Effect of Sett and Construction on Uniaxial Tensile Properties of Woven Fabrics

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ABSTRACT

The tensile behavior of woven fabrics is known to be affected by its sett and construction. This influence, when clearly understood, would make engineering of fabrics for tensile properties easier. Hence, this work is aimed at understanding the interdependence between the sett, construction and tensile behavior of woven fabrics. Experiments were conducted to study the effect of the number of load bearing and interlacing yarns, the spacing between them, and their interlacement pattern on the tensile behavior of the fabric, typically characterized by the percent yarn strength utilization in the fabric. The results reveal that the factors mentioned above along with the crimp of the constituent yarns and their interchange during the tensile deformation process, influence the tensile properties of the fabric. A significant influence of the distribution of interlacement was also observed.

INTRODUCTION

Tensile behavior of fabrics has been a subject of a great deal of research, and tensile testing has been widely used for industrial quality control as well as for product and process development. Fabric construction and more specifically the interlacement pattern and its distribution are important variables of woven fabrics, and a tool that can predict the changes in properties due to a change in construction should be useful in engineering a woven fabric. Such a tool can be employed for consciously choosing the fabric construction when the end use requirements change by a specified amount.

Studies on structure-property relationship of woven fabrics were started by Peirce (1937) who derived geometrical relationships between yarn spacing, yarn diameter, modular length and weave angle as a means for understanding the behavior of a woven fabric in different modes of deformation.

There have also been several attempts at characterizing weaves through factors like the Firmness of a cloth (Brierley, 1952), Fabric Tightness (Hamilton, 1964), Cloth Tightness (Love, 1954), Weave Firmness Factor (Milasius V and Reklaitis V,1988 & Milasius, 2000a), Integrated Structure Factor (Milasius, 2000b), Tightness Factor (Newton, 1995) and Construction factors (Russell, 1965) Kumari S (2005) developed a C++ program following the approach outlined by Ping and Greenwood (1986) and calculated the number of possible weaves for given repeat size and worked out their structural characteristics. Singh N. (2007) generated different programs to map regular as well as irregular woven constructions and calculated their values of tightness factor (Newton, 1995). It was observed that for many weaves only a few distinct values of tightness factor exist, indicating that weave tightness factor can not define each weave or interlacement pattern uniquely.

Moreover, most of the work done to predict either the tensile strength or the load-elongation behavior of woven fabrics is based on the behavior of a single yarn in the weave (De Jong S and Postle R, (1977), Haussy B et al, (2004), Hearle JWS and Shanahan JW, (1978), Kawabata S et al, (1973a, 1973b, 1979) Leaf GAV and Kandil KH, (1980)). However, during tensile loading a number of yarns work together to bear the load even in a repeat unit and more so in a sample of standard size. Hence logically a model that takes account of actual number and arrangement of load bearing and interlacing yarns in the test sample should yield more realistic results.

Keeping in view the limitations of the predictive power of weave tightness factor or of interlacement pattern of a single load bearing yarn for fabric tensile behavior, it is proposed to include the distribution pattern of interlacement in the entire repeat unit as an additional factor for understanding the effect of construction.

The present work was designed to experimentally study the effect of construction on tensile properties of woven fabrics and more specifically the effect of the number of load bearing and interlacing yarns and their spacing, weave factor, direction of testing and interlacement pattern on the tensile behavior of woven fabrics, specifically with respect to the percentage yarn strength utilization in the fabric.

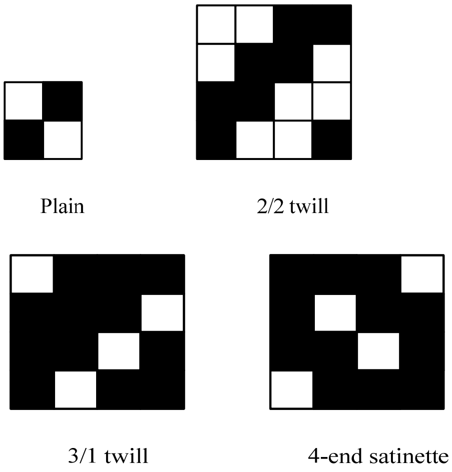
MATERIAL AND METHODS

Material

Cotton yarns of English count 30^s and 20^s respectively were used as warp (tensile strength of 3.04 N at 250mm gauge length, intrinsic strength of 1.75 gpd, 5.83% elongation at break) and weft (tensile strength of 4.21 N at 250mm gauge length, intrinsic strength of 1.62 gpd and 4.53% elongation at break) to prepare fabrics on a Somet Air jet loom running at 600 picks per minute with reed space of 1.45 meter. The yarn densities set on the loom were 38 ends and 22 picks per cm.

Four weaves were chosen for the study namely plain, 2/2 twill, 3/1 twill and 3/1 satinette and are identified as B1, B2, B3 and B4 respectively. Of the four weaves the plain weave has the highest index of interlacements, defined here as the ratio of the actual number of interlacements to the maximum possible ones. The other three weaves repeat on 4 ends and picks, have same index of interlacement, which is half of that of the plain, but differ in many other respects. Both the 3/1 twill and the 4-end satinette are unbalanced regular weaves based on the same floating pattern of individual yarns, that is, a float over three yarns followed by a float under one. However, the former exhibits a constant positive shift of one step whereas the latter exhibits positive cyclic steps of 2, 3, 2 and 1. The 2/2 twill is a balanced regular weave. The repeat units of all the four weaves are shown in *Figure 1* while their characteristics are listed in *Table I.*

The woven samples were initially dry-relaxed by keeping them for 72 hours in standard atmosphere (Temp: 27± 2ºC, RH: 65%) and allowed to relax. Subsequently the fabrics were wet relaxed by washing them at 60°C with 10% non-ionic soap on the weight of the fabric in a wash liquor having material : liquor ratio of 1:20 for 30 minutes followed by rinsing with normal cold water and drip drying. The dry and wet relaxed fabric samples were tested separately for their physical properties.


Plain

2/2 twill

3/1 twill

4-end satinette

FIGURE 1. Weave repeat units of different weaves studied

Based on the findings from the study of tensile behavior of fabrics of different weaves, it was decided to investigate the plain & satinette weaves in a range of pick densities, as the two weaves exhibited extreme behavior in the two principal directions of testing. Hence, plain & satinette fabrics were produced at two other pick densities (18 ppcm & 26 ppcm) on the same loom keeping all the other settings the same as before.

Parallel yarn bands of a fresh sample of warp yarns (warp2) and a 20^s unsized 100% cotton yarn (weft2) at 250mm gauge length were tested for tensile strength to determine the effect of the number of yarns and yarn spacing on the percentage single yarn strength utilization in the yarn band. For studying the effect of number of yarns on the percentage yarn strength utilization

TABLE I. Fabric characteristics

S.no	Characteristics of weave	Plain (B1)	2/2 twill (B2)	3/1 Twill (B3)	4-end satinette (B4)
1	Nature	Balanced, Regular	Balanced, Regular	Unbalanced, Regular	Unbalanced, Regular
2	Index of interlacement	1	0.5	0.5	0.5
3	Steps of interlacement	+1	+1	+1	+2/+3/+2/+1
4	Floating pattern	1/1	2/2	3/1	3/1

at 100mm gauge length, another lot from the warp yarns (warp3) and a yarn of the 20^s unsized 100% cotton yarn (weft3) were used.

Testing Methods

The standard ASTM methods followed for testing the yarn and fabric properties are listed in *Table II*. For studying the effect of number of yarns and yarn spacing on the tensile strength of a yarn band, the yarn band consisting of the required number of yarns, spaced according to experimental plan and held under equal tension, was mounted on a window made out of a cardboard strip. The two ends of the cardboard window, to which the ends of the yarns were taped, and gripped by the two jaws of the tensile tester. Subsequently the two arms of the cardboard window were cut out, thus effectively leaving only the yarn band under the grip of the two jaws.

TABLE II. Testing Standards followed

S.No	Description of the Test	Designation
1	Warp end count and filling pick count of woven fabric	D3775
2	Yarn number based on short-length specimens	D1059
3	Yarn crimp in woven fabric	D3883
4	Breaking force and elongation of textile fabric (strip method)	D5035
5	Tensile properties of yarn by the Single-strand method	D2256

RESULTS AND DISCUSSIONS

Yarn Testing

Effect of number of load bearing yarns

The warp2 and weft2 yarns were tested at gauge length of 250 mm on a tensile tester for single yarn strength as well as for multiple yarns held parallel to each other with 5, 10, 25, 50, 75 and 100 yarns in the band. The percentage strength utilization of yarns in a band was calculated in the following manner:

% yarn strength utilization (as mentioned in *Table III*.)

$$= \left\{ \text{test strength} \Big/ \text{no. of yarns x single yarn strength} \right\} \times 100 \quad - \quad \textbf{(1)}$$

The results *(Table III)* indicate that with a rise in number of yarns in a band the percentage strength utilization of the band of yarns initially decreases to a minimum and then stabilizes as the number of yarns increases. The stabilization was observed to occur for the bands with 25 and 50 yarns for the Warp2 and weft2 yarns respectively. The percentage yarn strength utilization stabilized for a band of 100 yarns at 85 % of single yarn strength for the 30s warp2 and to 92% of single yarn strength for the 20s weft2 yarns *(Figure 2)*. A higher value in the case of weft2 yarns was obtained in spite of a lower intrinsic strength of the latter (1.14) as compared to that of warp2 yarn (1.84). To investigate this aspect further, bands of parallel polyester monofilament (pmf) yarns of 364 denier having single yarn breaking strength 14.21 N, elongation at break 25.65% and intrinsic strength of 3.98 gpd were also tested to ascertain the effect of number of load bearing yarns on the breaking strength and to find out if intrinsic strength indeed has a bearing on stabilization of % strength utilization. The results do not support such a line of thought, as the band of 25 yarns of much stronger monofilament yarns showed 86% of single yarn strength *(Figure 2)*. However, a yarn band up to 25 only yarns could be tested for monofilament yarns, as a number beyond that showed slippage of yarns from the jaws before breakage occurred. It is not quite certain as to what value the % strength utilization would have stabilized the band of monofilament yarns, had it been possible to grip a larger number of yarns securely in the jaws.

Evidently a more detailed investigation of this aspect is called for. The change in percentage breaking extension of any of the band of yarns did not reveal any trend with a change in number of yarns in the band *(Table III)*.

This study, nevertheless, indicates that the percentage yarn strength utilization in a fabric specimen would also be influenced by the type of yarn and the number of yarns. A larger number of yarns can on one hand mean a higher strength due to a rise in number of load bearing elements but also a reduction in percentage utilization of the yarn strength. The drop in percentage strength utilization with a rise in the number of yarns must be due to a rise in probability of occurrence of the weakest link in a band containing a larger number of yarns as compared to one containing a smaller number. The average strength of the weakest link in a single yarn is expected to be higher than the strength of the weakest link in a band of yarns, each of the same length as the single yarn. Moreover, the inability to share the load equally may also be a contributing factor.

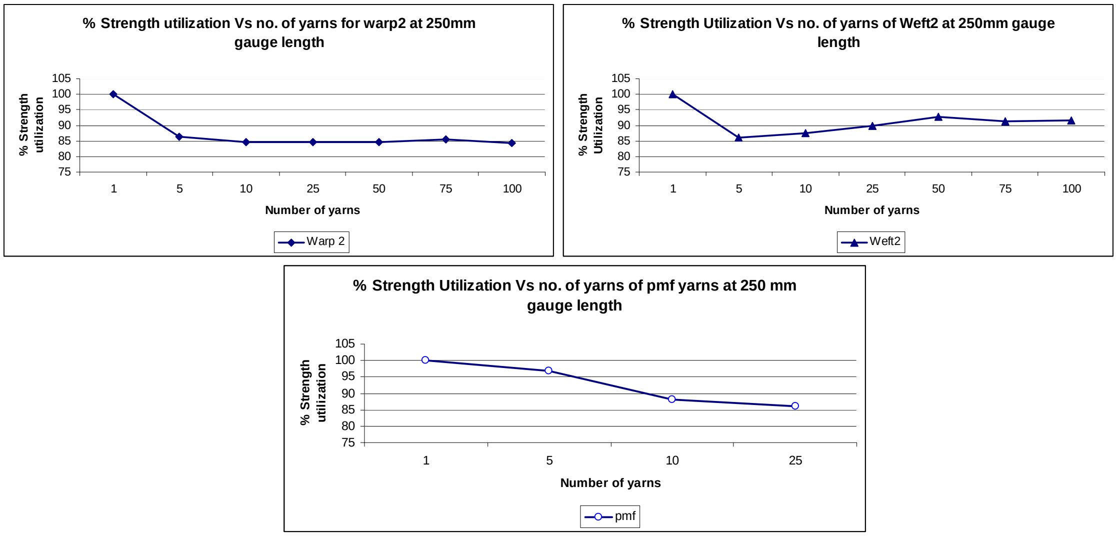


FIGURE 2 Change in % Strength utilization with number of yarns for warp2, weft2 and pmf yarns

TABLE III. Effect of number of yarns on tensile behavior at 250 mm gauge length

	Warp2					**Weft2**				
No of yarns	**Load at Break (N)**	**CV (%)**	**Extension at Break (%)**	**CV (%)**	**SU (%)**	**Load at Break (N)**	**CV (%)**	**Extension at Break (%)**	**CV (%)**	**SU (%)**
1	3.20	9.78	4.06	11.23	100.00	2.97	8.76	5.01	11.25	100.00
5	13.82	7.50	3.65	7.80	86.38	12.79	8.05	5.26	16.44	86.13
10	27.08	4.84	3.99	7.46	84.63	28.08	4.53	5.97	12.90	87.65
25	67.79	3.80	3.66	6.09	84.74	91.88	3.40	4.61	5.40	89.86
50	135.25	2.34	4.06	3.87	84.53	189.59	3.30	4.67	3.73	92.71
75	205.25	2.99	4.22	2.37	85.52	280.37	3.00	4.85	3.73	91.4
100	269.63	4.14	3.80	2.22	84.26	374.24	4.20	4.85	3.42	91.5

	Monofilament yarn				
No of yarns	**Load at Break (N)**	**CV (%)**	**Extension at Break (%)**	**CV (%)**	**SU (%)**
1	14.21	6.02	25.65	5.59	100.00
5	68.84	3.02	23.24	7.03	96.89
10	125.09	4.20	24.61	11.86	88.03
25	306.16	4.50	26.98	7.14	86.18

Effect of yarn spacing

Two parallel yarns, kept at a fixed distance of 1, 2, 3 and 4 cm spacing respectively were tested for tensile strength. The test was done for warp2, weft2 and monofilament yarns and the results are shown in *Table IV*. Statistical tests were conducted to find out if the change in average breaking load values observed with the change in yarn spacing were significant. The results indicate that the average breaking strength and elongation values of the monofilament yarns continued to decrease marginally with the rise in yarn spacing and then stabilized at a spacing of 3 cm and above. One may hence infer that monofilament yarns that are further away from the center of the specimen would contribute to a lower extent to the tensile strength of the band. For the 20^s weft2 yarns the stabilization occurred at 2 cm spacing, while the 30^s warp2 yarn did not show any significant change in average breaking load with increase in yarn spacing. The percentage breaking extensions reveal trends similar to that shown by the respective breaking loads.

The studies on effect of the number of load bearing yarns and the spacing between them reveal that while predicting the tensile properties of a fabric specimen, it is important to take into account the number of load bearing yarns as as well as their location. The importance of location can become critical when the yarns differ in tensile behavior.

TABLE IV. Effect of thread spacing on yarn tensile behavior at 250 mm gauge length

Number of Threads	**Thread spacing**	**Warp2 yarns**				**Weft2 yarns**			
		Load at Break (N)	**CV (%)**	**Extension at Break (%)**	**CV (%)**	**Load at Break (N)**	**CV (%)**	**Extension at Break (%)**	**CV (%)**
1	0cm	3.2	9.78	4.05	11.23	2.97	8.76	5.01	11.25
2	1cm	5.85	9.48	3.44	11.99	4.765	10.85	4.09	11.15
2	2cm	5.98	6.42	3.44	8.11	5.44	8.44	4.84	6.77
2	3cm	6	7.93	3.52	9.48	5.74	11.7	5.06	13.83
2	4cm	5.915	8.22	3.58	10.84	5.45	7.49	5.11	9.09

Number of Threads	**Thread spacing**	**Monofilament yarns**			
		Load at Break (N)	**CV (%)**	**Extension at Break (%)**	**CV (%)**
1	0cm	14.21	6.02	25.65	5.59
2	1cm	29	3.26	29.51	10.08
2	2cm	26.8	4.5	22.37	22.51
2	3cm	24.79	4.27	19.27	4.4
2	4cm	25.4	3.14	18.68	4.6

Fabric testing

The physical characteristics of four types of fabrics prepared (B1 to B4) at 22 ppcm in dry and wet relaxed states are shown in *Tables V* and *VI* respectively.

Effect of transverse yarns

The percentage strength utilization for a band of 100 yarns decreased to 85% for warp and 92% for weft when the yarns were tested at a gauge length of 250 mm as a band without any interlacement *(Table III)*. Accordingly, if it is assumed that the transverse yarns do not play any role in the load bearing process, then the expected fabric strength should be less than 85% of the theoretical strength for samples tested in the warp direction and less than 92% of the theoretical strength for samples tested in the weft direction, since the number of load bearing yarns is much more than 100 in the fabric samples tested. The average values of actual fabric strength obtained experimentally for the four fabrics and their theoretical and expected fabric strength values calculated from single yarn strength at 250mm gauge length are listed in *Tables V* and *VI* for dry and wet relaxed states respectively the calculations for the same are explained in the *Appendix*.

It is evident from the data in *Tables V* and *VI* that for four types of fabrics in the dry relaxed state in both warp and weft directions, the actual strength obtained experimentally is higher than that of the expected value calculated with yarn strength of 250 mm gauge length. While in the wet relaxed state, this is true only for plain and 2/2 twill fabrics tested in the weft direction. The actual fabric strength obtained is much less than the expected strength calculated with 250 mm gauge length for all the wet relaxed fabrics in the warp direction and for the 3/1 twill and satinette in the weft direction.

To ensure that the higher than expected values of tensile strength obtained experimentally were not due to shorter length of yarns in the fabric than that used for tensile testing of single and parallel yarns, the expected fabric strength with 100 mm yarn length was also calculated for samples tested in both the directions and relaxation states for the four fabrics of 22 ppcm. A length of 100 mm will include the total yarn length in the fabric after considering the crimp. The tensile test of parallel yarn bands with 5, 10, 25, 50 75 and 100 yarns were conducted at 100mm gauge length to check if the percentage strength utilization in the yarn band stabilized at 85% for warp and 92% for weft yarns at this gauge length

TABLE V. Average physical characteristics of 22DR fabrics

Direction	**Particulars**	**Plain (B1)**	**2/2 twill (B2)**	**3/1 twill (B3)**	**Satinette (B4)**
Warp	Ends per inch	100	100	100	100
	Warp crimp % (CV %)	10.89 (9.65)	8.53 (2.27)	8.72 (1.75)	5.12 (4.63)
	Actual Breaking Elongation% (CV %)	13.76 (3.50)	10.25 (9.32)	9.89 (4.43)	10.13 (5.04)
	Theoretical tensile strength with 250mm gauge (yarn) length (3.04 N)	608	608	608	608
	Theoretical tensile strength with 100mm gauge (yarn) length (3.2 N)	640	640	640	640
	Expected tensile strength with 250mm gauge (yarn) length	517	517	517	517
	Expected Tensile Strength with 100mm gauge (yarn) length	563	563	563	563
	Actual Tensile strength, N (CV %)	522 (2.56)	551.2 (9.98)	533 (4.49)	590 (5.49)
	Range of % yarn strength utilization in the fabric	83-89	72-103	81-94	87-103
Weft	Picks per inch	60	60	60	60
	Weft crimp % (CV %)	4.46 (4.35)	4.75 (6.56)	5.64 (4.54)	3.28 (10.65)
	Actual Breaking Elongation% (CV %)	7.2 (9.4)	7.47 (4.01)	6.84 (5.12)	7.46 (5.97)
	Theoretical tensile strength with 250mm gauge (yarn) length (4.21 N)	505	505	505	505
	Theoretical tensile strength with 100mm gauge (yarn) length (4.4 N)	528	528	528	528
	Expected Tensile Strength with 250mm gauge (yarn) length	465	465	465	465
	Expected Tensile Strength with 100mm gauge (yarn) length	486	486	486	486
	Actual Tensile strength, N (CV %)	588 (4.05)	497.86 (4.38)	492.3 (2.53)	502 (4.85)
	Range of % yarn strength utilization in the fabric	110-123	90-104	94-102	90-108

also. In order to distinguish these results from those at 250mm gauge length, the respective yarns here are termed as warp3 and weft3.
The results indicate that the percentage strength utilization at gauge length of 100mm for the yarn band stabilizes at 88% for warp3 and 91% for weft3 yarn. The values of theoretical and expected fabric strength calculated from single yarn strength at 100mm gauge length are also tabulated in *Tables V* and *VI* for dry and wet relaxed fabrics.

It can be seen that for the dry relaxed samples tested in the warp direction, the actual strength is higher than the expected values calculated at 100mm gauge length for satinette fabric only. While for the samples tested in the weft direction it is true for all the fabrics. In the wet relaxed state, this holds only for plain woven samples tested in the weft direction.

The above observations establish that the transverse yarns do have a bearing on the effective strength of the load bearing yarns.

Moreover, since the % strength utilization values obtained differ for each weave even though the number of load bearing yarns and, in case of the twill and satinette weaves, even the total number of interlacements are same, it follows that the manner of interlacement of the load bearing and transverse yarns also affects the tensile behavior of the test sample. It is worth noting at this stage that during the actual process of weaving, both warp and weft yarns undergo cycles of strain, which is bound to reduce the effective strength of yarns trapped in the fabric. This factor could not be accounted for and hence overestimated yarn strength values have been used in the calculations, notwithstanding which the effect of interlacements is clearly visible.

TABLE VI. Average physical characteristics of 22WR fabrics

Direction	**Particulars**	**Plain (B1)**	**2/2 twill (B2)**	**3/1 twill (B3)**	**Satinette (B4)**
Warp	Ends per inch	102	101	101	102
	Warp crimp % (CV %)	25.68 (1.86)	13.84 (3.63)	14.76 (4.18)	13.28 (3.11)
	Actual Breaking Elongation% (CV %)	31.35 (5.47)	22.52 (5.96)	24.42 (5.04)	21.2 (9.84)
	Theoretical tensile strength with 250mm gauge (yarn) length (3.04 N)	620	614	614	620
	Theoretical tensile strength with 100mm gauge (yarn) length (3.2 N)	653	646	646	653
	Expected Tensile Strength with 250mm gauge (yarn) length	527	521	521	527
	Expected Tensile Strength with 100mm gauge (yarn) length	555	549	549	555
	Actual Tensile strength, N (CV %)	428.8 (5.13)	458.5 (6.82)	440.1 (6.57)	468 (3.55)
	Range of % yarn strength utilization in the fabric	63-76	66-84	67-79	72-82
Weft	Picks per inch	68	64	66	64
	Weft crimp % (CV %)	6.36 (4.42)	6.2 (3.95)	7.08 (7.29)	5.58 (6.62)
	Actual Breaking Elongation% (CV %)	12.77 (7.1)	11.88 (9.68)	13.88 (5.36)	12.04 (7.37)
	Theoretical tensile strength with 250mm gauge (yarn) length	573	539	556	539
	Theoretical tensile strength with 100mm gauge (yarn) length	598	563	581	563
	Expected Tensile Strength with 250mm gauge (yarn) length	527	496	511	496
	Expected Tensile Strength with 100mm gauge (yarn) length	551	518	534	518
	Actual Tensile strength, N (CV %)	571.5 (3.5)	506 (2.2)	496.68 (5.0)	465.68 (3.17)
	Range of % yarn strength utilization in the fabric	93-106	91-98	79-94	84-93

Effect of Weave factor

In order to explore the possibility of any direct relation between the tensile behavior of the fabrics with their weaves as characterized by the weave factor (Milasius (2000a), the corresponding values ($P_{1,2}$) were calculated and the tensile properties of the fabrics tested in warp and weft directions in both dry and wet relaxed states were compiled *(Tables VII and VIII)*. The results clearly show that there is no direct relation between the weave factors and the breaking strengths or extensions of the corresponding fabrics. It is however observed that for weaves having the same index of interlacement (B2, B3 and B4) but differing in values of weave factor, which in turn is influenced by the distribution of interlacements, the breaking load values are significantly different, while the breaking extension percentages do not differ as much. This substantiates the effect of the distribution of interlacement pattern on % yarn strength utilization.

Effect of relaxation state of the fabric

The results of tensile testing of the four types of fabrics prepared (B1 to B4) with the same sett but different constructions are shown in *Tables V* and *VI*. The corresponding representative load-elongation plots are given in *Figures 3* and *4*. The representative plot for each sample, in terms of weave, state of relaxation and direction of testing, is located in the centre of the spread of load-elongation plots obtained from repeated tests on the same type of sample.

The state of relaxation of the fabric has apparently a significant effect on its tensile behavior. The dry relaxed fabrics yield a steeper load-elongation plot than the wet relaxed ones *(Figures 3 and 4)* which can be attributed to higher crimp in the wet relaxed fabrics *(Tables V and VI)* . The percentage strength utilization was however, found to be higher for all dry relaxed fabrics as compared to their wet relaxed states, while the yarns per inch and elongation at break values are higher for wet relaxed fabrics. Clearly the residual normal force between the interlacing and the load bearing yarns, prevailing in the dry relaxed state, creates an appreciable hindrance to inter-fiber slippage in the load bearing yarns during their tensile deformation. Furthermore, the substantially lower crimp values in warp and weft directions of dry relaxed fabrics enable the corresponding load bearing yarns to align their axis more closely to the direction of loading. These result in a higher breaking load and a lower breaking elongation.

Effect of weave

The range of values of percentage strength utilization for the wet relaxed fabrics of different construction and test direction at 22 ppcm is shown in *Table VI*. The representative Load-Elongation curves of all these fabrics in wet relaxed state are compared in *Figure 4*.

It can be clearly seen from *Table VI* that in spite of having the same index of interlacement, number of load bearing yarns in the specimen and with almost similar crimp, the strength utilization of 2/2 twill and satinette specimens loaded in the weft direction are significantly different. The satinette sample exhibits a lower percentage strength utilization in the weft direction than the 2/2 twill fabric. Similarly, the % strength utilization and the profile of load-elongation curves (Figure 4) differs significantly between satinette and 3/1 twill fabrics. These two separate observations confirm the influence of the distribution of interlacements on the strength, and one may generalize that weaves differing only in the distribution of interlacements would behave differently in tensile deformation.

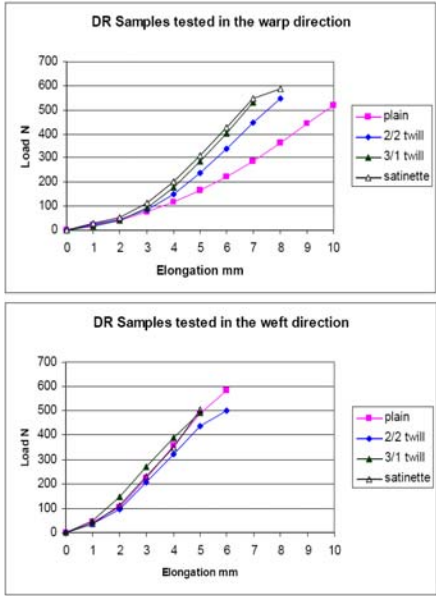


FIGURE 3 Load-Elongation curves of typical dry relaxed specimens of the four weaves at 22 ppcm

TABLE VII. Effect of weave factor on tensile properties of specimen (dry relaxed)

Fabric no.	Weave	Warp			Weft		
		P1	Breaking Load (N) warp way	Breaking Extension (%)	P2	Breaking Load (N)	Breaking Extension (%)
B1	Plain	1	522	13.76	1	588	7.2
B2	2/2 twill	1.2649	551.2	10.25	1.2649	497.86	7.47
B3	3/1 twill	1.333	590	10.13	1.333	502	7.46
B4	4 end satinette	1.2977	533	9.89	1.2977	492.3	6.84

TABLE VIII. Effect of weave factor on tensile properties of specimen (wet relaxed)

Fabric no.	Weave	Warp			Weft		
		P1	Breaking Load (N)	Breaking Extension (%)	P2	Breaking Load (N)	Breaking Extension (%)
B1	Plain	1	428.8	31.35	1	571.5	12.77
B2	2/2 twill	1.2649	458.5	22.52	1.2649	506	11.88
B3	3/1 twill	1.333	482.14	21.2	1.333	482.14	12.04
B4	4 end satinette	1.2977	440.1	24.42	1.2977	496.68	13.88

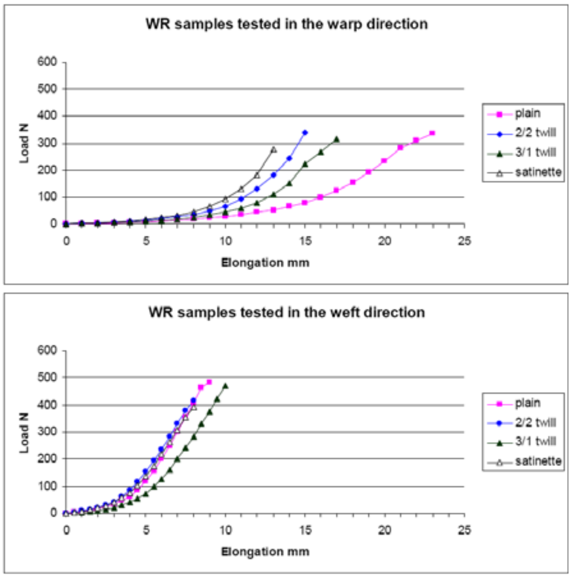


FIGURE 4 Load-Elongation curves of typical wet relaxed specimens of the four weaves at 22 ppcm

Effect of direction of testing

For wet relaxed samples tested in the warp direction, the satinette construction shows the highest yarn strength utilization followed by twills and plain weave samples *(Table VI)*. Assuming that the construction with the least crimp gets decrimped earliest, it can be surmised that the corresponding load bearing yarns would get aligned to the direction of loading earlier and the load can be sustained more effectively before failure takes place. This argument holds for samples tested in the warp direction. But an opposite trend was observed in the samples tested in the weft direction, which showed the least strength utilization in the satinette construction in spite of the same having the least crimp. The two twills exhibit intermediate values in all respects.

Moreover, the strength utilization values of plain constructions tested in warp and weft directions differ significantly from each other. In case of satinette fabric also, a similar difference was observed. This indicates that the intrinsic behavior of the same fabric can be quite different in the warp and weft directions i.e., the direction of testing (warp or weft) affects the test results. It is worth mentioning here that, the number of load bearing 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 the warp as opposed to the weft direction. This may lead to the difference in % strength utilization in the two cases and forms a subject of subsequent analysis.

The trend in % elongation at break is in tune with % crimp in the samples. More crimp yields higher breaking elongation.

Effect of pick density

Plain and satinette woven samples behaved very differently and in an exactly opposite manner as far as strength utilization is concerned *(Table VI)*. In order to check if a similar trend exists in other pick densities also, additional samples of plain and satinette weaves were prepared at different pick densities and tested for their tensile behavior. The general pattern of Load-Elongation behavior of the wet relaxed plain and satinette specimens of different pick densities when tested in the warp and weft directions are shown in *Figure 5* and the results are listed in *Table IX*.

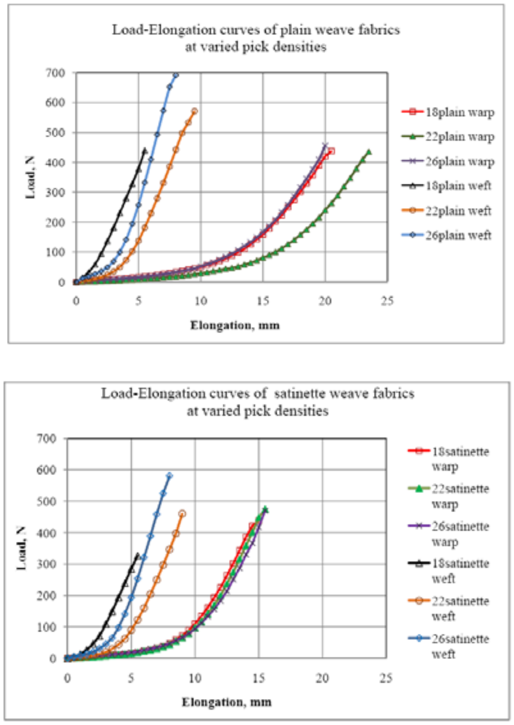


FIGURE 5. Load-Elongation curves of wet relaxed plain and satinette weave fabrics at varied pick densities

TABLE IX. Tensile test results on plain & satinette fabrics (wet relaxed) at varied pick densities

Variant	WARP WAY					WEFT WAY				
	epi	C$_1$%	Strength (N)	Elongation (E %)	SU (%)	ppi	C$_2$%	Strength(N)	Elongation (E %)	SU (%)
(-)[†] plain	101	16.25	439.1	27.04	59-82	52	3.02	438.2	7.89	83-97
		(1.41%)	(9.96%)	(6.09%)			(7.13%)	(4.41%)	(9.25%)	
(0) plain	102	25.68	428.8	31.35	63-76	68	6.36	571.5	12.77	93-106
		(1.86%)	(5.13%)	(5.47%)			(4.42%)	(3.50%)	(7.10%)	
(+) plain	102	24.54	453	28.7	61-80	70	5.236	694	10.42	112-123
		(1.80%)	(8.92%)	(5.22%)			(6.59%)	(2.61%)	(4.14%)	
(-) satinette	101	8.54	443.63	19.28	65-81	52	4.71	327	8.04	70-82
		(5.43%)	(6.39%)	(5.86%)			(7.75%)	(5.39%)	(9.05%)	
(0) satinette	102	13.28	468	21.2	72-82	64	5.58	465.68	12.4	84-93
		(3.11%)	(3.55%)	(9.84%)			(6.62%)	(2.07%)	(6.89%)	
(+) satinette	101	10.32	469.2	19.8	63-83	77	4.29	567	10.82	79-97
		(3.67%)	(8.01%)	(8.16%)			(9.44%)	(5.57%)	(5.43%)	

[†] (-), (0) and (+) denote the pick densities set on the loom 18, 22 and 26 ppcm respectively. Values given in bracket are of Co-efficient of variation.

The data in *Table IX* reveals no clear trend in % strength utilization values with a change in pick density and construction for samples tested in the warp direction. However for the samples tested in the weft direction, a steady rise in percentage strength utilization is observed with rise in pick density for both constructions. The earlier observation that satinette samples tested in the weft direction show the least strength utilization while plain woven fabric samples tested in the weft direction show maximum % strength utilization is valid for all pick densities. It is also observed that over the entire range of pick density, the difference in % strength utilization between plain and satinette fabrics when tested in the warp direction is not as noticeable as when tested in the weft direction.

Quite remarkably the plots of both the constructions when tested in the weft direction show a striking similarity for each pick density as well as for the changing pick density. Incidentally, as can be seen in *Figures 3, 4* and *5* the specimens tested in the weft direction exhibit higher modulus and lower elongation at break than those tested in the warp direction. This is attributed to the considerably higher crimp values in the warp direction of the tested specimens, as opposed to the weft direction.

Visual examination of the tested samples

The wet relaxed samples of 22 ppcm in plain, 2/2 twill, 3/1 twill and satinette constructions, which were ruptured during tensile testing, were visually examined. It was observed that all the samples tested in the warp direction tear along the jaw and all the samples tested in the weft direction exhibit randomly distributed multiple breaks *(Figure 6)*.

Assuming that the weft yarns are inserted under similar tension on the loom and therefore start bearing the load uniformly, the randomly distributed weak points in the weft yarns may break randomly and therefore the rupturing process of the corresponding specimen also may appear to be random. Jaw breaks are to be expected in samples that contract substantially in the transverse direction during tensile deformation. Such contractions are result of crimp interchange. Hence high crimp in load bearing yarns would logically lead to high shear force near the jaws. A perusal of crimp values in the samples *(Table IX)* 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 the weft direction specimen would suggest that shear deformation in these samples is not substantial.

Summary of Results and Discussion

The breaking strength of a single yarn is not fully utilized when the yarns are woven into a fabric. The percentage strength utilization depends on the total number of load bearing yarns as well as on the location of individual yarns vis-à-vis the central axis in the plane of loading. The % single yarn strength utilization decreases initially as the number of load bearing yarns increases until a critical value is reached at which it stabilizes. Similarly yarns located closer to the central axis in the plane of loading appear to be more effective in load bearing as compared

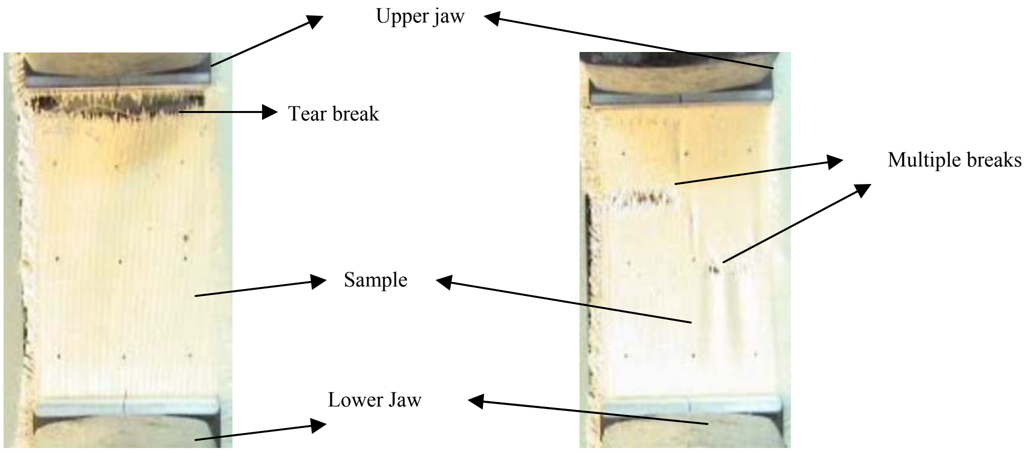


FIGURE 6 a) Tear break at Jaw in warp samples b) multiple breaks in weft samples to those further away. The magnitude of this effect, observed in the course of this study, is however not considerable.

In a woven fabric, the percentage utilization of yarn strength varies with the weave. The unique case of the difference in % strength utilization along the weft direction of the 2/2 twill and the Satinette fabric samples *(Table VI)*, in spite of both having nearly same values of crimp and yarn spacing in warp and weft directions as well as the same number of interlacement points, underlines the importance of the distribution of interlacement points in the crimp interchange process. Evidently the contact geometry of the interlacement points and the constraints surrounding them play a very important role.

From the foregoing it follows that the introduction of transverse yarns to a set of parallel load bearing yarns alters the tensile behavior of the latter, and the change varies with the number of interlacements as well as the distribution of interlacements in the test sample.

Since no correlation between the weave firmness factor (Milasius, 2000a) and load-extension behavior of the fabrics studied was found, it was concluded that weave factors can not be directly related to the tensile behavior of the woven constructions studied, although it may have a secondary influence.

These studies establish that the tensile behavior of woven fabrics is influenced by the relaxation state of the fabrics. The dry relaxed fabrics show steeper load-elongation curves and higher breaking strength than the wet relaxed ones. This is due to the frictional forces at the yarn to yarn contact points, which are weakened by wet relaxation, as well as the considerable rise in crimp values in both principal directions as a result of wet relaxation.

The direction of testing was found to have an effect on the tensile behavior as well as mechanism of rupture of the fabrics tested. Load-elongation curves of samples tested in the weft direction were steeper due to lower crimp in the load bearing yarns. It was also observed that all samples tested in the warp direction ruptured near the jaw in a tear like manner while all the samples tested in the weft direction showed multiple breaks distributed over the fabric surface. This appears to be caused by a combination of tensile and shear forces especially near the jaws, owing to a considerably larger degree of decrimping in the warp direction. The tensile force combined with the lateral force at the jaws causes a tear break near the jaws. The tear like break occurring mostly at the moving jaw also suggests the possibility of a non uniform strain distribution along the sample length, which will be investigated in a greater detail subsequently. Negligible shear force appears to have developed when the samples were tested in the weft direction. Evidently the extent of decrimping during tensile deformation of fabric governs the magnitude of shear force generated.

CONCLUSIONS

It can be concluded that the tensile behavior of a fabric, especially % yarn strength utilization is highly dependent on the crimp values in yarns along the load bearing and transverse directions, the extent of crimp interchange and its ease, and the number and distribution of the interlacement points as well as radial forces of compression at these locations. Higher crimp value in the load bearing direction may lead to a lower modulus, higher elongation and lower breaking strength, if the conditions of decrimping remain unaltered.

However, changes in yarn spacing, which accompany changes in yarn crimp values, play a significant role in the crimp interchange process as the contact geometry at the cross over points of interlacing yarns, effective stiffness of yarns linking these cross over points, and the actual number of cross over points also get altered. These factors affect the contour of the projection of load bearing yarns on the plane of loading, the undulations in the different yarns gripped between the two jaws and the amount of radial forces of compression acting on the load bearing yarns. A fabric with straight yarn, parallel to the direction of loading, having a large number of interlacements per yarn and high radial forces of compression will give high strength utilization. It appears therefore that the structure of a woven fabric sample, characterized by the sett, crimps and the yarn interlacement pattern has a bearing on the % strength utilization of the fabric and a suitable theoretical tool needs to be developed to account for the same.

The behavior of plain and satinette weave samples presents a study in contrast, as the % strength utilization of the corresponding samples in warp and weft directions exhibit opposing behavior. It is felt that a more detailed investigation of this aspect may reveal some important information.

A visual examination of the ruptured samples suggests that the tensile deformation of woven fabrics is accompanied by shear deformation. In addition to this, the occurrence of most of the tear breaks in the samples loaded in the warp direction near the upper jaw suggests the possibility of a strain gradient along the length of the sample which needs to be investigated in further studies.

APPENDIX

CALCULATION OF THEORETICAL AND EXPECTED FABRIC STRENGTH OF 22 PPCM WR PLAIN FABRIC

Theoretical fabric strength =
{Single yarn strength*yarns per inch* sample width (inches)}

For samples tested in the warp direction,
Expected fabric strength ≤ 85% and 88% of theoretical fabric strength at 250mm and 100mm gauge length respectively.

For samples tested in the weft direction,
Expected fabric strength ≤ 92% and 91% of theoretical fabric strength at 250mm and 100mm gauge length respectively.

Samples tested in the warp direction

Calculation with yarn strength measured at 250 mm gauge length
Single warp yarn strength = 3.04N;
epi = 102 and sample width = 2 inches
So, theoretical strength of fabric
= 102*2*3.04 = 620.6 N;
85% (*Table III*) of 620.6 N = 527.14 N
Hence, expected fabric strength ≤ 527.14 N

Calculation with yarn strength measured at 100 mm gauge length
Single warp yarn strength = 3.2 N at 100 mm gauge length;
epi = 102 and sample width = 2 inches
So, theoretical strength of fabric
= 102*2*3.2 = 652.8 N;
88% (*Table III*) of 652.8 N = 574.46 N. So,
Hence, expected fabric strength ≤ 574.46 N

Samples tested in the weft direction

Calculation with yarn strength measured at 250 mm gauge length
Single weft yarn strength = 4.21 N at 250 mm gauge length;
ppi = 68 and sample width = 2 inches
So, theoretical strength of fabric
= 68*2*4.21 = 572.56 N;
92% (*Table III*) of 556.24 N= 526.75 N
Hence, expected fabric strength ≤ 526.75 N

Calculation with yarn strength measured at 100 mm gauge length

Single weft yarn strength = 4.4 N at 100 mm gauge length;
ppi = 68 and sample width = 2 inches
So, theoretical strength of fabric
= 68*2*4.4 = 598.4 N;
91% (*Table III*) of 598.4 N= 550.53 N
Hence, expected fabric strength ≤ 550.53 N

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