence is in an opposite fashion in this particular case.

Figure 3 visually presents that the stress relaxation percentages of woven fabrics in the weft direction were more than that of the warp direction, except for fabrics A and I. Regarding the results presented, the higher stress relaxation is obtained for fabric I, whereas the minimum stress relaxation percent is presented by fabric B along with fabric C in the warp direction. This clearly shows that in the weft direction with reducing the pick per cm the capability of stress recovery for the specimens significantly grows (fabrics E, G and H). This increasing rate might be borne out in the rigidity of the structure in relation to the more or less pick per cm in the weft direction. In contrast, the stress relaxation percent decreases when the pick per cm increased (fabrics A, C and D). The results are comparatively in good agreement with previous works [22, 23].

Stress relaxation at the maximum speed (26 m/min)

The maximum speed of the spiral shaft was adjusted to 26 m/min. Because of the quicker rotational motion of the main shaft, greater torsional stresses became relatively available to rotate the fabrics. The stress relaxation of the samples was recorded, the mean values of which are shown in ***Figure 4***.

Figure 4 depicts that larger amounts of stress relaxation of woven fabrics in the weft direction (except samples G and I) are obtained even more than in the warp direction. It also shows that specimens C and F presented the lowest stress relaxation percent, which was for a 65% polyester and 35% wool content, respectively. Because of the low pick per cm the maximum stress relaxation percent was obtained for samples G and I. For the stress relaxation behaviour in the weft direction, from the classification in ***Figure 4***, the sample which has greater pick per cm shows the lowest stress relaxation percent (Sample C), whereas the maximum

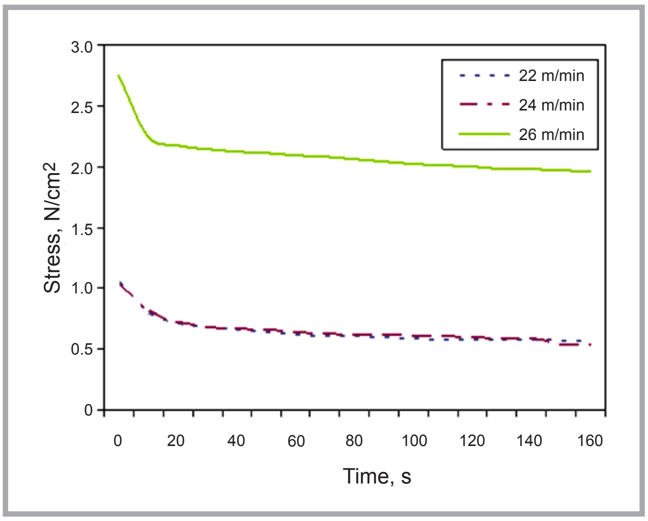

Figure 5. *Stress relaxation of fabric type D in three speeds towards warp direction.*

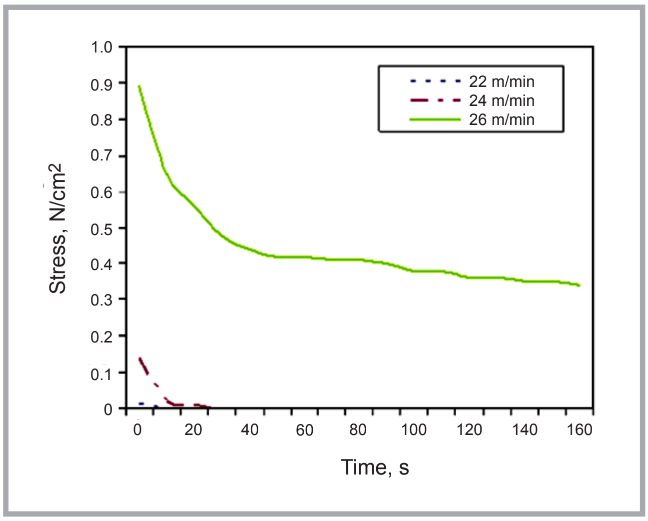

Figure 6. *Stress relaxation fabric type I in three speeds along weft direction.*

stress relaxation percentage was obtained for sample E because of the lower pick per cm. A conclusion could be made that the yarn content along the weft direction, fabric construction in the warp direction and the pick per cm in the weft direction are effective predominant parameters for the stress relaxation percent at this speed of the spiral shaft.

Overall comparison of stress relaxations

Along warp direction

In the last part the stress recovery of worsted fabrics was discussed in terms of the torsional stress versus the structural properties at different speeds of the spiral shaft. Since the stress recovery of fabrics is time dependent, it is very beneficial to consider how the structure reacts during the time after releasing the load. In order to make the concept more precise the stress relaxation procedure of sample D was carried out during 160 seconds after eliminating the torsional load along the warp direction. ***Figure 5*** shows the three different trends for each individual speed of the main shaft, which presents a varied rotational load over specimen D.

As shown in ***Figure 5***, over the first ten seconds torsional stress at the three speeds considerably decreased, since the stresses from the minimum and medium speeds of the spiral shaft lie consistently beneath the maximum one. It is noticeable that the crucial area to recover from most stresses upon the specimen is within the short period of time straightaway after releasing the torsional stress. After ten seconds the behaviour of the fabric in releasing residual stresses becomes more stable. It is quite clear from ***Figure 5*** that when the structure has suffered greater torsional forces (26 m/min), the reduction in the residual stress slope falls more than for the smaller torsional stress. Regarding this explanation, the elasticity of the specimen plays a critical role in overcoming torsional stress, although the structure was made from the minimum constituent of wool fibres.

Along the weft direction

In the previous part, the stress recovery of worsted fabrics is discussed in terms of unloading torsional strain versus the relaxation time through the different speeds of the spiral shaft for a particular sample in the warp direction. As presented in the latest parts the stress recovery of fabrics changes in a different fashion from the warp direction to the weft; however, it has to be evaluated how the structure responds during the time after releasing the load in the weft direction. For instance in fabric I, the stress relaxation procedure was recorded during the 160 seconds after getting rid of the torsional load. ***Figure 6*** presents three different trends for each individual speed of the main shaft, which illustrate the varied rotational load upon specimen I.

It is readily observed from ***Figure 6*** that the stress relaxation curve for fabric type I shows a significant reduction after releasing the torsional strain when the speed was adjusted to 26 m/min. After recovering just over 50% of residual stresses in the first 20 seconds, the trend roughly becomes flat or at least with fewer variations towards the end of the test period (solid line). The same trend as presented in ***Figure 5*** is seen for current sample (I) in terms of remarkable differences of recovering torsional stresses from each pace of experiment. It means that the stresses for specimens along both weft and warp direction at 26 m/min stood over two lower speed of experiment. Moreover although the stresses from 22 and 24 m/min are properly recovered in the first 20 seconds, sample (I) shows a precipitate reduction trend of releasing the whole of the residual stress when the speed was adjusted to 24 m/min. Eventually the structural properties stimulate the specimen by recovering from most of the deformation due to torsional stresses instantly after the unloading process.

Viscoelastic model implementation

When torsional strain is applied to a fabric and kept constant through time, the stresses exerted will either be partially or completely recovered through the equilibrium value (***Figure 5*** and ***6***). In other words, this phenomenon arises because the recovery forces of fabric are being

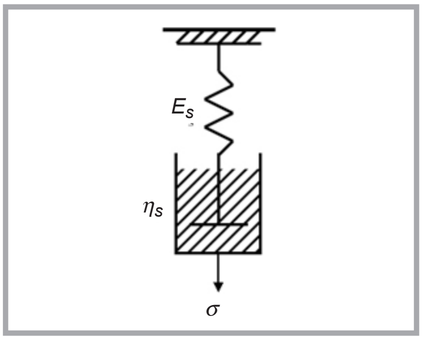

Figure 7. *Generalised viscoelastic Maxwell's model [1].*

Table 4. Correlation coefficients of Maxwell's Model with experimental curve for woven fabrics at 22 m/min.

Fabric code	σ(t$_0$)		τ		Correlation coefficient	
	warp	weft	warp	weft	warp	weft
A	0.29	-	0.016	-	0.89	-
B	0.65	0.42	0.005	0.009	0.75	0.91
C	0.97	0.72	0.004	0.004	0.78	0.84
D	0.82	0.42	0.003	0.007	0.79	0.87
E	0.34	0.21	0.010	0.020	0.84	0.82
F	0.57	-	0.004	-	0.80	-
G	0.36	-	0.024	-	0.90	-
H	0.75	0.50	0.005	0.010	0.89	0.88
I	-	-	-	-	-	-

Table 5. Correlation coefficients of Maxwell's Model with experimental curve for woven fabrics at 24 m/min.

Fabric code	σ(t$_0$)		τ		Correlation coefficient	
	warp	weft	warp	weft	warp	weft
A	0.52	0.98	0.010	0.002	0.86	0.74
B	1.36	0.22	0.002	0.090	0.89	0.97
C	1.73	0.47	0.002	0.009	0.86	0.87
D	0.82	0.81	0.003	0.002	0.84	0.84
E	1.05	-	0.005	-	0.86	-
F	0.57	0.33	0.004	0.030	0.77	0.92
G	0.35	-	0.050	-	0.97	-
H	0.31	1.99	0.020	0.010	0.87	0.94
I	-	-	-	-	-	-

Table 6. Correlation coefficients of Maxwell's Model with experimental curve for woven fabrics at 26 m/min.

Fabric code	σ(t$_0$)		τ		Correlation coefficient	
	warp	weft	warp	weft	warp	weft
A	2.03	1.30	0.002	0.002	0.86	0.81
B	1.85	0.57	0.001	0.006	0.71	0.86
C	2.17	2.06	0.001	0.001	0.82	0.80
D	2.32	0.79	0.001	0.004	0.76	0.90
E	0.89	0.41	0.001	0.010	0.79	0.78
F	1.63	1.23	0.001	0.002	0.82	0.77
G	1.79	0.75	0.002	0.001	0.79	0.79
H	0.98	2.18	0.002	0.002	0.78	0.70
I	0.99	0.65	0.006	0.005	0.72	0.83

destroyed during relaxation. As discussed earlier, the structural properties of the fabric play an important role in prefect stress recovery when the specimen is unloaded. To establish a clear understanding of this relationship and see whether this correlation would be observable between the structural properties and viscoelastic behavior of the worsted fabrics, two mechanical models based on Maxwell's and three-component Maxwell's models with a parallel-connect nonlinear spring were adopted as convenient tools[1].

Generalised Maxwell Model

To simplify the matter further, a Maxwell's model is developed which consists of a straightforward serial connection of the linear Hook's spring and Newton's dashpot, as shown in ***Figure** 7*. The expression for this model under constant deformation can be presented as ***Equation 3*** [1].

$$\sigma(t) = \sigma(t_0)e^{-\frac{t}{\tau}} \qquad (3)$$

where $\sigma(t)$ is final stress (N/cm^2), $\sigma(t_0)$ is initial stress of each part, t is time and $\tau = \mu/E$ is the relaxation time of each part. These parameters were measured from the outputs of the cylindrical recovery tester. The correlation coefficients were statistically obtained for stress relaxation values under a constant torsional strain at three different speeds (22, 24 and 26 m/min) along both directions. Results are represented in ***Tables 4, 5*** and ***6***.

Tables 4 to 6 show a good correlation coefficient between the stress relaxation of some specimens with parameters of the model has been obtained. Apart from

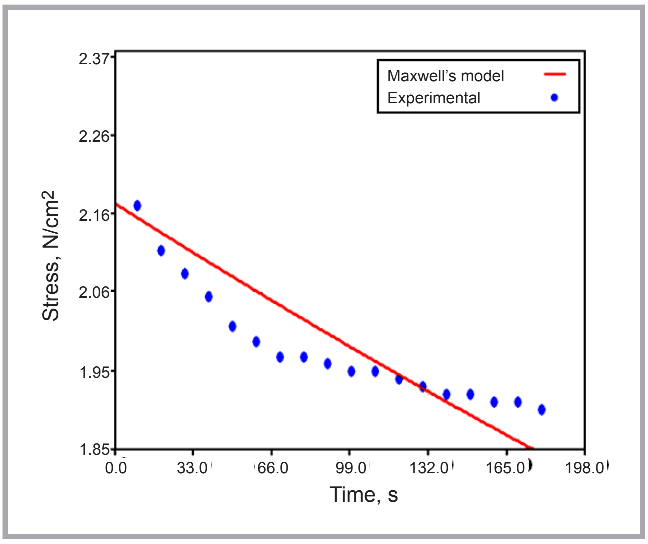

***Figure 8.** Experimental curve fitted with Maxwell's model for fabric type C at 26 m/min for wrap direction.*

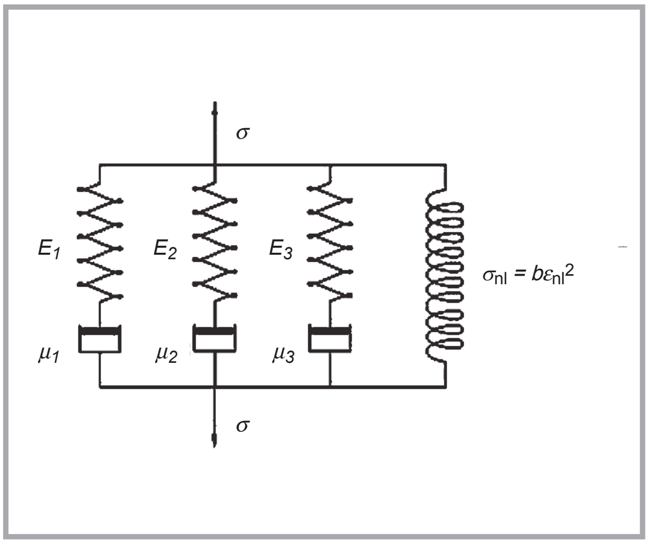

***Figure 9.** Three components Maxwell's model with parallel-connect nonlinear spring [1].*

Table 7. *Results of curve fitting experimental data with three component Maxwell's Model with parallel-connect nonlinear spring at 22 m/min speed along with correlation of coefficients.*

Fabric code	σ_1		σ_2		σ_3		τ_1		τ_2		τ_3		b		ε		Correlation coefficient	
	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft
A	0.22	0.11	0.22	0.10	0.22	0.11	673.9	25.75	573.3	11.86	573.2	0.67	0.89	0.07	0.99	0.31	0.75	0.99
B	0.27	0.27	0.28	0.27	0.19	0.27	10.96	522.8	312.4	511.1	3.5	579.7	0.44	1.05	0.67	1.06	0.99	0.84
C	-	0.13	-	0.15	-	0.22	-	46.33	-	45.38	-	4.75	-	0.64	-	0.81	-	0.99
D	0.28	-	0.14	-	0.07	-	6.51	-	62.9	-	36.73	-	0.74	-	0.87	-	0.99	-
E	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F	0.40	-	0.40	-	0.40	-	776.3	-	778.6	-	851.3	-	1.28	-	1.17	-	0.75	-
G	0.33	0.01	0.33	0.02	0.33	0.02	654.1	5.25	737.1	14.41	739.7	13.44	1.04	0.002	1.08	0.08	0.73	0.99
H	0.17	-	0.17	-	0.17	-	54.75	-	57.37	-	2.42	-	0.63	-	0.80	-	0.99	-
I	0.03	0.005	0.04	0.005	0.04	0.004	2.28	4.96	3.24	5.23	3.24	4.99	0.004	0.002	0.10	0.07	0.99	0.99

Table 8. *Results of curve fitting experimental data with three component Maxwell's Model with parallel-connect nonlinear spring at 24 m/min speed along with correlation of coefficients.*

Fabric code	σ_1		σ_2		σ_3		τ_1		τ_2		τ_3		b		ε		Correlation coefficient	
	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft
A	0.33	0.16	0.33	0.21	0.32	0.24	648.8	239.1	648.1	13.55	739.7	13.56	1.16	0.79	1.11	0.89	0.78	0.99
B	0.18	-	0.18	-	0.18	-	42.01	-	42.14	-	42.12	-	0.99	-	0.99	-	0.98	-
C	0.25	0.49	0.25	0.49	0.25	0.49	32.71	1023.4	32.6	935.3	32.91	935.1	1.12	1.28	1.06	1.20	0.99	0.77
D	0.14	0.12	0.18	0.12	0.34	0.12	9.55	28.65	9.57	28.65	252.4	28.65	0.61	0.76	0.78	0.88	0.99	0.99
E	-	0.08	-	0.08	-	0.08	-	710.8	-	823.3	-	862.2	-	0.47	-	0.77	-	0.60
F	0.44	0.13	0.44	0.14	0.44	0.11	1026.1	4.94	1072.2	13.82	1126.7	109.1	1.32	0.008	1.19	0.03	0.72	0.99
G	-	0.28	-	0.28	-	0.28	-	1306.8	-	1416.9	-	1388.4	-	0.86	-	1.03	-	0.70
H	0.11	0.62	0.12	0.62	0.12	0.62	16.88	34.13	33.38	34.1	0.45	34.12	0.23	0.66	0.51	0.82	0.99	0.99
I	0.17	0.08	0.17	0.08	0.17	0.08	1502.1	816.2	1477.1	788.3	1410.8	798.1	0.66	0.50	0.91	0.77	0.60	0.60

Table 9. *Results of curve fitting experimental data with three component Maxwell's Model with parallel-connect nonlinear spring at 26 m/min speed along with correlation of coefficients.*

Fabric code	σ_1		σ_2		σ_3		τ_1		τ_2		τ_3		b		ε		Correlation coefficient	
	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft
A	1.41	0.18	1.41	0.16	1.41	0.18	1297.1	44.21	1323.5	0.72	1316.4	34.54	2.43	0.99	1.60	0.99	0.82	0.99
B	0.83	0.07	0.83	0.27	0.83	0.20	1156.1	7.79	1090	64.57	1170.2	7.78	2.04	0.48	1.54	0.71	0.68	0.99
C	0.70	0.65	0.70	0.65	0.70	0.65	1181.5	1033.3	1181.4	1012.8	1439.9	1061.7	2.01	1.96	1.45	1.43	0.80	0.78
D	0.59	0.19	0.59	0.19	0.59	0.22	792.8	91.36	832.8	90.54	896.1	2.28	1.96	0.61	1.44	0.79	0.74	0.99
E	0.17	0.46	0.11	0.46	0.11	0.46	72.86	1148.8	7.41	1035.7	0.54	1067.3	0.83	1.22	0.91	1.18	0.99	0.65
F	0.11	-	0.11	-	0.26	-	0.79	-	5.89	-	64.94	-	1.16	-	1.08	-	0.99	-
G	0.30	0.09	0.30	0.16	0.30	0.09	22.54	6.14	22.54	67.04	22.54	0.55	1.15	0.75	1.07	0.87	0.99	0.99
H	1.45	0.83	1.45	0.83	1.45	0.83	1727.6	1005.2	1671.4	965.1	1655.8	1063.8	2.44	2.10	1.61	1.48	0.75	0.67
I	-	0.21	-	0.20	-	0.24	-	14.08	-	12.02	-	202.3	-	0.48	-	0.70	-	0.99

fabric type I, which already has a 100% stress relaxation value, statistical evaluation was preformed with different relative correlations for other samples. The correlation coefficient for specimen (I) did not make great sense when all the stresses had already been recovered, and the equation does not give significant values, especially for 22 and 24 m/min. It is of considerable interest to note that a higher correlation coefficient was obtained for those samples stressed by the 24 m/min rotational speed, whereas a lower correlation coefficient was calculated comparatively for samples at a 26 m/min speed of the spiral shaft. It has formerly been shown that (see page 68) the samples under torsional stress from 26 m/min had the worst stress relaxation recovery in most cases. It can also be stated that with increasing the torsional stresses, deviation from the linear viscoelastic behavior becomes more attainable. ***Figure 8*** shows typical graphs of Maxwell's model curve for fabric type C along with an experimental stress relaxation curve at 26 m/min along the warp direction. The solid curve presents results calculated from the model, while the dotted line shows the experimental results.

As can be seen, the predicted and experimental curves are in poor agreement for specimen C, which is due to the fact that a higher strain is applied to the structure, although the stress response is too small. The correlation coefficient measured for this specimen from ***Table 7*** is around 82%.

Three component Maxwell's model with parallel-connect nonlinear spring

In the current step the multi component Maxwell's model was employed to fit the mean fabric stress and relaxation parameters, supposing that the mechanical models with a greater number of basic components may explain the relaxation curve better. As shown in ***Figure 9***, this model consists of four elements in total, three Maxwell's model parallelised by a nonlinear spring. The non-linear spring was preferred to add to the general Maxwell's model in order to obtain better

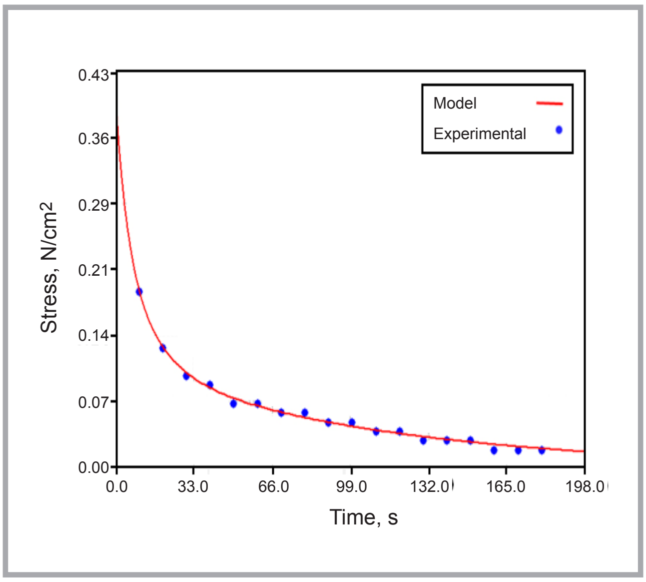

Figure 10. *Experimental curve fitted with three components Maxwell's model for fabric type F at 24 m/min along weft direction.*

agreement of stress values with the experimental curves. ***Equation 4*** expresses the stress relaxation for this model [1].

$$\sigma(t)=\sigma_1(t_0)e^{-\frac{(t-t_0)}{\tau_1}}+\sigma_2(t_0)e^{-\frac{(t-t_0)}{\tau_2}}+ +\sigma_3(t_0)e^{-\frac{(t-t_0)}{\tau_3}}+b\varepsilon(t_0)^2 \quad (4)$$

These parameters from the above equation were measured from the outputs of the cylindrical recovery tester. The correlation coefficients were calculated for stress relaxation values under constant torsional strain at three different speeds (22, 24 and 26 m/min) along both directions. Results are given in ***Tables 7, 8*** and ***9*** (see page 71).

As illustrated in the Tables above, massive calculation must be carried out to obtain appropriate evidence from the multi component model along with experimental results. Although it could be a drawback of this model due to having numbers of basic elements to be calculated, its performance to predict more accurate values is quite remarkable. Owing to this fact the best agreement with the experimental relaxation curve of the fabrics analysed was reported accompanied by a high correlation coefficient. The minimum correlation coefficient was observed for sample (I) when the speed was adjusted to 24 m/min. For the same fabric the linear viscoelastic behavior has been reported at 26 m/min with fitting through the generalized Maxwell's model (***Table 6***); however, the non-linear model is not able to describe the viscoelastic behaviour of this sample along warp direction (***Table 9***). On the other hand, when the speed of the experiment goes up by 2 m/min then the viscoelastic behaviour of the recent specimen shows great significance along the weft direction. It could be concluded that with increasing the experiment's speed, deviation from the linear behaviour of worsted fabric to the non-linear behaviour becomes quite manifested. Therefore the three component Maxwell's model with a parallel-connect nonlinear spring acts as a powerful model when the fabrics show non-linear viscoelastic behaviour during recovery from torsional stresses. ***Figure 10*** shows typical graphs of the multi component Maxwell's model curve for fabric type F along with an experimental stress relaxation curve for 24 m/min in the warp direction. The solid curve presents the results calculated from the model, while the dotted curve shows the experimental results.

Figure 10 presents that the predicted and experimental curves are in good agreement for specimen F. It turned out that with adding the non-linear spring within the Maxwell's model, there was a better ability to state precisely what the stress relaxation behaviour of the worsted fabric could be under constant torsional strain. The correlation coefficient measured for this specimen from ***Table 14*** is around 99%.

Conclusion

The aim of this paper was to evaluate the effect of experimental speed (spiral shaft speed) on the stress relaxation of worsted fabrics while maintaining a constant torsional strain. For this purpose three different speeds of the spiral shaft in a stress relaxation tester were consecutively adjusted. The result of this experiment showed that with increasing the speed of the experiment the stress relaxation decreases, but the residual stresses in woven fabrics increases. This behaviour becomes more controversial when the content and structural properties of the specimens change. The result also illustrated that the stress relaxation behaviour of woven fabrics is related to the viscoelastic properties of fibres used and to properties of fabrics such as fabric density (pick per cm), fabric content and fabric construction. In such a way, when the fabric density in pick per cm increases the stress relaxation percent decreases. In order to justify the matter further, stress relaxation curves corresponding to the three Maxwell's model with a parallel connect nonlinear spring were appropriately fitted in comparison with the curve fitting of results with the generalised Maxwell's model.

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