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Twist Direction Effect on the Mechanical Properties of Woven Fabric

Abstract
This work deals with the role that twist directions at the contact point of warp and weft play in the mechanical behaviour of fabrics. Two sets of 100 percent combed cotton yarns (20 tex) of different twist directions (Z & S) and six twist levels were produced and then used as wefts on an old type Dornier loom (weft insertion of 120 picks/min), in which the warp was 100% combed cotton yarns with 870 Z twist per meter. Hereby we obtained two sets of fabrics in which the warps were all the same but the wefts were different in the twist directions and twist levels. Then the fabrics were compared with respect to the yarn pull-out (two adjacent yarns were pulled out at the same time), the fabric formability (product of bending rigidity and reverse value of initial modulus) and fabric buckling (200-g tensile concentrated force was applied to the fabrics). The results show that the yarn pull-out force, fabric formability and fabric buckling force were greater in the fabrics in which the warp and wefts were unidirectional in the twist directions. In addition, in the group in which the warp and weft twist directions were the same, the maximum pull-out force, maximum formability and maximum buckling force belonged to the fabrics in which the nesting angle was around zero.

Key words *twist direction, woven fabric, crossing points, pull-out behaviour, concentrated loading.*

Introduction

Woven fabrics are constructed with lengthwise and cross wise yarns interlaced at right angles. Each set of yarns (wefts and warps) looks like parallel straight wires crossing the other set, and as a result the fabric resembles a screen. The interlacing points are the major locations where interactions between yarns in the two systems take place and through which the yarns form an interlocked structure. Without this interaction at the interlacing points, a woven fabric would be equivalent to sheets made of parallel but isolated yarns; the resultant properties would be entirely different from a practical fabric. In other words, this yarn interaction at the crossing points is the essential feature of woven fabric and will affect more or less all the fabric properties. In fact, engagement and friction between the warp and weft, which are directly related to the yarn surface configuration and fibre alignment at the intersection points, would play a role in fabric mechanical properties. In this respect, yarn twist, which identifies the yarn surface characteristic and fibre alignment, has an effect on fabric behaviour during handling, cutting, sewing and even final use.

In this study we look into the effect of the yarn twist direction at the interlacing points and show their effective difference in fabric mechanical properties. This is done by considering the pull-out behaviour of yarn from the fabric, which is an important indicator of the mechanism of yarn interactions within the fabric and a predictor of its various mechanical properties [1 - 4], its formability, which is the product of its bending and compressibility [5 - 7], and its buckling behaviour, which is a combination of the basic fabric modes (tensile, bending and shear) [8 - 11].

Experimental details

Materials and methods

Yarns: To find the effect of twist (level and direction) on fabric mechanical properties, two sets of 100% combed cotton ring spun yarns (in the S and Z twist directions), each containing 6 different twist levels (twist multiplier of 4, 4.5, 5, 5.5, 6, and 6.5), were produced. This was done by feeding high quality roving of 492 tex count to an old type Saco-Lowell Spinomatic with a 3 over 3 drafting system. Draft changes were used to control the yarn count and overcome the effect of different twist contractions within the yarns. These draft changes enabled a

Table 1. *Yarns specifications details used in this work.*

Yarns	S			Z		
Twist multiplier	19.68 tex			19.68 tex		
	Strength, cN	Elongation, %	C.Vm%	Strength, cN	Elongation, %	C.Vm%
4.0	9209/1	300/17	12.27	8618/1	074/16	12.31
4.5	9256/1	548/17	12.21	0188/2	276/17	12.18
5.0	9270/1	490/18	12.31	2550/2	336/17	12.41
5.5	1242/2	500/19	12.33	2105/2	596/19	12.30
6.0	3923/2	954/20	12.25	1500/2	748/20	12.24
6.5	9709/1	460/18	12.18	9022/1	010/19	12.33

Table 2. *Details of plain weave woven fabrics used in this experimental work.*

Fabric No.	Warp				Weft			
	Count,	Density	Twist		Count,	Density	Twist	
	tex	per cm	per meter	Dir.	tex	per cm	per meter	Dir.
1	19.68	24	870	Z	19.68	24	0870	S
2							0972	
3							1078	
4							1190	
5							1280	
6							1350	
7							0870	
8							0972	
9							1078	
10							1190	
11							1280	
12							1350	

constant yarn count for all twelve yarns produced.

Then the yarns (warp and weft yarns) were singed on a singing machine (model GRR/N, 1997) at a speed of 900 meters per minute to simply remove any possible existing hairs from the yarn surface.

The yarns produced were conditioned for 24 hours under standard conditions (65% R.H. and 22 °C). The yarn strength and elongation were measured with a testometric tensile tester (yarn test length 50 cm, pre-tension of 0.49 cN/tex and rate of loading was adjusted to give the specimen a time to break in 20 seconds). Yarn evenness was measured with an Uster Tester 3, in which the measurement length was 400 m/bobbin. Yarns specification details are shown in ***Table 1***.

Note the sample sizes for the tests are twice as much as was calculated based on the following formula:

$$K = (t \cdot CV/A)^2$$

where, K is the number of tests, t is the probability factor (1.96 for 95% probability), CV is the coefficient of variation, and A is the allowance error (5%).

Fabrics: From each party of the yarns a five meter roll of the fabric (based on the conditions shown in ***Table 2***) was woven on an old type Dornier loom, using a 24 ends/cm warp beam from singed combed cotton yarn (19.68 tex with 870 turns twists per meter). In this manner, two groups of fabrics, namely A (fabrics in which the warp and weft twist directions were the same (Z and Z),) and B (fabrics in which the warp and weft twist directions were opposite each other - Z and S) were produced. The only difference between the two groups of fabrics was in the twist direction.

The following precautions were also taken when weaving the fabrics.

In order to increase the weave-ability of the warp yarns without using any sizing materials, the sheet of warp beam was passed through a dilute caustic soda solution (250 grams of caustic soda per 100 litres of water) to inflate fibres inside the yarn and to prevent any yarn deformation. The caustified warp yarns then were separated (subdivided) right after leaving the squeeze rollers (where yarns were wet), and finally the separated sheets of warp were dried by a hot air drying system. The process of caustifying was done under a tension of 0.83 cN/tex. Hereby we obtained a warp beam with an acceptable weave-ability and no hair on the yarn surface.

To prevent yarn deformation, fibre movement due to shedding and possible abrasion between the warps and heddle eyes during shedding, a special harness (made up of a non abrasive nylon monofilament) was used.

The warp threads were drawn-in to form a 1/1 plain weave and threaded through reed dents one by one (the denting plan was one thread per one dent).
Compensating of the device was used to reduce the peak tensions caused by shedding.

Sample preparation and test procedure

Pull-out

First of all, it should be noted that the Pull-out test is based on holding the sample and pulling one or a few threads out from the fabric. In this experimental work this was done by a Shirly Testometric-Micro 350 tensile tester, shown in ***Figure 1***, with a 3.92 cN load cell and crosshead speed of 10 mm/min. Note that the upper jaw gripped only the upper portion of the threads which were going to be pulled-out, whereas the lower jaw gripped all the threads of the fabric specimen except the lower portion of the pulling threads.

From each fabric, five rectangular specimens (the sample size and shape is shown in ***Figure 2***) were cut and prepared for testing.

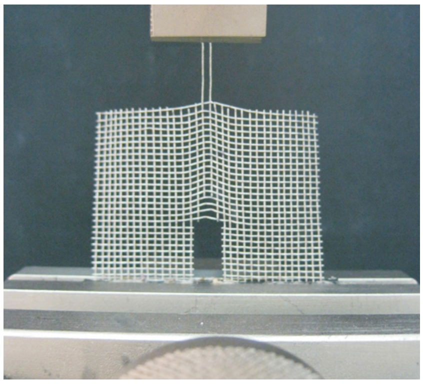

Figure 1. *Specimen mounted on the tensile tester.*

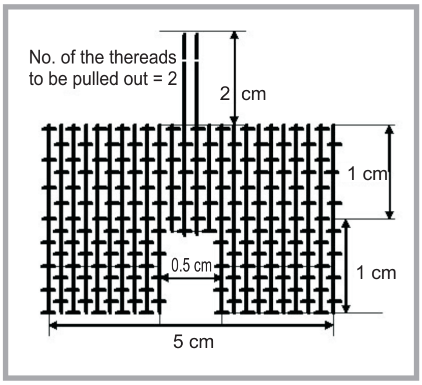

Figure 2. *Specification details of the specimen.*

The bottom edges of the fabric specimen were held by the lower jaw and the two adjacent warp threads were clamped and drawn out from the top edge of the fabric (at a rate of 10 mm/min) by the movement of the upper jaw of the tester. The

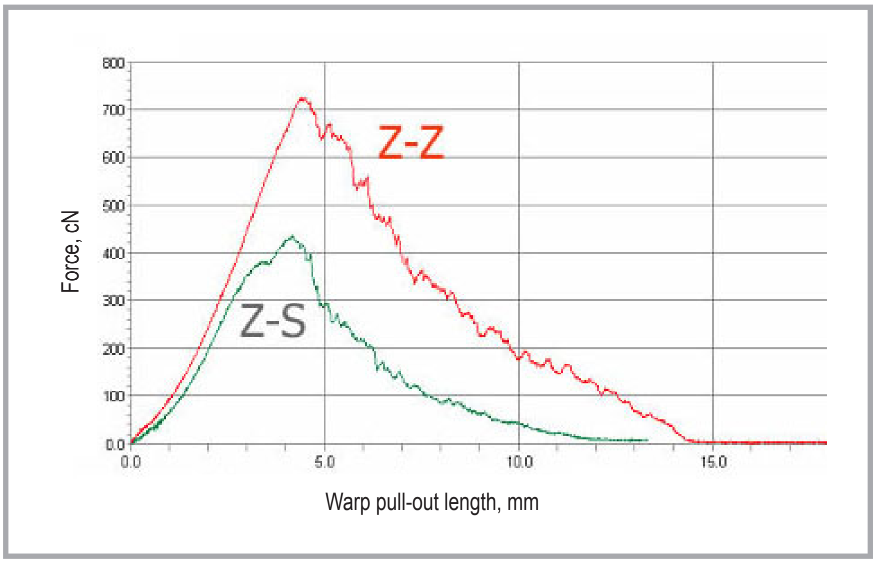

Figure 3. *Force-displacement curves of the pulled – out warp yarns (Fabric number 1).*

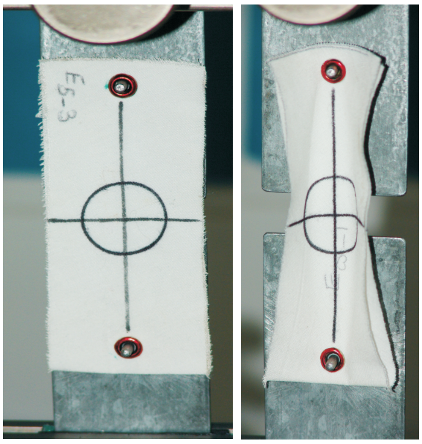

Figure 4. Attachment, sample and fabric buckling on the Testometric-micro 350 tensile tester.

pulled-out behaviour of the two adjacent warp yarns was recorded on the load-displacement chart of the tensile testing instrument (***Figure 3***).

Formability

Bending stiffness

Bending rigidity in the warp and weft directions was calculated based on the Peirce method according to ASTM D-1388-55T. For this purpose five samples of 30 × 300 mm dimension in the warp and weft directions were cut from each fabric. For each specimen the length of the slacking part of the sample was measured by the constant angle method. In this way the value of the bending length (for each direction) is the mean value of 20 readings.

Initial modulus

The initial tensile modulus (ratio of force to elongation increment taking place in the initial linear shape of the curve) of the fabric in the warp and weft directions was extracted from the low load tensile curves.

In order to find the value of the initial tensile modulus, five samples for which the bending rigidity was assessed were taken. Fabric force-elongation curves were registered on the Testometric-micro 350 Shirley development, with a load cell of 3.92 cN and cross head speed of 10 mm/min.

Formability calculation

Formability in the warp and weft directions of each sample based on the ratio of bending rigidity and initial tensile modulus of the corresponding direction was calculated (-B/IM-). The general unit fabric formability was calculated as a geometrical mean value.

Bias direction low load tensile behaviour

In order to compare the shearing behaviour of the two groups of fabrics, a rectangular specimen, 24 cm long and 5 cm wide, was cut from each sample fabric. Since the bias sample could develop shear strain under tensile stress, the strips were folded in half to form a double ply of face to face fabrics 12 cm long. Note, from each fabric five rectangular specimens were cut and prepared for testing.

Concentrated loading

The testing method is based on applying a 200 gram force over a small portion of the edge of the rectangular specimen [12]. Three rectangular specimens, each 24 cm long and 5 cm wide, were cut from each sample fabric (to the warp) and prepared for the concentrated loading test. To prepare the samples, an eyelet was inserted 1 cm from the ply ends opposite the fold,and the second eyelet was inserted 10 cm from the first one after possible slack was removed.

Then the samples were subjected to a single loading cycle at a rate of 10 mm/min with a 196.1 cN maximum force using a simple attachment to the jaws of the tensile tester (Testometric-micro 350 made in the Shirley developments) with a 3.92 cN load cell (***Figure 4***).

Discussion of experimental results

Yarn pull-out

The pull-out behaviour of a thread from the woven fabric helps to understand the engagement of the warp and weft at crossing points. Actually it shows how well they stick to each other. Naturally when two adjacent warp yarns are drawn from the fabric they rub the intersected weft yarns among themselves and they must overcome the friction force between the intersected weft yarns and themselves. Thus, as the engagement is higher, the force needed to overcome the friction force is also higher.

Pull-out curves

A few samples of the pull- out curves of the different fabrics are shown in ***Figure 5***. These curves illustrate the difference in the pull-out behaviour of the fabrics due to the effect of twist. All the

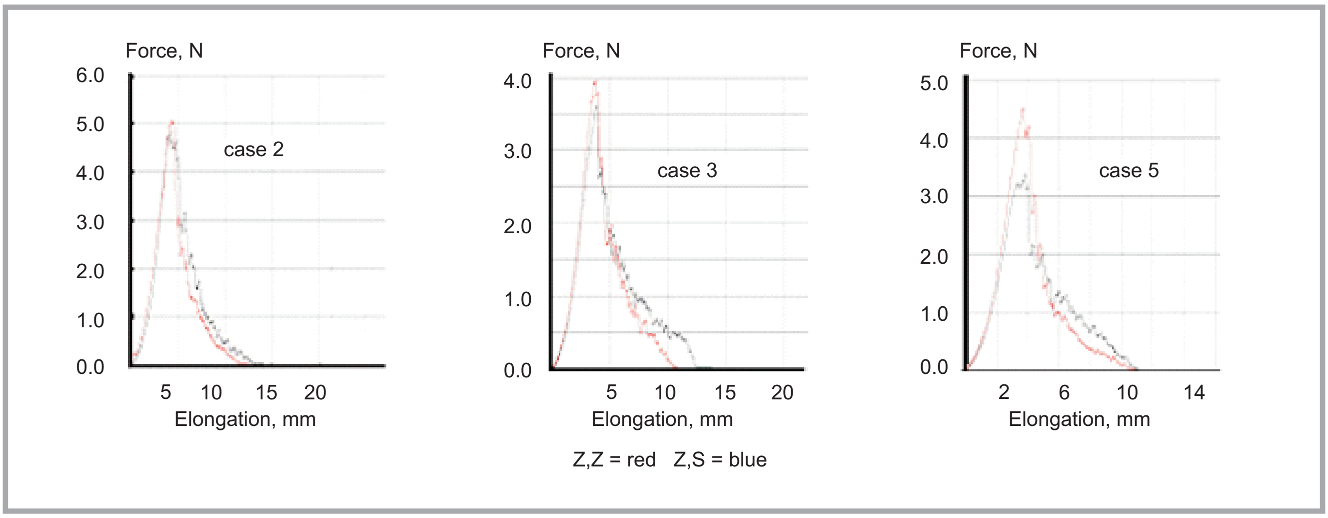

Figure 5. *Pull-out curves of different fabrics, indicating the differences between fabrics with the same twist direction and those with opposite twist directions.*

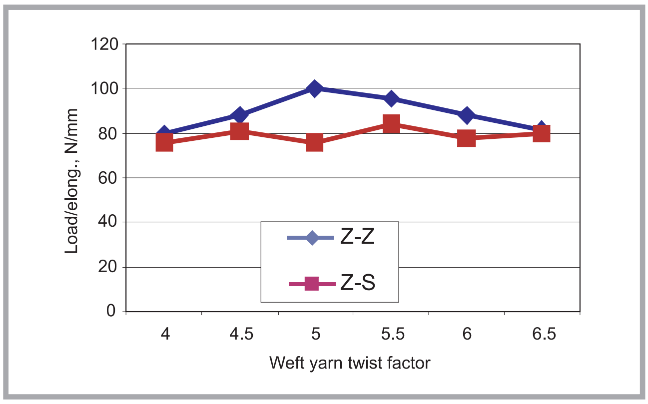

Figure 6. Initial slopes of the pull-out curve versus the weft twist factors.

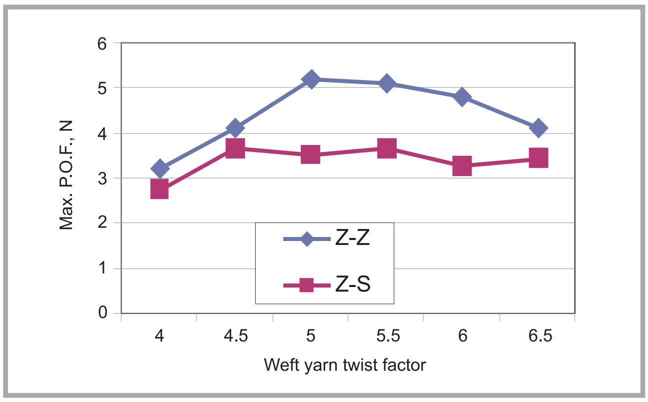

Figure 7. Twist factors versus the maximum pull-out force.

curves from the fabrics in which the warp and weft twist directions are the same (Z and Z) are located at the top of the curves of the fabrics in which the warp and weft twist directions are opposite each other (Z and S), meaning that for the fabrics in which the warp and weft are unidirectional, they are at a higher level of engagement. In other words, the movement of yarns at the crossing point for fabrics in which warps and wefts are opposite in the twist direction is easier and needs a lower amount of force to be drawn-out. Comparison of the curves of each group of fabrics (Z and Z or S and Z) illustrates the effect of the twist quantity

Slope of the incremental curve

This slope resembles how easy (or difficult) the warp yarns starts to draw-out. The easiness of the movement is related to the freedom of the pull-out yarn (from the surrenders) to move (or the dependency to the attached crossing yarns). If the pull-out yarn is free, the only deformation is the straightening of the pull-out yarn. However, if the pull-out yarns at the crossing points are stuck to some crossing yarns, then the movement is dependent upon the stickiness of the yarns and consequently is dependent upon the weft crossing yarn properties (especially bending behaviour). Actually the deformation contains warp yarn straightening and weft yarn deformation toward the pull-out direction.

Naturally, pulling out the yarn is affected by the entanglement of the outer layer fibres of the warp and weft yarns. Such a situation shows the effect of the warp and weft entanglement and nesting at the crossing points. Note that the warp pulling out procedure brings the weft crossing yarns into play, one by one in turn, so that the first one to come into play is that which is close to the moving jaw of the tensile tester, whereas the last one is that close to the edge of the fabric near the lower jaws of the tensile tester. The maximum pull-out force indicates the total force needed to move the yarn out. Therefore the initial slope shows how well the outer layer fibres of the warp and weft yarns got together and kept each other tight. In fact, as the entanglement and nesting between warp and weft yarns at the crossing point is higher, the initial slope of the curve is sharper. Clearly, when the weft is stuck to the warp, the weft behaviour (especially the yarn bending properties) affects the warp yarn pulling movement, with this effect reaching the maximum when perfect bedding occurs.

Table 3 and ***Figure 6*** show the initial pull-out slopes of all fabrics. It is seen that the initial slope of the fabrics in which the warp and weft twist directions are the same (group A) is higher than the other group in which the warp and weft twist directions are opposite each other (group B). Furthermore among this group (unidirectional twist), the highest initial slope values belong to fabric numbers 3 and 4.

Maximum pull-out force for two adjacent yarns

As was mentioned earlier, the maximum pull-out force indicates the total force needed to move the yarn out from the fabric. The relationship between the twist factor and maximum pull-out force for all fabrics are shown in ***Figure*** *7*. It is seen that the warp maximum pull-out force for the fabrics in which the warp and weft twist directions are the same (Z) is higher than that for the other group of the fabrics where the warp and weft twist direction is opposite each other (Z and S).

In addition, ***Figure*** *7* shows that among the fabrics in which the warp and weft are unidirectional in twist (A group fabrics), the highest pull-out force belongs to those fabrics with a weft twist factor of 5 - 5.5 (note: bend warp yarn twist helix angle is 41.89 and bend weft yarn twist helix angles are 48.24 - 50.93, making a total helix angle of 91.53 - 94.22 degree, respectively). However, in reality the to-

Table 3. Initial slope of pull-out curves of the warp yarns.

Twist factor	4.0	4.5	5.0	5.5	6.0
Initial pull-out slope for the A group fabrics	370/5	440/5	500/5	480/5	440/5
Initial pull-out slope for the B group fabrics	380/5	400/5	380/5	420/5	440/5

Table 4. Formability in details.

Twist factor	Bending rigidity, mN·mm				Compressibility (1/initial slope, mN/mm)			
	Warp direction		Weft direction		Warp direction		Weft direction	
	Z-Z	Z-S	Z-Z	Z-S	Z-Z	Z-S	Z-Z	Z-S
4.0	0.15850	0.05835	0.07207	0.05830	0.00070	0.00060	0.00140	0.00130
4.5	0.16627	0.07590	0.08748	0.06650	0.00130	0.00290	0.00180	0.00350
5.0	0.17880	0.09810	0.12104	0.08218	0.00220	0.00040	0.00410	0.00070
5.5	0.22369	0.11260	0.11290	0.04290	0.00270	0.00440	0.00127	0.00400
6.0	0.20497	0.10470	0.10570	0.04770	0.00370	0.00660	0.00220	0.00460
6.5	0.21529	0.05856	0.14205	0.03110	0.00270	0.00266	0.00290	0.00066

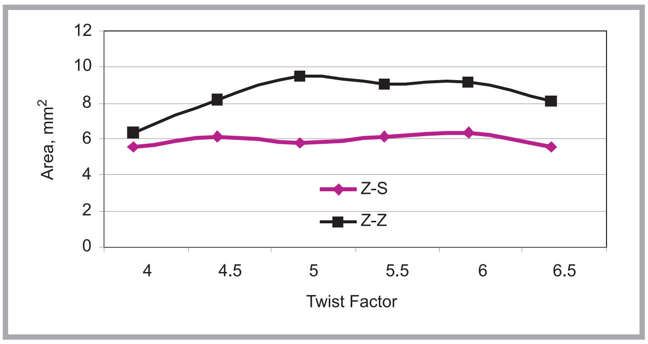

Figure 8. *Areas under the decremental curves for all fabrics.*

tal helix angle is lower than the angle calculated above due to the fact that the warp and weft at the crossing points do not have perfect bending (torus form), all fibres are not parallel to the twist directions and the phenomenon of flattening also occurs during bending. Yet the pull out force of our experimental investigation shows that commercial yarn twists prevent bedding if their twist directions are opposite each other but will permit bedding if the warp and weft twist directions are the same. Furthermore the maximum force needed to pull the yarn out from the fabric occurs when the total helix angle of the warp and weft goes up to around 50 - 55 degrees,that is (α_{warp} + + α_{weft}).

Area under the decremental curves

Figure 8 shows the area below the decremental curve for all the samples. This portion of the curve shows the manner in which the two warp pull-out yarns free themselves from the interlaced points. As the yarns are drawn out from the fabric, the ends of these two yarns leave the fabric, hence the number of crossing (interlacing) points is reduced. Actually this is a reduction in the force from the maximum to zero contact point. However, the areas under the curve for all fabrics in which the twist direction for the warp and weft are the same (A group fabrics) are higher than those under the curves for the other group of fabrics (B group fabrics), meaning greater work to be done to release the yarn at the contact point.

Comparison of the areas of the two groups of fabrics indicates that the greatest work done to pull-out the yarns from the fabric belongs to the one in which the weft yarn twist factor is 5 (fabric number 3)

Formability

The product of bending rigidity (measured on Shirly bending tester) and compressibility (reverse values of tensile initial slope), which is known as fabric formability, is compared in ***Figure 9***.

Considering the values in ***Table 4*** (bending rigidity and compressibility, see page 51) and despite the complexity of the formability, one can see that unidirectional warp and weft fabrics have greater formability.

Low load-tensile behavior in 45 degree bias direction

Fabric low-load tensile behaviour in the bias direction also shows the same results. ***Figure 10*** illustrates the difference between the curves of the two groups of fabrics. In all cases, the initial slope

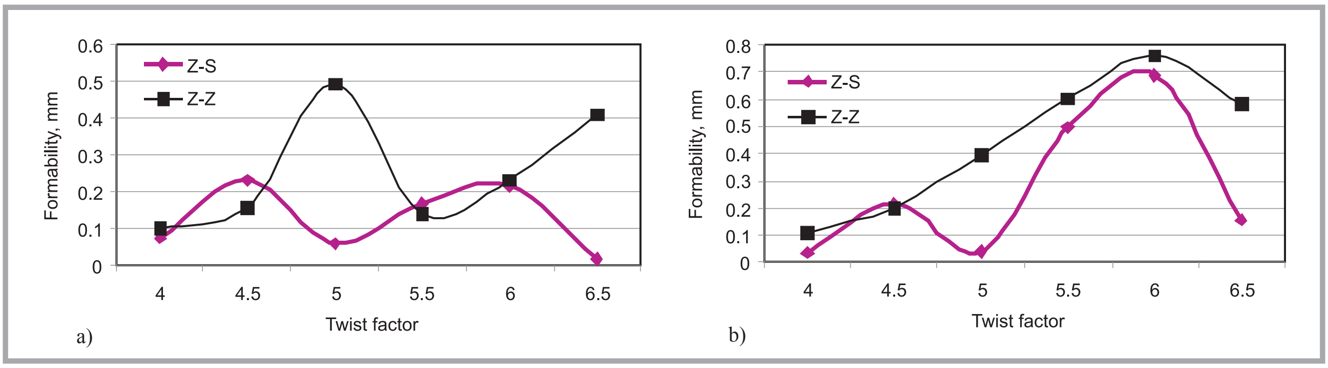

Figure 9. *Fabric formability against the total yarns twist angles at crossing points; a) weft and b) warp directions.*

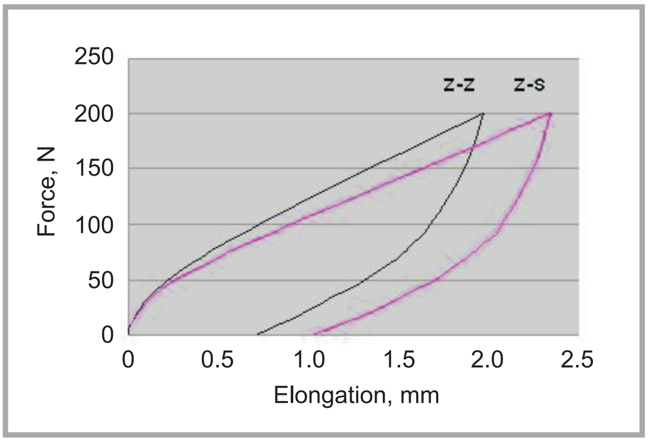

Figure 10. *Low load tensile behavior of the folded bias samples (from the Tensile Testometric).*

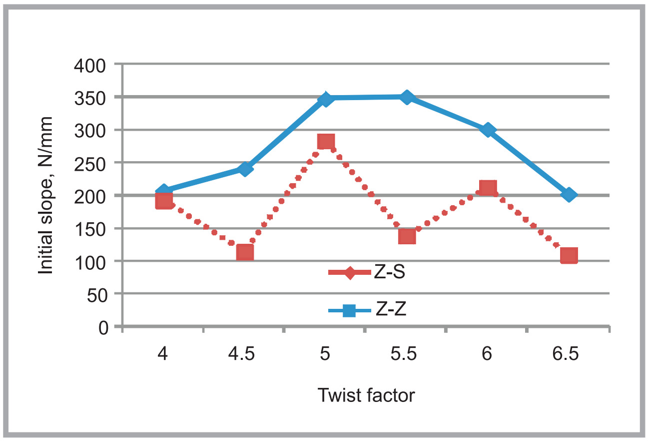

Figure 11. *Plot of the initial slopes of the low load tensile curves versus the nesting angles.*

of the curves of the fabrics in which the warp and weft are unidirectional (Z and Z) is higher. In addition, the final elongation for the fabrics in which the warp and weft twist directions are the same (Z and Z) is lower.

These differences between the curves indicate the fact that rigidity in yarns sliding over each other in the A group of fabrics (unidirectional warp and weft twist) is higher than for B group. In other words, shearing rigidity (threads sliding over each other at the crossing points) in the B group of fabrics is lower than that for group A fabrics. Furthermore,the highest initial slope belongs to fabric number 3, which contains weft yarns with a twist factor of 5 .

The difference between the two groups could be explained by considering the nesting or bedding of fibres at the crossing point. ***Figure 12.a***, illustrates the condition in which warp and weft threads are not unidirectional. In this case the twist direction causes fibres of the warp yarn to cross fibres of the weft yarn (fibres of one threads are perpendicular to those of the crossing thread) and consequently no convergency among the warp and weft yarns. Actually the warp and weft threads are forced to sit on each other. In other words, nesting or bedding among fibres of the warp and weft does not occur.

In the case where warps and wefts are unidirectional (***Figure 12.b***), fibres of the warp and weft yarns at the crossing points are twisted in the same direction. That is, the twist on the underside of the top thread is in the same direction as that on the upper side of the lower thread. Therefore engagement among the fibres of the two groups is possible. in such a condition; $\varphi = \beta - (\theta bw + \theta bf)$.

When φ is the nesting or bedding angle between top and bottom fibres in contact at the crossing point, β is the warp and weft crossing angle, which is 90°, θbw is the local helix angle at the inside of the bent warp yarn, and θbf is the local helix angle at the inside of the bent weft yarn.

For more information and details about the nesting angle, the local twist angle of the outer layer fibres at the crossing point(bent yarn), and the mechanics of bent yarns, one can refer to the outstanding works done by Stanley Backer, who used to be Professor of Mechanical Engineering at the Massachusetts Institute of Technology [13].

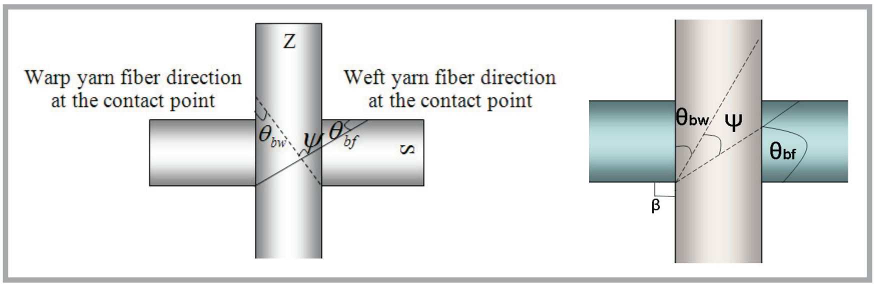

Figure 12. *Relationship between warp and weft yarns at crossing point (warp and weft nesting or bedding conditions); a) warp and weft twist directions are opposite, b) warp and weft twist directions are the same.*

Table 5. *Warp and weft twist helix angles and nesting at the point of contact where the yarns are bent over each other (for group A fabrics).*

Twist factor		4.0	4.5	5.0	5.5	6.0	6.5
Weft twist angle	Straight	24.13	26.75	29.25	31.63	33.9	36.05
	Bend(θbw)	41.89	45.23	48.24	50.93	53.35	55.52
Warp twist angle	Straight	24.15	24.15	24.15	24.15	24.15	24.15
	Bend(θbf)	41.89	41.89	41.89	41.89	41.89	41.89
$\theta bw + \theta bf$		83.78	87.12	87.12	92.82	95.24	97.41
$\varphi = 90 - (\theta bw + \theta bf)$		6.22	2.88	-0.13	-2.82	-5.24	-7.41

However, ***Table 5*** shows the nesting details calculated: warp and weft twist angles (helix angle of the outside fibre in the straight yarn and local helix angle at the inside of the warp and weft yarns bend (θbf)), total warp and weft twist angle at crossing points (θbw + θbf), and consequently, the nesting angles (90 - (θbw + θbf)) for all cases of production).

The plot of calculated nesting values (***Table 5***) versus the initial slopes of the low load tensile curves (***Figure 11***) highlights the fact that initial slope reaches its maximum value (highest rigidity to movement) when the nesting angle gets close to zero (cases 3 and 4), showing that higher parallelisation in the twist direction between the warp and weft causes higher rigidity at the contact points. In addition, the initial low load tensile behaviour of group B fabrics does not follow the same trends. Actually it shows the easy, uncontrolled irregular behaviour of the yarns due to the lack of yarn engagement at the crossing points.

Buckling due to concentrated loading

Figure 13 (see page 54) compares the bias fabrics' behaviors (Z & Z and S & S) due to the application of a 196.2 cN over a small portion (3 mm in diameter) of the edge of the 10 cm × 5 cm rectangular specimen (concentrated loading methods). The buckling point is the border of the fabric's in-plain and out of plain deformation. In fact, the lower portion of the incremental curve, below the critical point, resembles the in-plain fabric behaviour, and the upper part of the curve indicates the post buckling behaviour of the fabrics (***Figure 15,*** see page 55).

Comparison of the initial slope (IS) and buckling point load (ST), which are lower for group B fabrics (***Table 6***, see page 54), indicates easy in-plain movement for the fabrics in which the warp and weft twist directions are opposite each other.

Table 6 shows the specification of the buckling point (St and EB) due to the concentrated loading. Comparison of the values highlights the effect of the twist multiplier among the fabrics in which the warp and weft are unidirectional, showing that when the total twist angle of warp and weft threads gets to around 50 degrees (nesting angle reaches zero degrees) the buckling point load reaches its highest value.

Figure 14 shows the elongations at the buckling point (EB) and that at 39.2 cN (EF). The figure also indicates that the

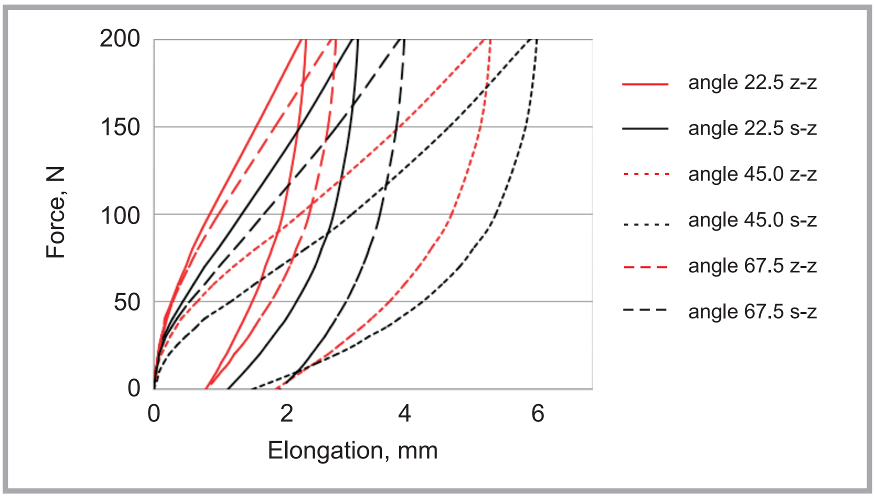

Figure 13. Load-extension curves of the bias samples due to the concentrated loading cycle.

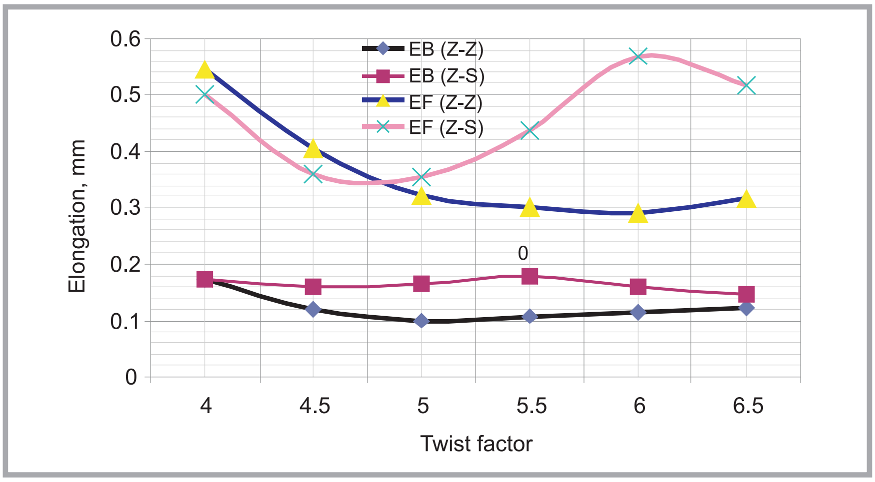

Figure 14. Effect of twist factor on the elongation of the fabric at the buckling zone.

buckling zone and fabric behaviour therein (or during buckling phenomenon) for the two groups of fabrics (i.e. Z-Z and Z-S) are completely different.

The elongation at the buckling point (EB) and that at 39.2 cN (EF) for the fabrics in group A where the warp and weft twist directions are the same follow the same trend, (having minimum elongation for fabrics with a weft twist multiplier of 5 - 5.5), whereas the buckling elongation (EB) and elongation at 39.2 cN (EF) for group B fabrics in which the warp twist direction is opposite the weft twist direction do not follow the same trend, indicating a well controlled behaviour during buckling phenomenon for the fabrics in which the warp and weft twist directions are the same (A group fabrics). At the same time, it shows higher engagement for fabrics in which the weft twist multiplier is between 5 - 5.5. In other words, in the group A fabrics the one whose warp twist angle and weft twist angle add up to 50 degrees yields a better engagement. Actually the difference in the buckling behaviour of the two groups of fabrics is due to that in the fibres' alignment and engagement at the crossing points. Practically when the warp and weft twist directions are the same, the twist on the underside of the top thread is in the same direction as that on the upper side of the lower thread (***Figure 16.a***). Such a condition is favourable for the threads to bed into each other and put the fabric in an equilibrium status, giving uniform deformation. In such a condition, in-plain movement prior to buckling due to concentrated loading is monotonous (the force applied to the fabric spreads all over the fabric uniformly), causing a delay in 'out of plane deformation'. As a result, uniform deformation and smooth rounded shape thereof, such as smooth rounded bending and buckling (which was also observed during testing ***Figure 16.a***) occur.

It is also worth mentioning that when the twist direction for the warp and weft is not the same (***Figure 16.b***), the twist on the underside of the top thread is in the opposite direction to that on the upper side of the lower thread. In this case the condition is such that the threads are not engaged (nesting angle is around 90º). They do not form a compact cloth (the weave and thread structure is distinct), especially when the twist is high, and as a result the effect of any torque existing in the yarn will affect the distortion of the fabric, meaning that the self deformation of the fabric (movement of the yarn in the structure) is not controlled. It can cause deformations such as the bias curling of the fabric or distortions like the skew of twill weave woven fabrics during relaxation [14]. However, in such a condition, the unit cells of the fabric do not act alike, and consequently the reaction of each unit cell will be different. In other words, the distribution of the concentrated load all over the fabric is not uniform, causing non-uniform in-plain deformation of the fabric and, as a result, a lower buckling point.

*Table 6. Features extracted from the concentrated loading curves; * F.T.M. stands for filling twist multiplier.*

F.T.M.*	Z and Z					Z and S				
	ST	IS	EB	EF	EM	ST	IS	EB	EF	EM
4.0	17.6	277	0.175	0.545	5.280	16.59	121	0.173	0.500	6.014
4.5	19.4	338	0.120	0.405	4.909	19.69	257	0.160	0.364	4.615
5.0	27.7	427	0.100	0.320	3.842	24.60	217	0.165	0.355	4.374
5.5	24.3	570	0.107	0.300	3.219	21.10	220	0.180	0.436	4.713
6.0	22.5	480	0.115	0.290	3.400	22.00	345	0.160	0.568	4.400
6.5	14.8	426	0.125	0.315	3.460	18.98	172	0.147	0.517	4.592

Conclusions

The following conclusions are drawn from this experimental work:

- Twist directions of the yarns at intersection points (Z and Z or S and Z) are

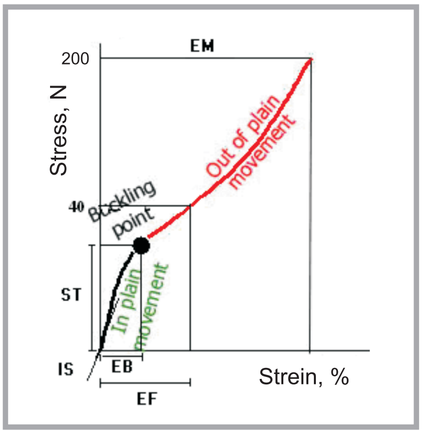

Figure 15. *Concentrated loading curve.*

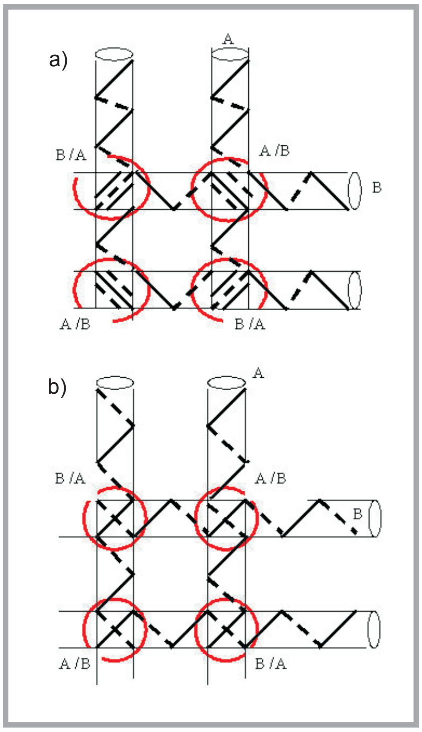

Figure 16. *Contact points and twist directions; a) Twist direction for both (warp and weft) is the same (Z-Z). b) Twist direction for warp and weft is not the same (Z-S).*

effective on fabric mechanical behaviour.

- The yarn pull-out force, fabric formability and fabric buckling force were greater for fabrics in which the warp and wefts are unidirectional in the twist direction.
- Among the group in which the warp and weft twist directions were the same, the maximum pull-out force, maximum formability and maximum buckling force belong to the fabrics in which the warp and weft yarns at the crossing points make a nesting angle of around zero degrees.
- The higher buckling point, pull-out force, fabric formability and initial slope of the 45° bias sample indicate higher rigidity in yarn sliding in the case of fabrics with a unidirectional twist direction, causing monotonous in-plane and out of plane deformations.

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