Mechanism and Formation of Woven Selvage Lines

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Abstract

This article discusses theoretically the mechanism of a woven selvage line and establishes basic knowledge about, among other things, its dynamic construction, the differences between the selvage and the body of a fabric, the process of stabilizing the form of a selvage.

1. Introduction

This work is an attempt to clarify the weaving mechanism of a selvage as part of a research into the function of weaving. Seldom is the selvage of a fabric specially woven. It is a by-product, so to say, of a fabric. However, it should not be ignored, because it improves the quality of a fabric, protects its ground and facilitates the processing and handling of the fabric. It is believed, therefore, that establishing a theoretical basis for obtaining a uniform selvage is an undertaking of practical value and will help to expand the range of research into weaving.

2. Selvage Weave Analysis

2-1 Assumptions

The process by which a selvage is woven and its position is stabilized is expressed schematically in Fig. 1. Plot an optional point 0 on the fabric plane as the axis of coordinates. Draw the X axis parallel to the fell of the cloth. Draw the Y axis at right angle to the X axis. Assume that the distance of the point from the Y axis when the warp and filling are first interlaced to form a selvage is $x_1=C$. This location is a function of $T_{-1}$, a force which pulls the selvage-formation point to the left; and of $T_{+1}$, a force which pulls that point to the right.

$$x_1=f(T_{-1}, T_{+1}) \ldots (1)$$

Assume that, with the progress of weaving cycles, $x_i$ transforms into, successively, $x_2$, $x_3$ and $x_i$ and is stabilized on reaching $x_n$. $x_i$, an optional point $x$ at that time, is given as a function of $x_i-1$. That is,

$$x_i=f(x_{i-1})$$

Also,

$$x_1=x_2 \ldots x_{i-1}=x_i=x_{i+1} \ldots x_n=x_n+1$$

This is continuous.

Hence, the position where the selvage is stabilized is given as a function depending on variables which indicate the position of the first selvage-formation point. This point being determined by vectors $T_{-1}$ and $T_{+1}$ of warp and filling, the selvage is rectilinearly uniform, if the above values are equal in all continuous weaving cycles. It is not clear, however, when $T_{-1}$ and $T_{+1}$ influence the shape of a selvage during a weaving cycle. We look into this matter by taking the crank circle as a time axis.

1. Formation of a selvage begins when warp and filling threads begin to be interlaced on the edge of a fabric. This time corresponds to the space between the bottom center and the back center in the crank circle after picking as shown in Fig. 2.

2. With the completion of the insertion of filling, the shuttle stops in the shuttle box on the receiving side. The filling waits for the next picking, while retaining a degree of tension.
3. Since initial picking corresponds to the dwell of a shedding cam, warp tension at this time does not change but keeps a value.

4. When the crank comes closer to the top center from the back center, the warp closes the shed, gripping the pick and solidifying their lateral direction.

5. As the crank rotates further and beats the front center, a reed forces the filling yarn into the fell of the cloth. The filling thread then produces an elastic elongation load corresponding to the difference between width of the reed and the width of the fell. However, since frictional resistance acts on the interlacing points, the elastic elongation of the filling thread generates between the interlacing points, thus preventing a lateral slip of the thread.

6. When the crank goes to the bottom center after beating, the temporary elastic elongation of the filling is regained and the initial selvage weave is fixed.

7. Then, the same motion is repeated, the selvage location repeats its elastic behavior—elongation and regaining of elongation—and reaches a stabilized position according to the conditions initially given.

Fig. 2 shows an outline of the foregoing process. The figure uses the following symbols:

- A = time of picking.
- B = time when warp thread begins to contact filling on the selvage.
- C = time when warp sheet begins to contact filling.
- D = duration of shuttle stop.
- $\angle TOT'$ = dwell.

We may conclude from the reasoning conducted thus far that the form and position of the selvage are fixed in the region between the bottom center and the top center, the region where warp and filling begin to be interlaced and where filling slippage is avoided by the friction resistance of the warp sheet.

Fig. 3 illustrates the yarn tension in this region on the selvage. The figure uses the following symbols:

- $P$ = standard plane on the same surface as fabric plane $XOY'$. 
- $Q$ = plane made by warp threads $OT'$ in over shed and warp threads $OT^*$ in under shed ($P \perp Q$). 
- $XX'$ = standard line on plane $P$, which corresponds to the fell.
- $YY'$ = standard line interlacing at right angles with $XX'$ on plane $P$.
- $O$ = intersection where $XX'$ and $YY'$ meet, this being selvage-formation point.
- $OW'$ = filling inside shed sheets.
- $OW$ = orthogonal projection on plane $P$ of $OW'$.
- $OT'$ = warp on edge of fabric (over shed thread).
- $OT^*$ = warp on edge of fabric (under shed thread).
- $OT$ = orthogonal projection on plane $P$ of $CT'$ and $OT^*$, which is a cross line between planes $P$ and $Q$.
- $CS$ = extension line of selvage edge on plane $P$.
- $CS'$ = selvage edge after fabric passes temple.
- $K$ = temple.
- $\angle \omega$ = angle made by $OX$ and $OW$ on plane $P$.
- $\angle \theta$ = angle made by $OS$ and $OY'$ on plane $P$.
- $\angle \theta_1$ = angle made by $OY$ and $CT$.
- $F_1$ = tension given to woven filling, the tension being parallel to the fell.
- $F_1'$ = tension of filling picked and remaining inside shed sheets.

Fig. 3 Warp and filling tensions in selvage
\[ F_1 = \text{component on line } OW \text{ of } F_2'. \]
\[ W_1 = \text{tension given to selvage edge } OS. \]
\[ W_2' = \text{tension of yarns in over shed.} \]
\[ W_2^* = \text{tension of yarns in under shed.} \]
\[ \text{and } W_1 = \text{sum of components on line } OT \text{ of } W_2' \text{ and } W_2^*. \]

If point \( O \) in Fig. 3 keeps a constant location between weaving cycles, then straight line \( OS \) may be considered a continuation of point \( O \). Therefore, selvage edge \( CS \) maintains a given relative position toward standard axis \( YY' \), and the selvage becomes rectilinear in shape. This condition can be defined as a function of warp and filling tensions by the following formula, considering the equilibrium of forces at point \( O \):

\[
W_1 \cos \theta_1 + F_1 \sin \omega = W_1 \cos \theta_1 \\
W_1 \sin \theta_1 + W_2 \sin \theta_2 = F_1 \cos \omega + F_2
\]

The condition of the contact of warp and filling threads at point \( O \) is represented in Fig. 4. Assume that the angle of contact of warp and filling is \( \varphi \), the angle of contact of filling and warp is \( \psi \), and the angles of their projection to plane \( P \) are \( \varphi_x \) and \( \varphi_x' \), where : \( \varphi_x = \theta_1 + \varphi_x' \), \( \varphi_x' = \pi - \omega \). Assume, too, that the coefficient of friction between warp and filling is \( \mu_1 \) and \( \mu_2 \) for \( \varphi_x \) and \( \varphi_x' \) and \( \varphi_x = \varphi_x' \) and \( \varphi = \varphi_x' \).

\[
W_1 = e^{\varphi_x} \cdot W_2 \\
F_1 = e^{\psi} \cdot F_2
\]

From formulas (4) and (5) is obtainable:

\[
\theta_1 = \tan^{-1} \frac{F_1 \cos \omega + e^{\psi} \cdot F_2 - W_2 \sin \theta_2}{W_2 \cos \theta_1 + F_2 \sin \omega}
\]

In eq. (6), the angle formed by the selvage edge to the standard axis in a given weaving cycle is expressed as a function of warp and filling tensions, assuming that \( \omega, \theta_1, \varphi_x \) and \( \mu_1 \) are constants determined by weaving conditions.

Let \( \gamma = \tan \theta \) and \( \gamma \) be defined as a function of selvage form. If \( \gamma \) is constant in all weaving cycles, the selvage becomes a uniformly straight line. However, a decrease in the differential coefficient of \( \gamma \) for \( W_2 \) and \( F_1 \) lessens variations in selvage form. The differential coefficient of \( \gamma \) calculated by formula (6) is:

\[
\frac{\partial \gamma}{\partial F_2} = \frac{(W_2 \cos \theta_1 + F_2 \sin \omega)(\cos \omega + e^{\psi})}{(W_2 \cos \theta_1 + F_2 \sin \omega)^2} \\
- \frac{(F_2 \cos \omega + e^{\psi} \cdot F_2 - W_2 \sin \theta_2) \sin \omega}{(W_2 \cos \theta_1 + F_2 \sin \omega)^2}
\]

\[
\frac{\partial \gamma}{\partial W_2} = \frac{(W_2 \cos \theta_1 + F_2 \sin \omega) \sin \theta_1}{(W_1 \cos \theta_1 + F_2 \sin \omega)^2} \\
- \frac{(F_2 \cos \omega + e^{\psi} \cdot F_2 - W_2 \sin \theta_2) \cos \theta_1}{(W_1 \cos \theta_1 + F_2 \sin \omega)^2}
\]

2-2 Experiments

2-2-1 Angle of Selvage Line

Angles formed by warp and filling threads to the standard orthogonal axis have been measured and are shown as \( \theta \) and \( \omega \) in Fig. 3.

The materials used in our experiments are listed in Tables 1 and 2. Cotton and filament looms, 180 and 160, respectively in r.p.m. and complete with shedding and positive let-off motions, were used.

Now to describe the procedure of the experiment. Leave alone several warp yarns drawn from the outer end of a selvage which will be observed. Sever either over shed yarns or under shed yarns of a 10 cm width from the outer end to the center of the fabric width. Dye the warp of the other side pink, so that, when the pink warp ends are lowered during opening and white picks are inserted into the under shed, the angle can be observed clearly.

Link a synchro-flash (Model SF 3210B manufactured by Dempa Seiki) to the cam shaft. Synchronize the time of flash with the time when the cut sheet is on the over shed. Place a camera exactly above the object to be photographed to avoid any angle discrepancy. Keep the room dark and open the aperture.
When the loom goes into operation, work the synchro-
flash for continuous photographing of the loci of ends
and picks. The flash time in our experiment was 1
ms and the wattage 350 w.

The experimental apparatus is shown in Fig. 5.

The results obtained are given in Table 3.

Let us apply these measured results to formulas
(6), (7) and (8). Since \( \theta_2 = 1.5^\circ \) and \( \omega = 7.4^\circ \),

Substituting measured results of \( \theta_2 \) and \( \omega \) as con-
stants into theoretical formulas transforms the angles
of selvage formation and the partial differential of
selvage formation into practical and comprehensible
forms.

Table 1 Properties of Yarn Specimens

<table>
<thead>
<tr>
<th></th>
<th>Cotton yarn</th>
<th>Nylon filament yarn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Raw yarn</td>
<td>Sized yarn</td>
</tr>
<tr>
<td>Count, Denier</td>
<td>40 s</td>
<td>40 s</td>
</tr>
<tr>
<td>Average breaking strength (g)</td>
<td>213</td>
<td>266</td>
</tr>
<tr>
<td>Percentage variations in breaking strength (%)</td>
<td>16.4</td>
<td>17.6</td>
</tr>
<tr>
<td>Average breaking elongation (%)</td>
<td>6.9</td>
<td>4.7</td>
</tr>
<tr>
<td>Percentage variations in breaking elongation (%)</td>
<td>12.0</td>
<td>12.3</td>
</tr>
<tr>
<td>Moisture regain (%)</td>
<td>7.2</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Table 2 Weaves of Specimens

<table>
<thead>
<tr>
<th>Weave</th>
<th>Cotton shirting</th>
<th>Cotton broadcloth</th>
<th>Nylon taffeta</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plain</td>
<td>Plain</td>
<td>Plain</td>
</tr>
<tr>
<td>Warp count</td>
<td>40 s</td>
<td>40 s</td>
<td>50</td>
</tr>
<tr>
<td>Warp density (number of yarns/inch)</td>
<td>76</td>
<td>133</td>
<td>104</td>
</tr>
<tr>
<td>Filling count</td>
<td>40 s</td>
<td>40 s</td>
<td>50</td>
</tr>
<tr>
<td>Filling density (number of yarns/inch)</td>
<td>69</td>
<td>72</td>
<td>91</td>
</tr>
<tr>
<td>Actual reed width (in)</td>
<td>38</td>
<td>38</td>
<td>50</td>
</tr>
<tr>
<td>Percentage shrinkage (%) of filling</td>
<td>6.2</td>
<td>3.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Table 3 Angles of Warp and Filling Threads on Selvage

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Angle (Sample size n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_2 )</td>
<td></td>
</tr>
<tr>
<td>Cotton shirting</td>
<td>1 3 3 1 3 0 1 2 1 2</td>
</tr>
<tr>
<td>Cotton broadcloth</td>
<td>1 3 0 2 2 2 1 0 1 1</td>
</tr>
<tr>
<td>Nylon taffeta</td>
<td>2 0 3 1 3 3 2 0 2 1</td>
</tr>
<tr>
<td>( \omega )</td>
<td></td>
</tr>
<tr>
<td>Cotton shirting</td>
<td>7 8 7 7 6 9 11 7 7 8</td>
</tr>
<tr>
<td>Cotton broadcloth</td>
<td>10 9 9 7 6 8 5 7 7 7</td>
</tr>
<tr>
<td>Nylon taffeta</td>
<td>8 7 6 9 7 8 9 8 8 8</td>
</tr>
</tbody>
</table>

Note: \( \theta_2 \): angle of ends; \( \omega \): angle of picks.

When the loom goes into operation, work the synchro-
flash for continuous photographing of the loci of ends
and picks. The flash time in our experiment was 1
ms and the wattage 350 w.

The experimental apparatus is shown in Fig. 5.

The results obtained are given in Table 3.

We find from Table 3 that \( \theta_2 \) and \( \omega \) vary slightly
between weaving cycles and from specimen to specimen.

Let us apply these measured results to formulas
(6), (7) and (8). Since \( \theta_2 = 1.5^\circ \) and \( \omega = 7.4^\circ \),

Substituting measured results of \( \theta_2 \) and \( \omega \) as con-
stants into theoretical formulas transforms the angles
of selvage formation and the partial differential of
selvage formation into practical and comprehensible
forms.

Fig. 5 Apparatus for measuring angle of selvage warp and filling

\[
\sin \theta_2 = 0, \quad \cos \theta_2 = 1, \quad \text{and} \quad \cos \omega = 1
\]

Therefore, from eq. (6) emerges:

\[
\theta_1 = \tan^{-1} \left( \frac{F_2 (1+e^{-\mu_3 s})}{W_2 + 0.13 F_2} \right)
\]

From formula (7) emerges:

\[
\left( \frac{\partial \gamma}{\partial F_2} \right)_{W_2} = \left( \frac{W_2 (1+e^{-\mu_3 s})}{W_2 + 0.13 F_2} \right)\frac{\partial F_2}{W_2}
\]

From eq. (8) emerges:

\[
\left( \frac{\partial \gamma}{\partial W_2} \right)_{F_2} = \left( \frac{F_2 (1+e^{-\mu_3 s})}{W_2 + 0.13 F_2} \right)\frac{\partial W_2}{F_2}
\]

Journal of The Textile Machinery Society of Japan
Eq. (9) shows that the higher the filling tension and the lower the warp tension, the greater the angle of selvage formation and that the effects of warp-filling friction are small in number.

Eqs. (10) and (11) show that even if warp and filling tensions vary, the angles of selvage formation vary only slightly, resulting in a neat or well-made selvage.

2 2 2 Warp tension

Variations in warp tension are closely related to variations in selvage form, as we have shown. While measuring variations in warp tension between weaving cycles and within a cycle, it was studied how to estimate warp tension between the fell and the heddle, which tension seems to have direct influence on selvage formation.

Fig. 6 shows the schematic pickup action of the tension analyzer used in our experiment. M in the chart is a fixed plate, with thread guides A and A' at both ends. The back of M has cantilevers L and L' fixed to axis O, with four gages R and R' sticking to the cantilevers. Yarn guides B and B', fixed to L and L', run through the dent in M and are placed on the same horizontal level as A and A'.

With tension given to a yarn, L and L' bent through B and B', with O as the center. The yarn became almost rectilinear and a distortion showed up on gages R and R'. This change in resistance value was relayed to the bridge circuit. The amount of output distortion is $950 \times 10^{-4}$, measured tension ranged from 0 to 150 g, and the maximum error after a comparative experiment was within $\pm 1\%$.

Measurement was done on the same conditions as described in the preceding section. The amount of tension was read from a tension chart formed at the time of beating by the reed. This meant accurate reading of timing. The threads measured were selvage yarns in the heddles in the front row, the measuring being done between the lease rod and the back rest. The results of the test are given in Tables 4 and 5.

From these measured results emerge the following facts:

<table>
<thead>
<tr>
<th>In broadcloth</th>
<th>In nylon taffeta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average selvage tension $\bar{W}_s = 32.8$ g</td>
<td>$\bar{W}_s = 15.9$ g</td>
</tr>
<tr>
<td>Variations in selvage tension $S_s = 5.6$ g</td>
<td>$S_s = 2.8$ g</td>
</tr>
<tr>
<td>Percentage variations in selvage tension $CV = 17%$</td>
<td>$CV = 17%$</td>
</tr>
</tbody>
</table>

After measuring tension variations between weaving cycles, we measured those within a weaving cycle. The conditions of measurement were the same as above.

Tension variations in cotton broadcloth within a
cycle are given in Fig. 7. In the chart, one weaving cycle ranges from 0 to 720°. Table 6 shows warp tension which fits crank angles obtained from the chart.

**Table 6 Warp Tension Variations within Weaving Cycle**

<table>
<thead>
<tr>
<th>Crank angle</th>
<th>Loom motions</th>
<th>Cotton broadcloth</th>
<th>Nylon taffeta</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>Take-up</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>90°</td>
<td>Beating</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>180°</td>
<td>Picking</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>270°</td>
<td>Let-off</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>360°</td>
<td>Take-up</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>450°</td>
<td>Beating</td>
<td>40</td>
<td>16</td>
</tr>
<tr>
<td>540°</td>
<td>Picking</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>630°</td>
<td>Let-off</td>
<td>20</td>
<td>9</td>
</tr>
</tbody>
</table>

Such warp tension variations within a weaving cycle are presumably due to warp distortions which vary according to crank angles. Table 7 lists warp distortions made by various motions of the loom and actually measured under the same conditions as in Table 6. Increases and decreases in distortions were measured on the assumption that the distance between the fell of the cloth and the back rest in the closed state of warp yarn was the standard length.

By calculating the correlation coefficient between the total amount of deformations in Table 7 and the warp tension in Table 6 concerning crank angles, it is determined as +0.85, and we find a correlation between them with 99% confidence.

Tension variations within a weaving cycle are observable between the back rest and the dropper box, as we have said. However, it is warp tension between the fell and the heddle that directly influences selvage shape. Direct measurement of this yarn tension being difficult, we studied how to estimate it from the actually measured yarn tension between the back rest and the dropper and found a correlation between the two.

**Table 7 Variations in Warp Distortion within Weaving Cycles**

<table>
<thead>
<tr>
<th>Crank angle</th>
<th>0°</th>
<th>90°</th>
<th>180°</th>
<th>270°</th>
<th>360°</th>
<th>450°</th>
<th>540°</th>
<th>670°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shedding</td>
<td>Closed</td>
<td>Over shed</td>
<td>Closed</td>
<td></td>
<td>Under shed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warp distortion in mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>By shedding motion</td>
<td>0</td>
<td>4.3</td>
<td>4.3</td>
<td>4.3</td>
<td>0</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>By beating motion</td>
<td>0</td>
<td>2.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>By let-off motion</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>By take-up motion</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>By easing cam</td>
<td>0</td>
<td>-5.0</td>
<td>-7.0</td>
<td>-5.0</td>
<td>0</td>
<td>-5.0</td>
<td>-7.0</td>
<td>-5.0</td>
</tr>
<tr>
<td>Total amount of distortion, mm</td>
<td>0.3</td>
<td>1.3</td>
<td>-2.7</td>
<td>-1.1</td>
<td>0.3</td>
<td>9.6</td>
<td>5.6</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Fig. 8 shows the warp line of cotton broadcloth, having the same measuring conditions as in Table 6, in under-shed state. \( T_A \)=yarn tension between the fell of the cloth and the heddle; \( T_B \)=yarn tension between the heddle and the lease rod; \( T_C \)=yarn tension between the lease rod and the back rest; \( \theta_1 \)=angle formed by \( T_A \) and \( T_B \); \( \theta_2 \)=angle of contact formed by the lease rod and the yarn; \( a \)=perpendicular distance between the fell and the heddle; \( b \)=vertical distance between the heddle and lease rod; and \( c \)=vertical distance between the lease rod and the back rest.

Assume that the thread in equilibrium state in the heddle eyelet is pulled to the fell of the cloth. The vertical pressure on the eyelet, then, is:

\[
2T_B \cos \left( \frac{\theta_1}{2} \right)
\]

Assuming that the frictional coefficient of the yarn and the eyelet is \( \mu_t \), tension \( T_A \) when the yarn begins to move is expressible thus:

\[
T_A = T_B + 2T_B \cos \left( \frac{\theta_1}{2} \right) \mu_t = T_B \left( 1 + 2 \cos \left( \frac{\theta_1}{2} \right) \mu_t \right)
\]
and

\[ T_b = T_c e^{\mu_2} \]

where \( \mu_2 \) is the frictional coefficient between the yarn and the lease rod. Therefore, if \( T_c = 1 \), the tension ratio among \( T_a, T_b \), and \( T_c \) is calculable by the following formula:

\[ T_a : T_b : T_c = (1 + 2 \cos (\theta_1/2) \mu_1) e^{\mu_2} : e^{\mu_2} : 1 \]

In the light of Fig. 8, \( \theta_1 \) and \( \theta_2 \) in eq. 12 are:

\[ \theta_1 = \tan^{-1}(a/d) + \tan^{-1}(b/d) \]
\[ \theta_2 = \pi - \tan^{-1}(b/(d-R)) \]
\[ -\sin^{-1}(R/(b^2 + d - R)^{1/2}) \]

where \( R \) = radius of lease rod.

\( \theta_1, \theta_2, \mu_1, \) and \( \mu_2 \) have different values according to warp shedding conditions. The calculated values of \( \theta_1 \) and \( \theta_2 \) and measured values of \( \mu_1 \) and \( \mu_2 \) are given in Table 8.

**Table 8** Measured Values of \( \theta_1, \theta_2, \mu_1 \) and \( \mu_2 \) in Cotton Broadcloth

<table>
<thead>
<tr>
<th>Shedding condition</th>
<th>Closing</th>
<th>Over shed</th>
<th>Under shed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_1 )</td>
<td>171.6</td>
<td>150</td>
<td>160.5</td>
</tr>
<tr>
<td>( \theta_2 )</td>
<td>2.9</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>( \mu_1 )</td>
<td>0.9</td>
<td>0.9</td>
<td>0.4</td>
</tr>
<tr>
<td>( \mu_2 )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Table 9** Longitudinal Warp Tension Distributions in Cotton Fabric

<table>
<thead>
<tr>
<th>Crank angle (degree)</th>
<th>Tension (g)</th>
<th>Fell-heddle</th>
<th>Heddle-lease rod</th>
<th>Lease rod-back rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (closed)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>90°</td>
<td>17</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>180°</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>450°</td>
<td>49</td>
<td>42</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>540°</td>
<td>36</td>
<td>32</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

As a result, we can predict warp tension between the reed and the fell of the cloth, which tension is directly related to weaving.

2-2-3 Filling tension

Filling tension was measured while filling yarns were pulled from a fixed shuttle at the same speed as the shuttle speed. Townsend reports that there is no difference in filling tension between commercial weaving and this method. The pickup and recording apparatus was the same as that used for warp tension measurement. Fig. 9 illustrates schematically the device to draw filling yarn.

![Fig. 9 Filling tension measured](image)

In Fig. 9, the yarn drawn out of a spool in the shuttle is held by a revolving disk and a nip roller. Drive the disk so as to adjust the circumferential speed of the disk to the shuttle speed and then measure yarn tension. Let the end of the yarn be sucked into a vacuum nozzle lest the yarn should get entangled.

**Table 10** Longitudinal Warp Tension Distribution in Nylon Taffeta

<table>
<thead>
<tr>
<th>Crank angle (degree)</th>
<th>Tension (g)</th>
<th>Fall-heddle</th>
<th>Heddle-lease rod</th>
<th>Lease rod-back rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (closing)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>90°</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>180°</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>450°</td>
<td>20</td>
<td>17</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>540°</td>
<td>16</td>
<td>13</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

Substituting the values in Table 8 into formula (12) and applying the measured values in Table 6, to the substitution gives us Table 9, which lists lengthwise warp tension distributions in the cotton fabric. Table 10 lists those in the nylon fabric.

**Table 11** Shuttle and Spool in Filling Tension Measurement

<table>
<thead>
<tr>
<th></th>
<th>Spool</th>
<th>Shuttle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total length (mm)</td>
<td>Nose dia (mm)</td>
</tr>
<tr>
<td>Cotton loom</td>
<td>175.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Synthetic loom</td>
<td>170.0</td>
<td>11.0</td>
</tr>
</tbody>
</table>

As a result, we can predict warp tension between the reed and the fell of the cloth, which tension is directly related to weaving.

2-2-3 Filling tension

Filling tension was measured while filling yarns were pulled from a fixed shuttle at the same speed as the shuttle speed. Townsend reports that there is no difference in filling tension between commercial weaving and this method. The pickup and recording apparatus was the same as that used for warp tension measurement. Fig. 9 illustrates schematically the device to draw filling yarn.

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<table>
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<tr>
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<th>Tension (g)</th>
<th>Fall-heddle</th>
<th>Heddle-lease rod</th>
<th>Lease rod-back rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (closing)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>90°</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>180°</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>450°</td>
<td>20</td>
<td>17</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>540°</td>
<td>16</td>
<td>13</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

Substituting the values in Table 8 into formula (12) and applying the measured values in Table 6, to the substitution gives us Table 9, which lists lengthwise warp tension distributions in the cotton fabric. Table 10 lists those in the nylon fabric.
The shuttle speed in our experiment was from 9 to 11 m/sec. Table 11 gives the size of the spool and the shuttle condition for the next experiment.

In Fig. 10, the reeling tension of the filling yarn is measured. The line drawn was converted into numerical values by the methods described in what follows, to facilitate analysis and comparison.

The whole reeling section was cut into three equal parts. They were referred to as the first stage, the intermediate stage and the final stage. Each stage was divided into 10 equal parts. Assume that the upper and lower limits of the yarn tension amplitude at the partition points are $h_n$ and $h_n'$. Then, average tension $\bar{h}$, percentage variation $CV$, and average total amplitude $\bar{a}$ are obtainable by $h_n$ and $h_n'$, as follows:

$$\bar{h} = \frac{\sum_{i=1}^{10} (h_n + h_n')/s}{10}$$

$$CV = \frac{\sum_{i=1}^{10} (h_n + h_n')/s^{1/2}}{\bar{h}}$$

$$\bar{a} = \frac{\sum_{i=1}^{10} (h_n - h_n')}{10}$$

Converting Fig. 10 into numerical values by this method results in Table 12.

Now to study variations in filling tension in the light of these measured results. $h_n - h_n'$ is the amplitude of filling tension in one chase. Assume that the yarn length in one chase is 2 inches and the actual reed width 50 inches. A line drawn for tension variations within a pick shows an amplitude of $\bar{a}$ and a frequency of 25. Fig. 11 is a typical pattern. The behavior of filling in relation to the crank angle is examined with the aid of the symbols in Fig. 11.

$$A = \text{shuttle begins its picking-motivated flight.}$$

$$B = \text{point where filling generates pretension. The filling located between the edge of the selvage and the eyelet of the shuttle enters the warp sheet; the shuttle continues to fly. Hence, the pirn begins to unravel. It receives static friction, and tension becomes intense.}$$

$$C = \text{warp is closed. Warp and filling begin to contact with each other. The shuttle has already passed through the shed formed by the warp. During this time, the filling contacts no warp, except the warp in the selvage.}$$

$$D = \text{shuttle reaches the box and stops.}$$

$$E = \text{beating imparts stretch tension to filling and increases yarn tension.}$$

To know the pre-tension in B, (1) loosen the yarn sufficiently between the shuttle eyelet and the measuring pickup device before it is pulled out, and (2) divide the yarn-drawing direction into two: the front of the shuttle (hereinafter referred to as condition A) and its rear of it (condition B). There is a difference between A and B in the state of contact between the yarn and the eyelet of the shuttle, as shown in Fig. 12. The results of this experiment are given in Table 13.

The initial load was higher than the average running tension. The greater the angle of contact between the yarn and the eyelet, the higher the initial load and the running tension.
The angle $\theta_A$ where the condition $A$ arises is calculated by the following formula:

$$\theta_A = 360^\circ \times \frac{2W}{S} \times \frac{N}{60}$$

where $\theta_A =$ crank angle of rotation from picking to point $A$.

$W =$ distance between eyelet of shuttle kept in box and selvage edge.

$S =$ shuttle speed.

$N =$ r.p.m. of loom.

Calculate, with the aid of eq. (15), $\theta_A$ for a fabric 38 inches wide woven on a loom 52 inches in reed space and 180 in r.p.m. In this case, the shuttle eyelet is ahead of the traveling direction of the shuttle when the shuttle runs from the left selvage to the right selvage; behind, when the shuttle runs in the reverse direction. The calculated results are given in Table 14.

### Table 13 Pretension of Unwound Filling

<table>
<thead>
<tr>
<th>Tension (g)</th>
<th>40s cotton</th>
<th>50-den nylon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>Pretension</td>
<td>Running tension</td>
</tr>
<tr>
<td>A</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>8</td>
<td>3</td>
</tr>
</tbody>
</table>

The starting time of frictional resistance in cotton broadcloth is about $30^\circ$ earlier than in nylon taffeta, because of the difference in shedding between filament and cotton looms. We also find that cotton surpasses the nylon fabric in frictional resistance.

By combining Tables 13, 14 and Fig. 13, we obtain Fig. 14. The chart concerns cotton broadcloth 38 inches wide woven on a cotton loom 52 inches wide and 180 in r.p.m. The chart shows that:

1. The left selvage forms when the filling is firmly held by the warp at a crank angle of about $298^\circ$. Filling tension at this time is 5 g. In other words, filling tension involved in forming of the left selvage is presumably 5 g.
(2) The right-hand selvage forms when the filling is firmly held by the warp at a crank angle of 310°. This is about the time when filling pre-tension generates. Therefore, filling pre-tension is presumably about 7 g. Clearly, then, the left and right selvages differ in the degree of filling tension which directly affects selvage formation. This filling tension we call “effective filling tension.”

The shuttle stops at a crank angle of 372° in the shuttle box. At this time, the filling is firmly held in place by the warp and has no bearing on filling tension related to weaving, even if “beating repercussions” occur.

2-2-4 Variations in selvage form

Knowing the angle formed by the selvage edge, the angle which is the standard line at the time of weaving, we shall know how uneven is the formed selvage. Fig. 15 illustrates this relationship. The following symbols are used in the figure:

- XX’ and YY’ = orthogonal standard axes.
- O = selvage-forming point.
- OR = warp in selvage edge.
- OP = stationary selvage edge.

The amount of displacement when selvage-formation point O in Fig. 15 shifts to point Q’ is calculable by the following expression:

\[ OQ’ = \delta - \delta_s = \Delta \delta = A (\tan \theta_1 = \tan \theta_0) \] .................................(16)

However, in the light of eq. (9),

\[ \tan \theta_1 = \frac{F_1 (1 + e^{-n\theta_s})}{W_s + 0.13 F_2} = l' \] .................................(17)

Also, if \[ \tan \theta_s = \tan \theta_1 = m \],

\[ \Delta \delta = A (l' - m) \] .................................(18)

In other words, the surface contour of the selvage-formation point is calculable if warp and filling tensions are known.

With the aid of Table 4, “Warp tension of cotton broadcloth,” the loci of the selvage surface contour have been estimated by eq. (18) and are given in Fig. 16. The photograph under the chart pictures the shape of the same section illustrated in the chart.
is seen that both the chart and the photograph agree well with each other. The estimate assumes $A=3$ mm, filling tension $F_2=10$ g $=\text{const.}$ and $1+e^{-r_B}=1$. The space between picks was actually about 0.3 mm but is given 3 mm in the chart. Therefore, the calculated value of unevenness was ten-fold.

2-3 Conclusions

Fig. 16 proves that the deviation of the surface from the plane of the selvage form depends upon warp and filling tensions at the time of selvage-weaving; and that the selvage edge angle is a parameter of the deviation.

How does the selvage-formation point varies according to warp and filling tensions and how do the tensions affect the coefficient of variations?

If point $P$ in Fig. 15 is stationary, the vertical distance between $P$ and the selvage-formation point is expressible thus: $PM=\delta$

In the light of eqs. (16) and (17), $P$

$$\delta = A \cdot I' = F(W_2 \cdot F_2) \ldots \ldots \ldots \ldots (19)$$

Distance $\delta$ when warp tension $W_2$ varies from 16 to 56 g and filling tension $F_2$ from 5 to 20 g is calculated from eq. (19) with the results given in Fig. 17.

Variations in warp and filling tension vs. variations in the selvage edge position have been estimated by eqs. (10) and (11) and are shown in Figures 18 and 19. Fig. 18 shows variations in filling tension

---

FIG. 17 Warp and filling tensions and selvage position

FIG. 18 Variations in filling tension and coefficient of variations in selvage-forming angle

FIG. 19 Variations in warp tension vs. coefficient of variations in selvage-forming angle
with warp tension constant; Fig. 19, vice versa. The variations range from 16 to 56 g for warp tension; from 5 to 20 g for filling tension.

(1) Fig. 17 shows that:
(a) The lower the warp tension and the higher the filling tension, the greater the selvage-formation angle.
(b) The lower the warp tension and the higher the filling tension, the steeper the gradient of the selvage-formation angle to the progress of warp and filling tensions.

(2) Figs. 18 and 19 show that:
(a) Percentage variations in the selvage-formation angle with variations in warp and filling tensions are conspicuous when warp tension is low. When warp tension is high, the percentage is low.
(b) The curve of variations in the selvage-formation angle is approximately of the first order when filling tension varies; of the secondary order when warp tension varies.

3. Features of Selvage Contrasted to Body of Fabric

What follows discusses the of the selvage contrasted to the body of fabric and how the border line between them should be handled.

3.1 Analysis Taking Warp Yarn as Beam

Think of warp yarn as a beam and assume that it sags under vertical force given to the beam axis. A typical pattern of this condition is shown in Fig. 20. MOL=warp yarn; P=vertical load; \( \delta \)=maximam amount of the sagging of warp at point O; \( l_1 \)=horizontal distance between M and O; \( l_2 \)=horizontal distance between O and L; \( l \)=horizontal distance between M and L; M=fell of cloth; O=angle of interlacing of warp and filling; L=back rest.

Assume that warp is put into equilibrium with load \( P \) by the amount of flexure \( \delta \); and that forces \( R_1 \) and \( R_2 \) act on points M and L. However, if \( l_1 \approx \infty, R_1 \approx R_2 \approx O \), and if the mass of warp in OL is extremely small, the elasticity of flexure in OL may be ignored. Therefore, load \( P \) and the rigidity of warp in MO are the main factors in flexure \( \delta \) produced by \( P \). That is, \( \delta \) is approximately obtainable by thinking of warp as a cantilever, provided the cross section of the warp is uniformly circular.

Therefore,
\[
\delta = \frac{P}{3EI} l_1^3
\]
\[
I = \frac{\pi}{64} D^4
\]
Hence,
\[
\delta = \frac{6.6P}{ED^4} l_1^3
\]
The size of \( P \) in eq. (22) can be expressed as in what follows. Point O at which vertical force \( P \) acts as in Fig. 20 corresponds to selvage-forming point O in Fig. 3. Therefore, force \( P \) which shifts point O to the direction of the X axis is:
\[
P = (W_1 \sin \theta_1 + W_2 \sin \theta_2) - (F_1 \cos \omega + F_2)
\]
However, approximately
\[
\sin \theta_1 \approx 0, \cos \omega \approx 1, \text{and } F_1 \approx F_2
\]
Accordingly,
\[
P = W_1 \sin \theta_1 -2 F_1
\]
Substituting the foregoing equation into eq. (22) gives us:
\[
\delta = \frac{6.6(W_1 \sin \theta_1 -2F_1)}{ED^4} l_1^3
\]
Assume \( \frac{6.6l_1^3}{ED^4} = \rho \), then:
\[
\delta = \rho \cdot P
\]
although \( \delta \) is influenced by the spacing between warp yarns also.

Fig. 21 shows the relationship between the spacing among strands of warp yarn and flexure \( \delta \), in which \( H \)=spacing between strands of warp yarn; \( D \)=diameter of warp yarn. If \( \delta < H \), only one strand of warp yarn supports force \( P \). If \( \delta > H \), more than one strand of warp yarn support \( P \), which is uniformly distributed to each strand. Thus, when \( \delta_1 \leq H, \delta_1 = \rho P, \text{when } H < \delta_1 \leq 2H, \delta_1 = \rho P/2, \text{when } 2H < \delta_1 \leq 3H, \delta_1 = \rho P/3, \text{and further, when } (n-1)H < \delta_1 \leq nH, \delta_1 = \rho P/n \)

where \( n \)=number of strands of warp yarn loaded with \( P \), \( \delta \) being determined by \( P \) and \( n \), and \( n, \) by \( H \).

The above relationship was investigated by practical calculation, using a 40s cotton fabric as an example. First, \( \rho = \frac{6.6l_1^3}{ED^4} \) was obtained. By actual measurement
\[
l_1=5 \text{ mm}
\]
\[
E=600 \text{ kg/mm}^2
\]
\( E \) being a value obtained from an S-S curve for cotton 40s sized yarn carrying a 30 gram load.
Assume $D=0.15 \text{ mm}$

Then,

$$\rho=2.7 \text{ mm/kg} \times 10^3$$

Now to calculate load $P$. Warp tension $W_i$ and filling tension $F_i$ are, as we have shown, approximately $40g > W_i > 20g$ and $10g > F_i > 1g$

And

$\theta=17^\circ$

Therefore, $P$ is calculable as follows from eq. (23), the positive and negative signs indicating a loading direction:

$$8g \geq P \geq -10g, \quad |P| \leq 10g$$

Assume $\rho=2.7 \text{ mm/kg}$. $\delta$, when $P$ is varied from 0 to 10 grams and $n$ from 1 to 12, is calculable by eq. (26). Table 15 tabulates $\delta_*$ so calculated.

$\delta_*$ in this table to a given $P$ is determined when $n$ is determined

The values of $nH$ when $H$ is 0.2, 0.3 and 0.4 mm, respectively, in terms of the spacing between strands of warp yarn is given in Table 16.

$\delta_*$ to $P$ is undeterminable by Table 15 alone, because $n$ is undetermined and, therefore, the space between columns is undetermined. However, since $\delta_*$ should satisfy the conditions $(n-1)H < \delta_* \leq nH$ in eq. (26), its value can be estimated by Table 16. For example, the values of $\delta_*$ when $P=5g$ and $H=0.3mm$ are as in Tables 15 and 16. The following values are obtained, as $\delta_*$ and $nH$ to $n$, from Tables 15 and 16.

$n: 4 \ 5 \ 6 \ 7 \ 8 \ 9 \ 10$

$\delta_*$: 3.5 2.5 2.2 1.9 1.7 1.5 1.4

$nH: 1.2 \ 1.5 \ 1.8 \ 2.1 \ 2.4 \ 2.7 \ 3.0$

$\delta_* < nH$ for the same $n$, $n \geq 7$

However, when $n \geq 8$,

$$(n-1)H=2.1 > \delta_* = 1.7$$

which disagrees with

$$(n-1)H < \delta_*$$

When $n=7$,

$$(n-1)H=1.8 < \delta_* = 1.9 < nH=2.1$$

which satisfies the conditions in eq. (26). That is, when $n=7$,

$\delta_* = 1.9 \text{ mm}$

This relationship is illustrated in Fig. 22. The value obtainable is located in the section where straight lines $nH$ and $(n-1)H$ cross curve $\delta_*$ and is $\bar{\delta}_*$ when $n=7$. In case $P$ and $H$ vary, $\bar{\delta}_*$ is still obtainable in exactly the same way. Table 17 gives $\bar{\delta}_*$ to $P$ when $H$ varies.

---

**Table 15 Table of $\delta_*$**

<table>
<thead>
<tr>
<th>$P (g)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
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<td>5</td>
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<td>6</td>
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<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

---

**Table 16 nH Calculated**

<table>
<thead>
<tr>
<th>$H$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.4</td>
</tr>
</tbody>
</table>

---

**Table 17 P & H vs. $\delta_*$**

<table>
<thead>
<tr>
<th>$H$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.4</td>
</tr>
</tbody>
</table>

**Fig. 21 Flexure of warp**
Table 17 is graphically given in Fig 23. The figure shows that:

1. The higher the compressive force given to the selvage-formation point, the higher the selvage flexure. However, the percentage increase in flexure under a load decreases gradually. This is because strands of warp yarn carrying a load increases in number.

2. The greater the spacing between strands of warp yarn, the higher the selvage flexure under the same compressive force. The larger the spacing between strands of warp yarn, the higher the selvage flexure. This phenomenon, too, can be explained by the rate of increase in the number of strands of warp yarn carrying a load.

3. Selvage flexure in 40 s cotton broadcloth is ±2.3 mm in relation to the center line if the spacing between strands of warp yarn is 0.2 mm; approximately ±3.3 mm, if the space is 0.4 cm, as in, say, cotton shirting.

3.2 Features of Selvage Produced by Beating with Reed

The distribution of warp tension toward the fabric width is considered another factor distinguishing the selvage from the body of the fabric. It is quite conceivable that weaving function and the quality and quantity of a fabric vary with variations in warp tension. Beating with the reed is discussed here as influencing the distribution of warp tension. Fig. 24 illustrates the relations between the warp yarn and the reed. The figure uses the following symbols:

- \( M \) = warp-weaving point on fell.
- \( R, R' \) = points of contact of warp and reed.
- \( XX' \) = fell of cloth.
- \( X_1'X_1 \) = straight line passing \( R \) and parallel to \( XX' \).
- \( YY' \) = warp axis intersecting with \( XX' \) at right angle.

\[ MRR'Q = \text{warp line}. \]
\[ || = \text{reed}. \]
\[ T_1, T_2 = \text{warp tension}. \]
\[ \theta_z = \angle YMR. \]
\[ \theta = \angle X_1RM. \]
\[ \Delta \phi = \text{angle formed by} \ T_2 \text{with reed at point} \ R. \]

The force with which a reed squeezes warp at point \( R \) is expressed as the difference between components of \( T_1 \) and \( T_2 \) in the \( X_1X_1' \) direction. Assume this force to be \( P \) and reed dents perpendicular to \( X_1X_1' \).

\[ P = T_1 \cos \theta - T_2 \cos \left( \frac{\pi}{2} - \Delta \phi \right) = T_1 \cos \left( \frac{\pi}{2} - \theta_2 \right) - T_2 \cos \left( \frac{\pi}{2} - \Delta \phi \right) \]
The angles formed by warp yarn located from the selvage edge to the central section and the standard axis $YY'$ perpendicular to the fell of the cloth shrink as warp gets close to the center, finally dwindling to zero when warp is parallel to $YY'$ (see Fig. 25). Eq. (27) can be approximately transformed into:

$$
P = T_1 \cos \left( \frac{\pi}{2} - \theta_1 \right) - T_2 \cos \left( \frac{\pi}{2} - \Delta \phi \right)
$$

$$
= T_1 \left( - \cos \left( \frac{\pi}{2} + \theta_1 \sin \frac{\pi}{2} \right) - T_2 \left( - \cos \left( \frac{\pi}{2} + \Delta \phi \sin \frac{\pi}{2} \right) \right) \right.
$$

$$
= T_1 \theta_1 - T_2 \Delta \phi
$$

Assume that the vertical distance between the reed and $XX'$ are $\gamma$. Assume $\Delta \phi = 0$. Assuming $T_1 \Delta \phi = 0$, then $P = - \Delta x \cdot T_1$, because $\theta_2 = \Delta x / \gamma$, as in Fig. 25. Presumably, warp yarn near the selvage edge generates surplus tension equivalent to distortion, because the frictional force of the reed exceeds that of warp yarn near the center. Presumably, too, the deformation and permanent elongation of yarn are, therefore, higher. These assumptions were experimentally verified. The conditions of the experiment are given in Table 18.

### Table 18 Specimen for Testing Warp Tension Distribution

<table>
<thead>
<tr>
<th>Type</th>
<th>Automatic cotton loom</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>160</td>
</tr>
<tr>
<td>Beam width</td>
<td>44 inch</td>
</tr>
<tr>
<td>Actual reed width</td>
<td>40 inch</td>
</tr>
<tr>
<td>Number of heddles</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fabric specimen</th>
<th>Warp</th>
<th>Filling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (thread/in)</td>
<td>45s 65/35 cotton/polyester</td>
<td>Same as above</td>
</tr>
<tr>
<td>Width in greige</td>
<td>38 inch</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 26 gives the average values of the experiment involving three tests. The warp yarn was all front-row heddle yarn. The chart shows that warp tension near the selvage is higher than in the central part. The border line between the selvage and the central part is not clear but is located about 70 mm from the selvage toward the center.

3-3 Effects of Filling Tension on Selvage

The preceding section discussed warp tension distribution and distortion as characterizing the boundary between the selvage and the ground. Another feature distinguishing the selvage from the body of the fabric is filling tension, which influences the two differently.

We proceed to discuss the difference in weaving and weave between the selvage and the ground by using a function of selvage form. One of the features of selvage weaving construction is that the filling yarn bends on the warp yarn. Except in the selvage, the filling is straight and connects side by side with warp. The bending may be considered analogous to the condition shown in Fig. 3, in which angle $\omega$ of the filling expands $180^\circ$ along axis $XX'$. The function of selvage form is expressible by the following formula in the light of eq. (6):

$$
\gamma = F_1 \cos \omega + e^{-\mu \tau} F_2 - W_1 \sin \theta_2
$$

$$
= W_2 \cos \theta_2 + F_2 \sin \omega
$$

Except in the selvage edge, $\omega = -180^\circ$, for the above-mentioned reason. Therefore, in the above formula,

$$
sin \omega = 0 \quad and \quad cos \omega = -1
$$

And from the experimental results,

$$
sin \theta_2 = 0 \quad and \quad cos \theta_2 = 1
$$

Hence, assume $\gamma$ at this time to be $\gamma_0$.

$$
\gamma_0 = \frac{F_2 (e^{-\mu \tau} + 1)}{W_1}
$$

where $\gamma_0$ = dynamic equilibrium at the point of intear-
ing of warp and filling, hereinafter referred to as a function of equilibrium at the interlacing point. \( \gamma_f \) and \( \gamma \) are both obtainable from the ratio of filling tension to warp tension, but \( F_2 \) in \( \gamma_f \) differs from \( F_2 \) in \( \gamma \). \( F_2 \) in \( \gamma \) is the tension of the filling bent on the selvage edge and has a force to hold the selvage construction fabric. \( F_2 \) in \( \gamma_f \) has an entirely opposite force, because the filling does not flex. Filling tension on the selvage edge restricts weaving construction toward the center of the fabric. However, except on the selvage edge, it works in the opposite way to the warp at every pick and has no influence similar to that at the selvage edge.

We now proceed to obtain percentage transformations of function \( \gamma \) of the selvage line and function \( \gamma_f \) of equilibrium at the interlacing point in relation to variations in warp and filling tensions and to investigate the behaviors of such functions. Percentages transformations of \( \gamma \) and \( \gamma_f \) are calculable, respectively, by the following equations:

\[
\frac{\partial \gamma}{\partial F_2} W_2 = \frac{W_2(1+e^{-\rho_2 \phi})}{(W_2+0.13 F_2)^2} \\
\frac{\partial \gamma}{\partial W_2} F_2 = \frac{-F_2(1+e^{-\rho_2 \phi})}{(W_2+0.13 F_2)^2}
\]

and

\[
\frac{\partial \gamma_f}{\partial F_2} W_2 = \frac{(e^{-\rho_2 \phi\beta}-1)}{W_2} \\
\frac{\partial \gamma_f}{\partial W_2} F_2 = \frac{-F_2(e^{-\rho_2 \phi\beta}-1)}{W_2}
\]

These calculation formulas show that the higher the warp and filling tensions, the lower the percentage transformations of the function of the selvage line; but that the percentage variations in the function of equilibrium at the interlacing point is independent of the amount of filling tension or variations in the tension.

The fact that the direction, function and size of filling tension and its variations all differently influence the equilibrium behavior of the interlacing point is, in our opinion, one point distinguishing the selvage from the body, as we have said.

### 3-4 Density of Warp

We have seen that the effects of warp and filling tensions on weaving construction differ between the selvage and the other areas of a fabric. Presumably, then, warp and filling densities vary, depending on the width direction of a fabric. Fig. 27 shows the areas where warp and filling densities were measured in our experiment—with the results given in Table 19.

![Fig. 27 Positions where warp and filling densities were measured](image)

The figures in Table 19 are the average of two readings in the same measured area. Five measurements were made in different areas within one section. Therefore, the average per section was obtained from 10 measured values.

As shown in Table 19, warp density within 10 mm of the right and left edges of the selvage is higher than in the other areas of the fabric. Warp density within 10-20 mm of the edges of the selvage is about the same as in the central part. Filling density is almost the same in the whole width. These experimental findings also seem to illustrate that filling tension in the selvage operates to pull fabric con-

<table>
<thead>
<tr>
<th>number/inch</th>
<th>Section A</th>
<th>Section B</th>
<th>Section C</th>
<th>Section D</th>
<th>Section E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warp</td>
<td>Filling</td>
<td>Warp</td>
<td>Filling</td>
<td>Warp</td>
</tr>
<tr>
<td>1</td>
<td>57</td>
<td>30</td>
<td>51.5</td>
<td>28</td>
<td>52.5</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>29</td>
<td>52.5</td>
<td>28</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>55.5</td>
<td>27</td>
<td>53</td>
<td>28</td>
<td>52</td>
</tr>
<tr>
<td>4</td>
<td>56</td>
<td>29</td>
<td>53</td>
<td>29</td>
<td>51.5</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>29</td>
<td>52</td>
<td>29</td>
<td>51</td>
</tr>
<tr>
<td>( \bar{x} )</td>
<td>55.9</td>
<td>29</td>
<td>52.3</td>
<td>28.7</td>
<td>51.7</td>
</tr>
</tbody>
</table>
4. Transitional Characteristics of Stabilization of Selvage Form

As warp and filling tensions vary, so the point of interlacing of warp and filling on the selvage shifts and the selvage form becomes uneven in varying degrees. Let us study, by means of a transfer function, the response process of variations in selvage form.

Assume that the input is warp and filling tensions; the output, selvage form. Incidentally, our purpose is not a quest for a control system but an investigation of the variation process of the element system. Assuming that variations in selvage form are a continuous shifting of the positions of picks at the selvage weaving point, we analyze them as variations in function $\gamma$ of selvage form.

In the light of eq. (9),
$$\gamma = \frac{F(1 + e^{-\gamma s})}{W + 0.13 F},$$
where $W =$ warp tension; $F =$ filling tension.

Assume from the experimental results that:
$$W > 0.13 F$$
$$1 + e^{-\gamma s} = k$$
Then,
$$\gamma = \frac{kF}{W}$$
where $W$ and $F =$ input and $\gamma =$ output.

We see from this formula that the system is nonlinear. However, the input on one side in the early stage of variations may be ignored and the system can be handled by simple calculation by thinking of it as linear. Here we use the following symbols:
$W_0 =$ stationary value of warp tension.
$F_0 =$ stationary value of filling tension.
$\gamma_0 =$ stationary value of function of selvage line.

And
$$W - W_0 = v$$
$$F - F_0 = h$$
$$\gamma_0 - \gamma = m \cdot \theta$$
where $m =$ constant.

Hence,
$$\gamma_0 = \frac{kF_0}{W_0}$$
In the light of eqs. (28), (31) and (32),
$$m \cdot \theta = \gamma_0 - \frac{kF}{W_0}$$
Substituting eqs. (29) and (30) into the preceding equation gives us:
$$m \cdot \theta = \gamma_0 - \frac{k(h + F_0)}{v + W_0}$$

Transform this expression as follows:
$$m \cdot \theta = \frac{h}{F_0} + \left( \frac{v}{W_0} \right)^2 - F_0 - \frac{h - v}{W_0} \cdot \gamma_0$$

Assume the above formula to be:
$$h < F_0 \text{ and } v < W_0$$
Then,
$$m \cdot \theta = \frac{h}{F_0} - \gamma_0 - \frac{v}{W_0} \cdot \gamma_0$$

When filling tension in eq. (33) is stationary,
$$h = 0$$
Therefore,
$$m \cdot \theta = - \frac{\gamma_0}{W_0} \cdot v$$

That is, the changed part of the function of selvage form is what is obtained by multiplying the value of the early stage (stationary value) of the function by percentage variations in warp tension.

Assuming that the number of pickings after tension has varied is $\Delta n$; and that tension variations accompanying it are $\Delta v$, the following equation emerges if the function of selvage form is proportional to $\Delta v/\Delta n$:
$$m \cdot \theta = - m \frac{\Delta v}{\Delta n}$$

Therefore,
$$\Delta v = - \frac{\Delta \theta}{\Delta n}$$
Substituting eq. (35) in to eq. (33) gives us:
$$\theta = - \frac{\gamma_0}{W_0} \int \theta \, dn - \frac{\gamma_0}{F_0} \cdot h$$
Then, when warp tension is stationary,
$$v = 0$$
Hence,
$$m \theta = \frac{n}{F_0} \gamma_0$$

In the response in the early stage, where the system is believed to be linear, by handling the situation in the similar way to warp tension,
$$\frac{dh}{dn} = \theta$$
Thus,
$$h = \int \theta \, dn$$
Substituting eq. (37) in to eq. (33) gives us:
$$\theta = - \frac{\gamma_0}{W_0} \cdot v - \frac{\gamma_0}{F_0} \int \theta \, dn$$
Taking the Laplace transform of eq. (36)
$$\Phi(s) = - \frac{\gamma_0}{W_0} \cdot \Phi(s) - \frac{\gamma_0}{F_0} \cdot H(s)$$
which, re-arranged, transforms into:
\[ \phi(s) = \frac{-\gamma_s}{F_0} \frac{W_s \cdot s}{1 + \gamma_s \cdot H(s)} \]

Assuming from here:

\[ \begin{align*}
W_s &= T_s \\
\gamma_s &= k_s \\
\frac{F_0}{W_s} &= k_0
\end{align*} \]

Then,

\[ \phi(s) = \frac{-k_s \cdot T_s \cdot s}{1 + T_s \cdot s} \cdot H(s) \]

Dive Laplace formation to eq. (38) and assume:

\[ \begin{align*}
F_0 &= T_s \\
\gamma_s &= k_0 \\
\frac{W_s}{F_0} &= k_s
\end{align*} \]

Then,

\[ \phi(s) = \frac{k_0 \cdot T_s \cdot s}{1 + T_s \cdot s} \cdot V(s) \]

Eqs. (40) and (42) are formulas of a transfer function which gives the response of the selvage form function to variations in warp and filling tensions.

The element, which has a transfer function generally represented by the above expression, turns out to be an element connecting, in a series, the first-order element and the differential element.

By using the transfer function obtained here, we calculate the output response to the fixed input and draw the standard curve of the response. On the basis of eq. (40), we study a case where filling tension varies abruptly.

**Condition 1**

Warp tension (low) 15 g
Filling tension (high) 10 g → 15 g (higher)

In the light of eq. (32),

\[ \gamma_s = 0.66, \text{ provided } k = 1 \]

\[ H(s) = \frac{15 - 10}{s} = \frac{5}{s} \]

Substituting this into eq. (40) gives us:

\[ \phi(s) = -\frac{5 k_s T_s}{s(1 + T_s \cdot s)} \]

which, when inversely transformed, is:

\[ \theta = L^{-1} \left( -\frac{5 k_s T_s}{s} \right) = L^{-1} \left( -\frac{5 k_s T_s}{s} \right) \]

From formula (41) is obtainable \( k_s = 0.066 \), \( T_s = 22.7 \)

By applying this to eq. (43), the relationship between \( n \) and \( \theta \) is obtainable as shown in Fig. 28. If we vary filling tension in Fig. 28 from 10 to 15 g, then \( \theta \) indicates 0.33. Assuming that \( \theta = (l - n) \) of formula (18), then the unevenness of selvage form \( \Delta \delta \approx \text{approx } 1 \text{ mm.} \)

However, the value is not the absolute but relative index. The time constant is 22.7 picks.

**Condition 2**

Warp tension (low) 15 g
Filling tension (high) 15 → 2 g (low)

Here, \( \theta = 13 \), \( k_s e^{-\frac{13}{T_s}} \), \( k_s = 0.066 \), \( T_s = 15 \)

Fig 29 shows a response curve. In this case the relative index of \( \Delta \delta \) is 2.5 mm and the time constant 15 picks.

**Condition 3**

Warp tension (high) 30 g
Filling tension (low) 5 → 10 g (higher)

The response curve in this case is shown in Fig. 30. Here, \( \Delta \delta \) is low enough to be ignored and the time constant is as high as 176 picks.

Now to investigate abrupt variations in warp tension with the aid of eq. (42).

**Condition 4**

Filling tension (high) 10 g
Warp tension (low) 25 → 20 g (lower)

Substituting this into eq. (42) and inversely transforming it results in:

\[ V(s) = \frac{5}{s} \]

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The response is shown in Fig. 31. In this case, time constant is 15 picks and the unevenness is 0.6 mm.

Condition 5 Filling tension (high) 10 g
Warp tension (higher) 30 → 35 g
The response is illustrated in Fig. 32. The time constant is 30 picks and corrugation is extremely slight.

Condition 6 Filling tension (low) 5 g
Warp tension (lower) 15 → 10 g
Here the time constant is 15 and the unevenness is approximately 0.3 mm.

The surface contour of the selvage has so far been investigated by calculating the response of the selvage form function when warp or filling tension is subjected to abrupt variations. The experiment just described shows that, with a high time-constant and slight unevenness of selvage form, the variation curve of selvage form is mild; but that, with a low time-constant and notable unevenness of selvage form, the selvage form varies considerably.

5. Summing up

By analyzing the mechanism and formation of a selvage through weaving structure, we have deduced a selvage line function and thus obtained a clue to clarifying selvage-weaving. The selvage line function clarifies the effects of warp and filling tensions on selvage form and appearance, thus giving us basic knowledge of how to make a neat or well-built selvage.

We have also grasped the features of a selvage in contrast to those of the ground by thinking of selvage warp as a beam and by observing reed oscillation resistance, the effects of filling tension, etc., which are weaving factors featuring a selvage.

Finally, we have calculated, by means of a function of the selvage line, the response of the stabilizing process of selvage form. The response process has been expressed schematically. A selvage must be such as to add to the good appearance of the fabric and be uniform if it is to facilitate subsequent operations and finishing. However, uniform weaving conditions are indispensable for making a neat and uniform selvage, so much so that a fabric is judged by its selvage. It is from this point of view that the present article discusses some aspects of selvage-weaving. The author will be happy if this work gives some new knowledge about weaving technology.