The construction phase’s influence to the moving ability of cross-sections of woven structure

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Abstract. The purpose of this study is to work out bases to predict properties for single layer flat woven fabrics depending on changes of construction phases. A structural model of cross-section of single layered fabric is described based on the Pierce’s model. Form transformation of the yarn like straight, semi-arch and arch yarn is considered according to the alteration of yarn tension under the theory of Novikov. The value contributions to movement index of warp and weft yarn and their total moving ability in cross-sections at all structure phases of fabric are summarized.

1. Introduction

It is well known that woven fabrics in textile composites are extremely complicated materials and do not conform to any of the ideal parameters which normally are assumed in engineering structural analysis and mechanics [1, 4]. From the geometric viewpoint, the woven fabric mostly consists of cross-section of lines of two systems, located mutually perpendicularly. The smallest group of yarn interlacing, including all design of fabric, is called unit cells (or repeat) as illustrated in Figure 1.

![Figure 1. Single coverage as minimal structure cell of woven structure.](image)

These cross-sections are transitions or passes depending on the place where they lie in the given crossing, above or below any line. According to the theory of Topology, woven fabric’s interlacing can be considered as mathematical knots. Their mutual binding in pattern is considered as original topological criterion of evaluation of the fabric.

2. Yarn form transformation on cross sections.

The research in the field of single layer fabric structure, noticed that the changing phase of fabric’s structure influence the moving ability of the yarns in the fabric. The moving indicator, which is used [1, 3], considers only V-equilibrium phase of the fabric structure as described by the Novikov’s theory [2]. However, in this study the change of moving ability of threads in a fabric depending on the phase of the structure was investigated.
It is well known that, woven fabric's cross-sections are formed as an interlacing structure, which consists of two systems of yarns that conditionally take flattened form of a straight line, and crimps like arches or semi-arches as it is illustrated in Figure 2.

![Figure 2](image)

| a) straight – straight | b) straight – semi-arch | c) arch – straight |
|------------------------|------------------------|-------------------|
| d) semi-arch – semi-arc | e) semi-arch – arch    | f) arch – arch     |

**Figure 2.** All possible cross-sections of two yarns

According to the study of woven fabrics geometry by Pierce’s model [4], two dimensional fabrics repeat were built up by superimposing linear and circular yarn segments to produce the desired shape. Hence, combinations of yarn cross-sections will be studied. First combination of pair is “straight-arch” (see Figure 2 (c)).

It is admitted that the warp is maximum stretched and formed as a straight line, and weft crimp has the arch form. At the first phase, warp will be as much as possible tight [2], but the weft crimp will be in the form of maximal curved arch. Further, in the consequent phases, the arch form will be transformed, and on final IX phase, it will take the form of a straight line. The moment when yarn is transformed and allows some mobility to its pair is interesting. Weft, which is in the form of maximum curved arch in I phase, does not allow to move to its pair in any direction because it surrounds the pair as much as possible (see Figure 3).

![Figure 3](image)

**Figure 3.** Pair of straight-arc

The crimp of the weft loses the curvature in the subsequent phase, thus the surrounding degree of the pair decreases. Before the thread will take the form of a straight line, it will remain as an arch, but
with different curvature. The transformation of the crimp into the straight line, which depends on the construction phase, is shown in Figure 5.

As it can be observed in Figure 5 (a), the weft crimp with maximal bending across the warp at construction phase I does not allow any mobility space to the warp. The warp has been transformed and it has taken the form of arc as shown in Figure 5 (b) in phase II with less bending of warp. This transformation will continue with the changing of the phases, and the weft crimp will keep the form of arch in eight phases from phase I until VIII, but bending of the weft will vary (see Figure 5 (b, c, d, e, f, g, h).

Similar situation happens in the case with a semi-arch as shown in Figure 6 (a, b, c, d, e, f, g, h). It could be seen on a sample of «straight – semi-arch». As mentioned above, the warp is straight and the weft is in the form of "semi-arch" (see Figure 4).

Figure 4. Pair of straight – semi-arch

At the first phase warp is at maximum tightened and takes the form of a "straight line", and the weft crimp is at maximum bending it as shown in Figure 6. Thus, it leaves open space for moving one part to the pair. As much number of phase increases, the weft crimp’s height around the warp will decrease, and to final IX phase weft will take the form of a straight line. Transformation of semi-arch into a straight line can be seen in Figure 6. In each subsequent construction phase, weft will remain semi-arch, until then it will reach IX phase and will take form of a straight line.

| Phase of Construction | Arc | Semi-arch |
|-----------------------|-----|-----------|
| I                     | a   |           |
| II                    | b   |           |
Figure 5. Yarn shape transformation depending to phase of construction

Figure 6.
Depending on the overlapping and cross-sections, the yarns of warp or weft can be formed as "straight line", "semi-arch" and "arch". Each yarn has two directions of mobility, and depending on the combination, the mobility degree changes. Each yarn of the interlaced pair defines the mobility of the other one because the pair consists of two components. Hence, each position of the forming pair yarn gives a certain degree of mobility to the second one.

The free moving possibilities of yarns in all three chances, "Straight line" gives to the pair possibility of moving in two directions. "Semi-arch" bends around its pair on half and by that, gives freedom of movement in one direction only. "Arch" – due to its constructive form, completely bends around the pair, and does not allow moving to its pair in any directions.

For a quantitative evaluation of any overlapping, it is necessary to define contributions of each component. The general moving indicator of a pair “w” will be equal to the sum of contributions of warp and weft, and it looks as follows:

\[ w = w_{warp} + w_{weft} \quad (1) \]

Each yarn in the pair has two directions of mobility, to the right and to the left side. Depending on the form, it can be straight line, “semi-arch” or arch shaped. Each yarn will allow some amount of freedom to the second yarn. Therefore, the straightened yarn allows the maximum degree of mobility to the second yarn it the pair in two directions, and its moving indicator is: \( w_{straight} = 2 \).

Semi-arch formed yarn due to its constructive form limits freedom for moving to the second yarn only in one direction, from the possible two directions, and allows moving possibility only in one direction. Its moving indicator is as follows:

\[ w_{semiarch} = 1. \]

The arch formed yarn completely bends around its pair making yarn and it does not give any possibility of moving to the second one. Its moving indicator is as follows:

\[ w_{arch} = 0 \]

The maximum contribution to the moving ability of the pair is imposed by straight yarn and its contribution is equal to «2», the highest indicator of moving ability of the pair will be in couple "straight -straight", and the moving indicator for this pair will be equal to «4», that is

\[ w_{\text{max}} = w_{warp-straight} + w_{weft-straight} = 2 + 2 = 4 \]

The minimum contribution to the moving ability is in the couple arch-arch since the contribution of each component of the pair is equal to zero, accordingly its sum equals to zero as well.

\[ w_{\text{max}} = w_{warp-arch} + w_{weft-arch} = 0 + 0 = 0 \]

Intermediate couples like "straight - semi-arch", "semi-arch - semi-arch" and "straight - arch" have respectively intermediate indicators in the range of 4 to 0, "4" is maximum, while "0" is minimum.

Quantitative index exists for each form of yarn, which is called “movement index”. Depending on the position of pair making parties, the indicator of “move index” of yarn will be equal to "2", "1" and "0" accordingly.

Having known the move index of each component in couples (Table 1) it is possible to calculate move index of any couple (Table 2), and further having summarized all cross-sections it is possible to calculate it for all unit cell the above given indicators are applicable for yarn couples, which are in the construction phase V.
Table 1. Contribution unit to total moving

| Pair creators | Unit of move index |
|---------------|-------------------|
| Straight      | 2                 |
| Semi-arch     | 1                 |
| Arch          | 0                 |

Table 2. Thread cross sections and their contribution to total moving ability of the pair

| №  | Cross section                  | Contribution of each part | Total move index of cross-sections |
|----|--------------------------------|---------------------------|-----------------------------------|
| 1  | straight - straight            | 2+2                       | 4                                 |
| 2  | straight - semi-arch           | 2+1                       | 3                                 |
| 3  | straight - arch                | 2+0                       | 2                                 |
| 4  | semi-arch - semi-arch          | 1+1                       | 2                                 |
| 5  | semi-arch - arch               | 1+0                       | 1                                 |
| 6  | arch - arch                    | 0+0                       | 0                                 |

The transformation of above-mentioned six types of couples and their movement index, depending on a construction phase is follows.

a. The couple “straight – straight”: Such case takes place when some yarns of one system are passing over several yarns of the other system, for example in matt rib 4/4. In this couple of yarn, regardless of a construction phase, the indicator of movement index for each component will be maximum. Thus, if in couple one component is “straight”, it will provide the maximum freedom of movement to the second yarn. In other words, if “straight” component participates in a couple of yarns, it will provide movement freedom to another component of pair in two possible directions. In this case, the contribution of “straight” to the general move index equals to "2". In addition, the general indicator of movement index in a couple for all phases of the structure will be maximum, equal to "4".

b. On other side, there is a couple “arch – arch”. This couple of yarns, consisting of arches bent around each other, practically has no space to move. At first sight, it is so, but this couple will be examined in more details and depending on change of number of construction phases. It is known that one component of pair will be straight at the first or ninth construction phase, despite of the form it had initially. In woven unit cell, it can be a warp at phase I or weft at the phase IX. However, by the phase change, tension and height of the crimp also changes and the yarn will change its form too. In this case, warp is curved as an arch form, in phase I yarn will be in the form of a straight line. Therefore, its movement index will be identical to the straight line, which is maximum “2". As the number of phase construction increases, the crimp of warp is increasing. Further, the warp will be transformed and finally will accept the initial form of arch to the last phase IX with the minimum movement index, which is equal to "0". The weft’s form transformation and its move index will change in opposite way. At the construction phase I the weft is in a maximally crimped form and the minimum movement index. It will gradually take the form of a straight line on the phase IX with maximum move index "2". In central phase V, heights of crimps and form of threads will be identical, and move index will be identical, equal to "1". The total move ability of couple in all possible structure phases will be equal to "2".
The following couple of yarns, which we will analyzed, is a couple “straight – arch”. This couple consists of two opposite poles of yarn forms. Their elements were shown above. In this case, the warp is forming a straight line and weft is in an arch form. Quantitative indicators of movement index, which make this couple, will be identical as in the above seen cases. That means a straightened warp with the maximum indicator of movement index in all the ninth structure phases is equal to "2". The weft with arc form in the construction phase I will be transformed to straight line on phase IX, and an indicator of its movement index will change from "0" in the I phase to "2" in the phase IX. The total movement index of this couple increases from "2" on phase I to "4" in phase IX.

d. Indicators of couple “straight - semi-arch” differ from the above mentioned. Depending on the construction phase, “semi-arch” also changes its form. In addition, in the case seen above, the warp will be “straight” and the weft will have “semi-arch” form. As it is seen above, the warp provides maximum degree of freedom to the couple of yarns in both directions that means movement index is equal to "2". In this case, the weft in the form of semi-arch partially bends around the warp and limits its freedom of movements. In the phase I of construction, this form bends around it’s the second yarn as much as possible, keeping “semi-arch” form. Leaving to the pair only one direction to move means that movement index of this element, in this case, will be equal to "1". Further, in another side – in the phase IX of construction, the weft takes the form of straight line due to high tension, and its contribution to the total move ability of the pair will be maximum "2". In all intermediate phases, there will be a yarn transformation from the greatest possible semi-arch form in phase I to a straight line in the phase IX. Contribution to the general move ability in each phase will increase from "1" at phase I to "2" in the construction phase IX. The move index of this yarn in central phase V is "1.5". The step between the subsequent phases equals to "0.125". The total move ability of this pair will increase from "3" on phase I to "4" in the last phase IX.

e. Two identical forms of yarns participate in a unit cell of fabric as “semi-arch - semi-arch”. Both of these yarns change the location, that means a yarn, which was on the surface, passes down, and the second one passes from down into surface. Their movement index and curvature radii are identical at the phase V. However, behind of the equilibrium phase V, the bending radii of each yarn will be changed, one thus increases the bend, and another becomes “straight”. In all cases above, the warp will be at form of straight line at the first phase with the maximum movement ability. The weft at this phase will take the most curved form of “semi-arch”, and can provide to the other yarn mobility equal to "1". In other end phase, when the warp takes the form of the most curved “semi-arch” with a movement index equal to "1", weft will become “straight” because it will have a higher tightening and will make maximum contribution to the general movement ability.

f. More difficult situation is observed with couple “semi-arch – arch”. The matter is that, as well as in couple “straight – arch” or a “straight - semi-arch”, components of this couple of yarns will not make equal contributions to the general move ability. If a “semi-arch” is a warp, and weft is in the form of an “arch”. At the first construction phase, the “semi-arch” is under more tension and looks “straight”. Further, by the evolution of construction phases, the warp will gradually accept the initial form. On the phase IX warp will take “semi-arch” form with the indication of move index equal to "1". The weft from the initial “arch” form at phase I will be back transformed to the phase IX and it will take the form of “straight” due to higher tension. The move index of the weft will change from "0" at the phase I to "2" to the phase IX. There are three possible forms of yarn and their changing of movement indexes is given in Table 3.
Table 3. Change yarn’s move index depending on a structure phase

| Form of the yarn | Number of construction phase |
|-----------------|------------------------------|
|                 | I   | II  | III | IV  | V   | VI  | VII | VIII | IX |
| Straight        | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2    | 2  |
| Semi-arch       | 1   | 1.125 | 1.25 | 1.375 | 1.5 | 1.625 | 1.75 | 1.875 | 2  |
| Arch            | 0   | 0.25 | 0.5  | 0.75 | 1   | 1.25 | 1.5  | 1.75  | 2  |

Summing the analysis, made above: all possible couples and changes of their movement indices depending on a construction phase are given in Table 4.

Table 4. Summary table of values of contributions to move index of yarns of warp and weft, and their total move ability in cross-sections on all structure phases of fabric.

| Type of pairs, which imitate cross sections on construction phase V | Move ability of the yarns in cross sections | Number of construction phase |
|-------------------------------------------------------------------|---------------------------------------------|------------------------------|
|                                                                  | I   | II  | III | IV  | V   | VI  | VII | VIII | IX |
| «straight - straight»                                            |     |     |     |     |     |     |     |       |    |
| $w_o$                                                             | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2     | 2  |
| $w_y$                                                             |     |     |     |     |     |     |     |       |    |
| $w$                                                              | 4   | 4   | 4   | 4   | 4   | 4   | 4   | 4     | 4  |
| «straight – semi arch»                                           |     |     |     |     |     |     |     |       |    |
| $w_o$                                                             | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2     | 2  |
| $w_y$                                                             | 1   | 1.125 | 1.25 | 1.375 | 1.5 | 1.625 | 1.75 | 1.875 | 2  |
| $w$                                                              | 3   | 3.125 | 3.25 | 3.375 | 3.5 | 3.625 | 3.75 | 3.875 | 4  |
| «straight - arch»                                                |     |     |     |     |     |     |     |       |    |
| $w_o$                                                             | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2     | 2  |
| $w_y$                                                             | 0   | 0.25 | 0.5  | 0.75 | 1   | 1.25 | 1.5  | 1.75  | 2  |
| $w$                                                              | 2   | 2.25 | 2.5  | 2.75 | 3   | 3.25 | 3.5  | 3.75  | 4  |
| «semi arch – semi arch»                                          |     |     |     |     |     |     |     |       |    |
| $w_o$                                                             | 2   | 1.875 | 1.75 | 1.625 | 1.5 | 1.375 | 1.25 | 1.125 | 1  |
| $w_y$                                                             | 1   | 1.125 | 1.25 | 1.375 | 1.5 | 1.625 | 1.75 | 1.875 | 2  |
| $w$                                                              | 3   | 3   | 3   | 3   | 3   | 3   | 3   | 3     | 3  |
| «semi arch – semi arch »                                         |     |     |     |     |     |     |     |       |    |
| $w_o$                                                             | 2   | 1.875 | 1.75 | 1.625 | 1.5 | 1.375 | 1.25 | 1.125 | 1  |
| $w_y$                                                             | 0   | 0.25 | 0.5  | 0.75 | 1   | 1.25 | 1.5  | 1.75  | 2  |
| $w$                                                              | 2   | 2.025 | 2.25 | 2.375 | 2.5 | 2.625 | 2.75 | 2.875 | 3  |
| «arch - arch»                                                    |     |     |     |     |     |     |     |       |    |
| $w_o$                                                             | 2   | 1.75 | 1.5  | 1.25 | 1 | 0.75 | 0.5  | 0.25  | 0  |
| $w_y$                                                             | 0   | 0.25 | 0.5  | 0.75 | 1 | 1.25 | 1.5  | 1.75  | 2  |
| $w$                                                              | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2     | 2  |
3. Conclusions
According to the results, considerable change of indicator of moving ability of arch and semi-arch, depending on change of a structure phase, is visible. This change is very important because during the calculation of some characteristics of woven fabrics the moving ability of yarns in it plays an essential role in the properties of textiles.

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