Effect of Construction on Strain distribution in Woven Fabrics under Uniaxial Tensile Deformation

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ABSTRACT
Woven fabrics form an integral part of technical textiles where strength is of prime importance. Amongst various factors found to affect the tensile properties of woven fabrics, change in weave and numbers of yarns is expected to alter initial crimps, ease of crimp interchange and fabric assistance in both the principle directions of testing. Accordingly, a strain analysis of plain and satinette woven fabric samples in raveled strip testing mode were undertaken in this work. The samples were generated under similar weaving conditions while varying only the pick density systematically. An analysis of the strain pattern reveals many interesting observations, the most significant ones being (1) the direct relation between the percentage yarn strength utilization in fabric with the uniformity of strain levels along the two principal directions and (2) a significant difference in the strain distribution of samples tested along warp and weft directions irrespective of the construction.

Keywords: Structure of woven fabric, uniaxial tensile properties, strain distribution

INTRODUCTION
Recently, an upsurge in the use of textiles for various technical applications, especially as a precursor for composites, has occurred. A majority of the applications where mechanical performance is the most important parameter employ woven textiles. An understanding of the factors influencing the behavior of woven fabrics would translate into the facility of designing the fabrics according to end-use requirements. The performance of the woven fabrics has therefore captured the curiosity a number of researchers.

Kumpikaite and Sviderskyte [1] concluded that the breaking elongation of woven fabrics increases with increase in rigidity of weave and weft setting. One may infer from this that a change in weave and sett may affect the strain developed in the test sample during tensile deformation. Another study [2] concluded that fabric weave and sett are important in deciding its weavability. Both studies, however, were confined to fabrics made of multifilament yarns in the warp direction only. Fabrics made of spun yarns may offer a different behavior. Banerjee, Mishra and Ramkumar [3] studied woven fabrics made of 100% cotton spun yarn and suggested the possibility of a strain gradient along the sample length during the process of tensile deformation which may be influencing the fabric performance.

Milasius [4] proposed weave firmness factors P_1 and P_2 for making an estimation of fabric properties and reviewed factors proposed by other authors [5] to quantify weave and was of the opinion that they failed to give an exact estimation of the influence of weave on fabric properties. This author proposed weave firmness factor φ which had a wider applicability in deciding weavability of fabrics. Gupta, Fangning and Seyam, [6] attempted to predict the tensile behavior of woven fabrics by proposing a generalized model which also considered the interlacement distribution pattern of the weave. They, however, considered only one actual 100% woolen fabric to validate the results. Kawabata, Masako and Kawai [7] introduced the resistance offered by transverse yarns and presented a model for prediction of tensile properties of woven fabrics. The aspect of strain developed in the sample during tensile loading and its influence on the results obtained was not considered in either of the works [6, 7].

Babur [8] explored the possibility of predicting the stress-strain behavior of the composite as a whole from the localized strain values using micromechanical models, while Hu and Wang [9] used the strain energy method to detect damage in woven fabric composites. Swan and Kosaka [10] worked on the relationship between the structure and properties of inelastic mechanical composites. The importance of strain developed in the sample as a measure of the results obtained was acknowledged by all the three authors.

Most of the work done on the study of the tensile properties of woven fabrics and composites so far has evolved around modeling the behavior of interlacement of one load bearing thread with one or more interlacing threads or that of a repeat. However, a fabric sample tested for its tensile properties usually consists of a very large number of load bearing and crossing threads which surely interact amongst themselves and influence the final outcome. Similarly, during the actual process of deformation on a tensile testing system, the fabric bands in the vicinity of the jaws experience a greater constraint to deformation as opposed to those near the center of the specimen. Moreover, during the process of crimp interchange in uniaxial deformation, the load bearing threads start losing crimp and straighten, thereby becoming progressively aligned to the fabric plane, while simultaneously getting inclined to the load bearing direction due to width wise contraction of the specimen. The extent of this inclination varies along the length of every load bearing thread as well as from one thread to the other. The threads at the center of the sample width remain more or less straight, while inclination of those away from it increases with increase in their distance from the center. The inclination along any thread is least near the jaws and maximum near the center of the sample length for most cases.

Evidently the constraints imposed by the two jaws, one of which moves while the other remains stationary, could generate a strain pattern in the specimen being deformed, and it is entirely likely that there would be an interplay between the construction, the strain distribution, and the percentage utilization of yarn strength at rupture of the specimen.

While studying the effect of number of load bearing and interlacing threads, the spacing between them and the interlacement pattern on the tensile behavior of four different types of woven fabrics [3], a great deal of variation was observed in their percent yarn strength utilization, although the samples were generated under identical conditions. Especially the plain and satinette weft samples showed extreme behavior, and it was felt that a study of strain distribution over the entire specimen during tensile deformation near the break may lead to important insights. It was proposed that different samples, due to the difference in their distribution of interlacement pattern as well as other structural differences may cause the strain to flow differently. To study this, it was decided to record the strain in different bands and strips of the test sample as explained later in the experimental methods section. The percentage yarn strength utilization of the yarn in the fabric was treated as a pivotal parameter for ranking the efficiency of the structure.

MATERIAL AND METHODS

Material

Cotton yarns of English count 30^s and 20^s were used as warp and weft respectively to develop fabric samples on a Somet Air jet loom running at 600 picks per minute with reed space of 1.45 meter. Plain and 4-end satinette fabrics with 38 ends per cm in the warp direction were prepared at three different levels of pick density (18, 22 and 26 picks per cm) for the strain analysis. The repeat units of plain and satinette weaves are shown in *Figure 1*. The breaking load and elongation of warp yarns was 2.24N and 4.15% and that for weft yarns was found to be 3.93N and 5.2% when tested at 500mm gauge length.

X		X	
	X		X
X		X	
	X		X

Plain

X	X		X
	X	X	X
X		X	X
X	X	X	

Satinette

FIGURE 1. Repeat units of plain and satinette weaves ('x' represents warp over weft).

Experimental Methods

The fabrics were wet relaxed and then tested for some physical properties, namely yarn count, crimp, ends and picks per cm, and tensile behavior[1]. The tensile behavior was tested according to ASTM-D5035 with 2 inch wide and 3 inch long samples. The percent single yarn strength utilization in the fabric (%SU) was calculated according to Eq. (1). In addition, the strain distribution over the surface of a fabric specimen while being subjected to uniaxial tensile loading was measured.

$$\%SU = \frac{\text{Fabric Breaking Load x 100}}{\text{2 x number of load bearing yarns per inch x Single Yarn Strngth}} \tag{1}$$

Study of Strain Distribution

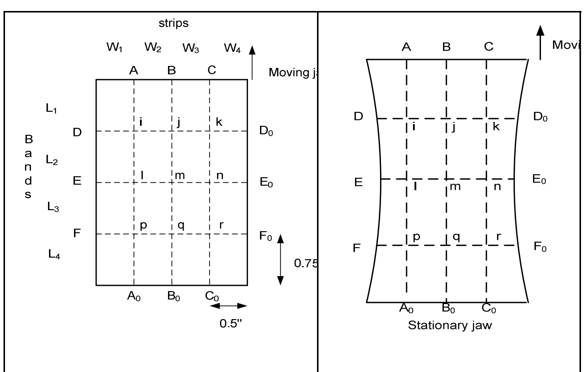
In order to study the strain distribution in a fabric specimen subjected to uniaxial tensile loading; it was decided to estimate tensile strain at different locations of the specimen at 75% of breaking strain.

Sample Marking [11]

The scheme of marking the samples for studying strain distribution is illustrated in *Figure 2a*. The intersection of vertical lines A-A_0, B-B_0, and C-C_0 with horizontal lines D-D_0, E-E_0, and F-F_0 yields 21 tracking points marked on the specimen as mentioned below.

- A, B and C: on the line where moving jaw grips the fabric.
- A_0, B_0 and C_0: on the line where stationary jaw grips the fabric.
- D, i, j, k and D_0: 0.75" below the moving jaw.
- E, l, m, n and E_0: 1.5" from both the jaws (middle line of the specimen).
- F, p, q, r and F_0-: 0.75" above the stationary jaw and 2.25" below the moving jaw.

Horizontally, the tracking points were marked at 0.50", 1", and 1.50" away from the left edge of a fabric specimen. This process splits a specimen into four horizontal bands L_1, L_2, L_3 & L_4 and four vertical strips W_1, W_2, W_3 & W_4 resulting in 16 cells each 0.50" wide and 0.75" high (*Figure 2a)*. The segments A-i, B-j, and C-k form the first horizontal band $L_{1,}$ the next band L_2 contains the segments i-l, j-m, and k-n, while the segments l-p, m-q and n-r form the third band L_3 and the band L_4, just above the stationary jaw, contains segments p-A_0, q-B_0, and r-C_0. There are four vertical strips -W_1 (near the left edge) with segments D-i, E-l, and F-p; W_2 having segments i-j, l-m, and p-q; W_3 comprising of segments j-k, m-n, and q-r and W_4 (near the right edge) contains the segments k-D_0, n-E_0, and r-F_0. *Figure 2b* represents the schematic view of a hypothetically deformed specimen.



a) undeformed state | b) deformed specimen

FIGURE 2. Schematic diagram [11] of specimen prepared for analyzing the strain distribution during tensile testing.

Recording the Deformation of the Fabric Specimen

The videos of the samples during tensile deformation were recorded using a Sony CMOS Handy cam (4Mp resolution) fixed on a rigid tripod and operated by remote control to ensure steady filming. Thereafter, individual frames, corresponding to 75% of breaking strain were extracted from the videos using Windows Movie Maker and the images were edited using Microsoft Office Picture Manager so that each frame enclosed only the complete specimen and no other machine parts. The coordinates of all twenty one points were extracted from individual images using Image J, and strain in all segments was calculated. Microsoft Office Visio 2003 – Application software in MS Office was used to draw the strain profile of the specimen.

Expressions of Strain

The line where the stationary jaw grips the specimen was taken as the ‘X axis’ and the bottom left corner of the specimen on the line was chosen as the origin (0, 0). The ‘y’ axis coincided with the left edge of the undeformed specimen along its length. The co-ordinates of points were noted as (x_p^0, y_p^0), (x_q^0, y_q^0), … (x_k^0,y_k^0) in the undeformed state of the fabric. Co-ordinates of points (say of the point ‘p’) after 25%, 50%, and 75 % of the breaking strain were denoted as (x_p^1, y_p^1), (x_p^2,y_p^2), and (x_p^3,y_p^3) respectively. This paper deals with the deformation at 75% of breaking strain only.

Taking the point p as an example, the length and width wise displacement of any point on the fabric specimen from its original location can be expressed by Eq. (2) and Eq. (3).

The expression of strain in each of the three lengthwise segments in the band L_1 can accordingly be stated as in Eq. (2a) to Eq. (2c). Expressions of strain in rest of the segments in bands L_2, L_3 and L_4 can similarly be worked out using:

$$\Delta y_p = \text{The displacement along the length of the specimen at 75\% of Breaking Strain} = (yp_3 - yp_0) \quad (2)$$

$$\Delta x_p = \text{The displacement along the length of the specimen at 75\% of Breaking Strain} = (xp_3 - xp_0) \quad (3)$$

$$\text{Strain in the segment A-i} = \frac{(\Delta y_A - \Delta y_i)}{(y_A - y_i)} \quad (2a)$$

$$\text{Strain in the segment B-j} = \frac{(\Delta y_B - \Delta y_j)}{(y_B - y_j)} \quad (2b)$$

$$\text{Strain in the segment C-k} = \frac{(\Delta y_C - \Delta y_k)}{(y_C - y_k)} \quad (2c)$$

The values of x_D, x_E and x_F was taken as zero since they lie on the Y-axis. The expression of contraction in each of the three widthwise segments in the strip W_1 was calculated as follows

$$\text{Contraction in the segment D-i} = \frac{(\Delta x_i - \Delta x_D)}{x_i} \quad (3a)$$

$$\text{Contraction in the segment E-l} = \frac{(\Delta x_l - \Delta x_E)}{x_l} \quad (3b)$$

$$\text{Contraction in the segment F-p} = \frac{(\Delta x_p - \Delta x_F)}{x_p} \quad (3c)$$

Contraction in other segments in strips W_2, W_3 and W_4 was also calculated by employing similar principle as outlined above.

Pin-Joint Diagram

To visualize the number and disposition of load bearing and transverse threads in the fabric specimens, the pin joint diagrams of the samples were prepared with Microsoft Office Visio assuming the interlacement point to be pin-joints. The specimen length was 2 inch x 3 inch, but the number of threads shown in the diagram are actual number of threads divided by 20, rounded off to nearest integer, for ease of representation.

RESULTS AND DISCUSSIONS

Fabric Construction and Tensile Properties

Table I presents the fabric construction parameters and the tensile test results of the fabrics under study. It is worth mentioning here that at a given pick density, the plain and satinette fabrics differ only in interlacement pattern, and this results in difference in the initial crimp in the two principle directions in the fabrics as also in the percent yarn strength utilization (%SU). At all the three pick densities, the difference in the % SU of the two fabrics is prominent when tested in the weft direction, with the satinette fabric depicting much lower values. However, the difference in the initial crimps in the load bearing direction is more evident when the samples are tested in the warp direction with the plain fabrics showing much higher values.

For a given weave, the data in *Table I* does not show a drastic change in %SU with change in pick densities, though a change in direction of testing does. The difference in the % yarn strength utilization between the samples tested in two directions is found to be significant by t-test. It is worth mentioning here that the interlacement pattern and number of threads for the unit cell is same for a given weave for both the directions of testing. The difference in total number and linear densities of load bearing and transverse threads in the test specimen seems to be the main cause of difference in crimp and hence tensile behavior when the direction of testing is changed. For both the weaves and at all the three pick densities, the crimp in the load bearing yarns for samples tested in the warp direction is higher, accompanied by lower %SU as compared to the weft direction. This may indicate that crimp in the load bearing direction may be one of the factors affecting %SU for a given sample, with higher crimp resulting in lower utilization of single yarn strength.

Owing to the testing mechanism, the load bearing yarns in fabrics with lower initial crimp will get decrimped to a larger extent at any given point of time. This would mean that the corresponding load bearing yarns would get more aligned to the direction of fabric plane and so will be able to sustain the load more effectively before failure takes place. Moreover, the number of transverse yarns offering fabric assistance are much higher (>300) when the fabric is tested in the weft direction than when tested in the warp direction (150-230). Taking the crossover points as pin joints gripping the yarns, each load bearing yarn may be divided into a number of segments at intervals along its length. A structure with higher number of transverse yarns would consist of more number of shorter segments of load bearing yarns being subjected to tensile loading than one with lower number of transverse yarns (*Figure 5*). Thus, lower initial crimp, leading to straighter load bearing yarns, more aligned to the fabric plane, combined with higher fabric assistance may explain higher %SU when the fabrics are tested in the weft direction for a given structure. Besides, structures with higher initial crimp have larger residual crimp in the load bearing yarn at any given point of time, making them more inclined to the fabric plane and thus reducing their contribution to overall fabric strength. This further lowers the % SU when a structure is tested in the warp direction compared to that in weft direction.

While comparing satinette and plain structures when tested in the weft direction, it may be worth noting that satinette structure has larger floats and hence fewer crossover or interlacement points compared to the plain structure. This corresponds to lower fabric assistance as also a number of larger segment lengths between two crossover points along the length of load bearing yarn and hence lower %SU for satinette structures.

One may infer from the foregoing discussion that the intrinsic behavior of the same fabric can be quite different in the warp and weft directions. The number of load bearing and transverse yarns and their interlacement distribution, the crimp in load bearing and cross directions as well as number of complete repeat units in the test zone are different when samples of a fabric are tested in warp as opposed to in the weft direction. This affects the tensile behavior, particularly %SU of the specimen.

Visual Examination of the Samples

A visual examination of the rupture of samples studied for tensile behavior revealed that for all pick densities, the samples tested in the warp direction demonstrated catastrophic tear break near the moving jaw while those tested in the weft direction exhibited randomly distributed multiple breaks.

This observation conforms to that made by Banerjee, Mishra and Ramkumar [3] for 22ppcm fabrics. Assuming that the weft yarns are inserted under similar tension on the loom, they are expected to bear the load uniformly. The failure of randomly distributed weak points in the weft yarns would lead to multiple breaks in the samples tested in the weft direction. Multiple breakages are also expected for the samples tested in the warp direction by the same logic. However, catastrophic tear breaks are observed in this case.

Jaw breaks are to be expected in samples that contract substantially in the transverse direction, especially near the jaws during tensile deformation. Such contractions are result of crimp interchange. Hence high crimp in load bearing yarns would logically lead to high contraction and hence high shear force near the jaws. A perusal of crimp values in the samples (*Table I* shows that the warp yarns have invariably much higher crimp than the weft yarns, irrespective of the weave or pick density.

The absence of jaw breaks in weft way specimen would suggest that shear deformation in these samples is not substantial. The tear like break occurring mostly at the moving jaw also suggests the possibility of a non uniform strain distribution along the sample length. An analysis of strain distribution in the test samples was done to ascertain this.

TABLE I. Tensile test results on plain & satinette fabrics at three pick densities.

Weave	**Threads per inch**		**Tensile Test Results**							
			WARP WAY				**WEFT WAY**			
	epi	ppi	Crimp (%)	Strength (N)	Elongation (%)	Avg. SU (%)	Crimp (%)	Strength (N)	Elongation (%)	Avg. SU (%)
Plain	101	52	16.25	439.1	27.04	97.04	3.02	438.2	7.89	107.21
	102	68	25.68	428.8	31.35	93.84	6.36	571.5	12.77	106.93
	102	76	24.54	453	28.7	99.13	5.236	694.5	10.42	126.23
Satinette	101	52	8.54	443.63	19.28	98.04	4.71	327.3	8.04	80.01
	102	64	13.28	468	20.94	102.42	5.58	465.68	12.4	92.57
	101	77	10.32	469.2	19.8	103.70	4.29	567.67	10.82	93.80

Strain Pattern Analysis in Plain and Satinette Samples

A sample coding pattern showing the picks per centimeter, construction (p = plain and s = satinette) and direction of testing (w = warp and f = weft) has been employed for categorizing the samples. The samples with highest and lowest percentage strength utilization of each construction were additionally labeled by H and L respectively, while the sample, whose load-elongation curve was in the middle of L-E curve dispersion of that category and which also had breaking load and breaking elongation values nearest to that of the mean value for that category, was labeled as M. For example, the code 26pfH refers to a 26ppcm plain woven fabric tested in the weft direction showing highest %SU in the category. All the 36 samples (24 H and L from each of the 12 categories and 12 M samples) were analyzed for strain distribution.

Figure 3 shows the strain pattern exhibited by 26pfH, the sample with highest SU of 131.4% while *Figure 4* shows that of 18sfL, the sample with lowest SU of

75.5%. The lines AA_0, BB_0, CC_0….FF_0 depicted in *Figure 2a* are represented in *Figure 3 and 4* as A, B, C….F respectively. The values of $\bar{A}$, $\bar{B}$, $\bar{C}$, $\bar{F}$ are the mean strains experienced along the respective lines. The four values given on the right side of the pattern are mean values of tensile strain in the bands L_1 to L_4 and the four values given below the pattern are the mean values of contractive strain in the strips W_1 to W_4 respectively.

It can be seen from *Figure 3* that the strain distribution is fairly uniform across the sample with highest % SU while a not so uniform strain distribution combined with high contraction in one of the bands is visible in *Figure 4*.

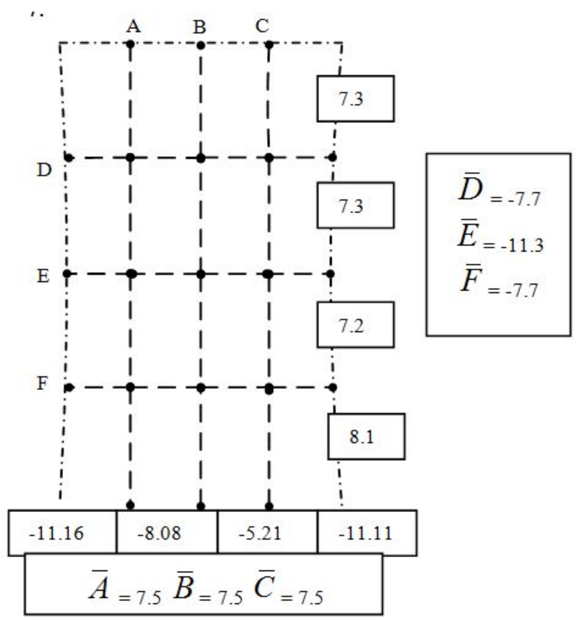


FIGURE 3. Strain pattern of 26pfh at 75% of breaking strain.

In *Table II*, the columns $\bar{A}$, $\bar{B}$, $\bar{C}$ list the mean strain along the three vertical lines A, B and C while $\overline{L1}$, $\overline{L2}$, $\overline{L3}$ *and* $\overline{L4}$ show the mean strains in the bands L_1 to L_4. Similarly, in *Table III*, the columns $\bar{D}$, $\bar{E}$, $\bar{F}$ list the mean percentage width wise contractions experienced along the three horizontal lines D, E and F while $\overline{W1}$, $\overline{W2}$, $\overline{W3}$ *and* $\overline{W4}$ list the values for the strips W_1 to W_4. The last column of *Table III* lists the section where maximum width wise contraction was observed.

The following observations have been made from the data presented in *Tables II and III*.

- The length wise strain across the strips is almost always the same ($\bar{A} \approx \bar{B} \approx \bar{C}$). This is true for all specimens and shows that the load bearing yarns along the central half of each specimen experienced uniform strain. It means that the samples were mounted properly in the testing equipment and that the moving and the stationary jaws linked together by the fabric specimen always remained in the same plane.

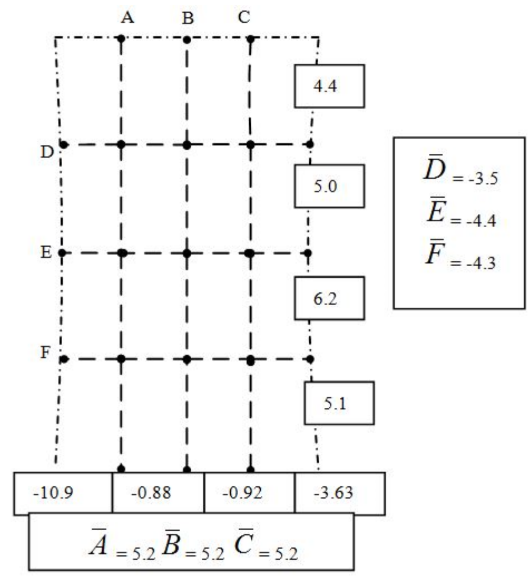


FIGURE 4. Strain pattern of 18sfl at 75% of breaking strain.

- Out of all the 36 samples arranged in decreasing order of percent strength utilization, the top five samples are of plain fabrics tested in the weft direction i.e. of category pf. Moreover, L samples belonging only to the category of pf (26pfL, 22pfL and 18pfL) are encountered in the top 19 samples. In addition, amongst all H, M and L samples, the category 26pf exhibits the highest strength utilization. This substantiates the observation that in all respects the 26ppcm plain samples tested in the weft direction exhibit higher strength utilization than other combinations. The strain distribution is also uniform in these samples combined with symmetrical contractions on both sides of BB_0. Lower crimp in load bearing direction, combined high number of transverse yarns and interlacement points may be the contributing factors to higher strength.

- It can also be seen from the data in *Table II and III* that the 18 pcm satinette samples tested in the weft direction show the minimum strength utilization of all the samples studied. The strain distribution is also non-uniform for samples with lower %SU and so are the % contractions. The non-uniform distribution of interlacement or gripping points may have lead to the variation in strain profile in the sample and hence a lower %SU.

- The first 16 samples in decreasing order of % strength utilization and having strength utilization of more than 100%, exhibit maximum waisting at the centre of the specimen; that is $\overline{E}$ was the highest (*Table III*) in all these cases.

- The 26pfH sample exhibits the highest yarn strength utilization among all fabrics. It was observed that the strain across both the strips and bands in this sample was distributed in a fairly even manner (*Figure 3*). Maximum waisting occurred in the centre of the specimen. The width wise contraction is also found to be in a narrow range and symmetric along the edges. Yarns along the length were also loaded uniformly.

- The 18sfL sample exhibits the lowest strength utilization. As in the 26pfH sample, the yarns along the central half of the length were loaded uniformly ($\overline{A} \approx \overline{B} \approx \overline{C}$). But the strain across the bands is not so uniform (*Figure 4*). While $\overline{L1}$ is low and $\overline{L3}$ is high, $\overline{L2}$ and $\overline{L4}$ are nearly equal and have intermediate values. Unlike the 26pfH sample, the waisting or contraction was also not symmetric. The values of $\overline{E}$ and $\overline{F}$ are almost equal, but that of $\overline{D}$ is lower. The contractions $\overline{W2}$ *and* $\overline{W3}$ are very low and similar while $\overline{W1}$ is high (-10.9) and $\overline{W4}$ is low (-3.63).

Based on an analysis of rest of the data listed in *Tables II and III* along similar lines combined with the strain patterns in *Figures 3 and 4*, it may be inferred that the rupture of fabric samples is associated with the following strain patterns

- High strain in a particular band (L) accompanied by high contraction along one of the edges ($W_{1 \text{ or } 4}$). This was observed with most of the samples tested in the warp direction irrespective of the construction. Such samples exhibited jaw breaks.

- Evenly distributed strain across the bands and strips leading to multiple point break. This was observed with most of the samples tested in the weft direction irrespective of the construction.

- Irrespective of the nature of fabric rupture, yarns along the central half of a specimen length exhibit uniform loading.

TABLE II. Strain pattern in the load bearing direction.

Code	%SU	$\bar{A}$	$\bar{B}$	$\bar{C}$	$\overline{L1}$	$\overline{L2}$	$\overline{L3}$	$\overline{L4}$
26pf H	131.4	7.5	7.5	7.5	7.34	7.33	7.23	8.11
26pfM	125. 8	6.2	6.2	6.2	5.20	6.06	6.67	6.85
26pfL	120.5	7.5	7.5	7.6	6.00	8.67	5.32	10.07
18pfH	114.6	6.7	6.7	6.7	7.70	5.15	5.24	8.76
22pfH	113.9	10.4	10.4	10.4	11.59	10.41	9.11	10.41
26swH	112.9	14.2	14.2	14.2	17.30	13.56	14.48	11.43
22swH	111	14.2	14.2	14.2	15.99	13.05	14.45	13.49
18pwH	110.9	18.8	18.8	19.3	20.95	18.56	18.43	18.07
18swH	109.8	16.6	16.6	16.6	14.40	15.00	17.50	19.51
26pwH	108.6	21.1	21.1	21.1	20.95	22.59	20.01	20.82
18pfM	107.5	5.7	5.6	5.6	7.50	5.90	4.98	4.15
22pfM	107.0	8.8	8.8	8.8	6.14	8.11	8.77	12.04
26sfH	103.9	9.1	9.1	9.1	8.0	9.33	8.00	11.04
22swM	103.8	16.8	17.4	17.5	18.34	18.19	13.61	18.83
26swM	103.8	16.6	15.6	16.3	14.50	15.65	14.58	19.88
22pwH	102.9	24.4	24.4	24.4	23.80	24.02	26.05	23.78
26pwM	99.7	19.8	20.3	19.8	17.91	21.48	18.70	21.75
22pfL	99.5	7.4	7.3	7.4	6.81	8.40	4.41	9.93
18pfL	98.4	4.4	4.4	4.4	4.35	4.44	4.26	4.55
22swL	97.9	14.1	14.1	14.1	14.04	13.82	12.80	15.84
18swM	97.8	12.9	12.9	12.9	14.97	12.22	12.40	11.91
18pwM	96.7	18.9	18.9	18.9	15.22	20.00	17.78	22.74
26sfM	95.8	8.6	8.6	8.6	6.82	9.16	7.58	10.76
22pwM	95.3	23.7	24.3	24.4	26.56	25.48	22.33	22.22
22sfH	95.2	10.6	10.6	10.6	11.39	10.97	8.28	11.68
22sfM	91.4	9.3	9.3	9.3	13.33	6.59	7.25	10.10
22sfL	89.6	10.5	10.5	10.6	7.74	10.90	10.26	13.38
18swL	87.6	10.5	10.5	10.5	9.68	10.67	12.42	9.25
18sfH	87.5	6.7	6. 7	6.7	5.63	8.24	6.36	6.51
22pwL	86	21.8	21.8	21.8	21.14	21.89	25.20	19.00
26swL	85.2	11.6	11.6	11.6	12.34	12.10	10.60	11.27
26sfL	84.8	8.2	8.1	7.6	9.67	4.61	9.23	8.33
26pwL	83	19.6	19.6	19.6	20.94	18.84	20.66	18.06
18pwL	80.0	17.3	17.7	17.1	17.23	18.45	16.78	17.11
18sfM	79.9	6	6	6	7.20	6.17	3.08	7.38
18sfL	75.5	5.2	5.2	5.2	4.48	5.04	6.25	5.14

TABLE III. Contraction pattern in transverse direction.

S.No.	Code	%SU	$\overline{F}$	$\overline{E}$	$\overline{D}$	$\overline{W1}$	$\overline{W2}$	$\overline{W3}$	$\overline{W4}$	Max of $\overline{D}, \overline{E}, \overline{F}$
1	26pfH	131.4	-7.7	-11.3	-7.7	-11.16	-8.08	-5.21	-11.11	$\overline{E}$
2	26pfM	125. 8	-4.2	-5.8	-5.0	-5.21	-3.49	-5.56	-5.87	$\overline{E}$
3	26pfL	120.5	-9.7	-9.7	-9.7	-15.24	-4.99	-4.17	-14.58	$\overline{E}$
4	18pfH	114.6	-2.6	-3.3	-1.6	-5.5	1.97	-1.43	-4.95	$\overline{E}$
5	22pfH	113.9	-4.5	-8.9	-5.5	-10.2	-1.59	-1.59	-11.74	$\overline{E}$
6	26swH	112.9	-15.7	-16.6	-15.0	-23.31	-10.20	-8.97	-20.75	$\overline{E}$
7	22swH	110.96	-11.6	-13.2	-11.3	-16.19	-7.10	-7.50	-17.33	$\overline{E}$
8	18pwH	110.9	-14.3	-15.9	-15.8	-22.95	-10.20	-11.11	-17.14	$\overline{E}$
9	18swH	109.8	-12.1	-15.0	-13.8	-19.75	-9.98	-8.93	-15.97	$\overline{E}$
10	26pwH	108.6	-10.3	-10.6	-9.7	-13.80	-10.10	-12.61	-4.23	$\overline{E}$
11	18pfM	107.5	-1.7	-0.9	-1.8	-2.23	0.00	0.00	-3.61	$\overline{E}$
12	22pfM	107.0	-4.6	-4.9	-3.6	-10.41	-1.75	0.00	-5.26	$\overline{E}$
13	26sfH	103.9	-7.7	-9.1	-7.6	-13.26	0.00	-3.03	-16.16	$\overline{E}$
14	22swM	103.8	-11.9	-13.6	-12.9	-7.74	-14.92	-8.83	-19.75	$\overline{E}$
15	26swM	103.8	-13.7	-13.9	-11.8	-14.66	-10.10	-6.25	-21.57	$\overline{E}$
16	22pwH	103	-12.8	-15.8	-10.5	-22.76	-8.59	-10.89	-10.00	$\overline{E}$
17	26pwM	99.7	-8.9	-9.1	-12.3	-12.3	-10.00	-12.37	-5.75	$\overline{D}$
18	22pfL	99.5	-1.8	-7.63	-4.4	-10.0	3.79	-8.12	-4.14	$\overline{E}$
19	18pfL	98.4	-6.0	-4.1	-4.8	-13.14	0.00	-2.26	-4.52	$\overline{F}$
20	22swL	97.9	-9	-13.1	-9.9	-14.75	-8.51	-6.04	-13.39	$\overline{E}$
21	18swM	97.8	-8.9	-11.5	-11.6	-18.37	-8.21	-8.51	-7.60	$\overline{E}$
22	18pwM	96.7	-10.7	-12.3	-12.2	-15.93	-9.04	-9.19	-12.77	$\overline{E}$
23	26sfM	95.8	-6.5	-6.6	-6.5	-10.97	-1.15	-4.60	-9.48	$\overline{E}$
24	22pwM	95.3	-9.2	-5.4	-6.6	1.59	-12.28	-3.51	-14.04	$\overline{F}$
25	22sfH	95.2	-5.9	-8.7	-7.1	-18.2	-3.95	2.08	-8.82	$\overline{E}$
26	22sfM	91.4	-5.4	-3.2	-2.4	-8.4	-0.97	-2.30	-3.09	$\overline{F}$
27	22sfL	89.6	-5.1	-5.7	-5.9	-12.2	0.98	-1.01	-9.95	$\overline{D}$
28	18swL	87.6	-10.4	-13.2	-11.7	-15.00	-6.13	-8.69	-17.33	$\overline{E}$
29	18sfH	87.5	-5.7	-6.4	-4.3	-10.24	1.01	-4.74	-7.99	$\overline{E}$
30	22pwL	85.9	-12.3	-14.0	-11.8	-21.97	-8.02	-9.76	-11.19	$\overline{E}$
31	26swL	85.2	-12.8	-15	-14.0	-21.75	-5.97	-9.42	-18.63	$\overline{E}$
32	26sfL	84.7	-10.4	-9.8	-8.3	-16.96	-5.08	-2.08	-14.06	$\overline{F}$
33	26pwL	82.9	-8.2	-8.9	-8.2	-11.85	-8.02	-8.88	-5.15	$\overline{E}$
34	18pwL	80.0	-6.7	-7.4	-9	-9.09	-11.42	-6.28	-4.04	$\overline{D}$
35	18sfM	79.8	-2.6	-1.6	-2.6	-3.49	-2.19	-2.38	-1.18	$\overline{F} + \overline{D}$
36	18sfL	75.4	-4.3	-4.4	-3.5	-10.9	-0.88	-0.92	-3.63	$\overline{E}$

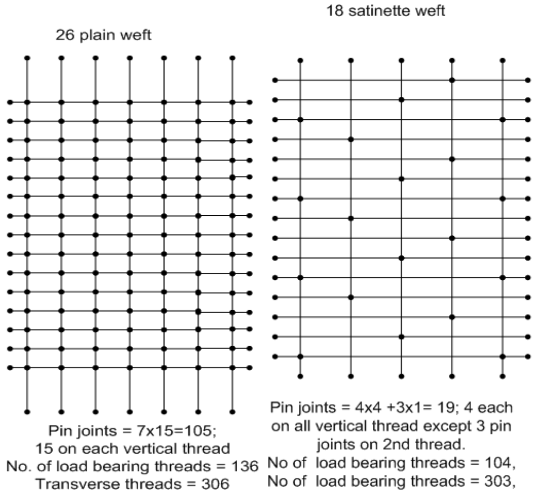


FIGURE 5. Pin-joint diagram of samples with a) highest %SU and b) lowest %SU.

CONCLUSIONS

The Strain Pattern Analysis, which has been employed as an analytical tool to study the behavior of fabrics in tensile loading mode, reveals two categories of sample behavior. The first category consists of the samples exhibiting catastrophic break, which also seem to experience a non-uniform distribution of strain across the sample. The samples under study, when tested in the warp direction with high yarn crimp in the load bearing direction fell in this category. More specifically such samples, exhibiting tear like rupture near one of the jaws, develop high tensile strain in a particular band across the sample accompanied by high widthwise contraction along one of the edges of the specimen. Such specimens do not show high % yarn strength utilization.

The second category consists of specimens showing high yarn strength utilization and exhibit evenly distributed strain across and along the fabric. A high yarn strength utilization is usually accompanied by maximum widthwise contraction at the centre of the specimen. It is also inferred from the strain analysis that fabric specimens which exhibit low lengthwise extension and low widthwise contraction, i.e. those having low yarn crimp in the load bearing direction, utilize the yarn strength more efficiently in presence of favorable assistance provided by the interlacements between yarns in the load bearing and the transverse directions. The key to woven fabric design therefore, at least in so far as tensile deformation is concerned, lies in identifying the most favorable combination of number of interlacements and their distribution within a design repeat coupled with number and linear density of yarns in the two principle directions that maximizes the fabric assistance while minimizing the yarn crimp.

REFERENCES

[1] Kumpikaite E.; Sviderskyte A.; The Influence of Woven Fabric Structure on the Woven Fabric Strength, *Materials Science (MEDZIAGOTYRA),* 12(2), 2006, 162-166.

[2] Kumpikaite E.; Milasius V.; Influence of Fabric Structure on Its Weavability, *Materials Science (MEDZIAGOTYRA)*, 9(4), 2003, 395-400.

[3] Banerjee P. K.; Mishra S; Ramkumar T; Effect of Sett and Construction on Uniaxial Tensile Properties of Woven Fabrics, *Journal of Engineered Fibers and Fabrics*, 5(2), 2010, 8-21.

[4] Milasius, V.; An Integrated Structure Factor for Woven Fabrics Part I: Estimation of the Weave, *Journal of Textile Institute*, 2, 2000, 268-276.

[5] Milasius V.; An Integrated Structure Factor for Woven Fabrics. Part II: The Fabric Firmness Factor, *Journal of Textile Institute*, 2, 2000, 277-283.

[6] Gupta B. S.; Fangning S.; Seyam A. M.; A Generalized Model for Predicting Load–Extension properties of Woven Fabrics, *Textile Research Journal*, 67(12), 1997, 866-874.

[7] Kawabata S, Masako N.; and Kawai H.; The Finite Deformation theory of Plain Weave fabrics part 2: The Uni-axial Deformation theory, *Journal of Textile Institute*, 62(2), 1973, 47-61.

[8] Deliktas B.; Role of strain concentration factors in predicting the inelastic behavior of laminated composite material, *Composites: Part B*, 40, 2009, 267–274.

[9] Hu H.; Wang J.; Damage detection of a woven fabric composite laminate using a modal strain energy method, *Engineering Structures*, 31, 2009, 1042-1055.

[10] Swan C. C.; Kosaka I.; Homogenization-based Analysis and Design of Composites, Computers & Structures, 64(1-4), 1997, 603-621.

[11] Ramkumar T.; Effect of Construction on Tensile Properties of Woven fabrics, *M. Tech. Thesis*, Department of Textile Technology, I.I.T. Delhi, India. 2008.

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