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Computer Aided Construction of Reinforced Weaves Using Matrix Calculus

Abstract
This paper describes mathematical modelling of traditional graphic structures within textile materials using binary matrices, which is made possible by the binary nature of these structures. An algorithm is presented for woven design construction (weave draft, threading draft, treadling draft and tie-up), as well as an algorithm for weave reinforcement using binary matrices. The general advantage of the algorithm is its simplicity and execution speed. Application of the weave reinforcement algorithm is also presented in this paper, and the computer program, written in C#, shows the ease of its implementation, opening the way to integration into existing and new CAD/CAM packages.

Key words: *mathematical models, matrices, woven fabric, weave design, CAD, reinforcement.*

Introduction

Woven structures are created by co-ordinated combining and interlacement of two sets of threads: one vertical or warp, and the other one horizontal or weft. Traditionally, the representation, planning and development of these structures require a graphic representation of the repeating weave draft, as well as representation of the threading, treadling and tie-up. Although the representation of woven structures is quite simple, it still takes time and certain experience of textile technology for its development. The representation of woven structures and their development, supported by the development of information technologies, is mathematically adapted for computer operations. CAD/CAM systems for textiles, just like electronically driven looms, work in a binary system (0, 1), using the well known fact that thread interlaces can be defined in two ways only. Thinking along these lines, the designer of new woven structures and weave drafts need not be a textile engineer; he/she just has to know how to use a computer and should have a few bright ideas, i.e., some CAD systems have the generation of weave draft separated from other options, and most of them use a manual entry for the basic woven structure – weave draft. In the entry process, the combining and development of new and complex weave draft problems can arise, while faults are inevitable in the case of manual entry [1].

A possible solution for such problems is the structural development of weave drafts (woven fabric decomposition) based on the use of binary matrices and operations on them. The analogy of matrix and graphical operations in computer theory and practice has been used for many years, thus it is a logical step to apply similar principles to woven structures.

Investigations in this field performed in the past were mostly concerned with finding and suggesting an appropriate mathematical model or software algorithm for the representation of woven structures. The first papers were published about 50 years ago, and more recent papers that describe the use of information technologies in textile technology are 20 years old only a few of them have been published recently [2] but some investigations in this field mainly concerned the binary coding of basic woven structures and their representation, trying to construct an appropriate algorithm for the woven design computation [3, 4]. Others were headed in various directions, from the design of mathematical models for some weave drafts all the way to algorithms for multilayered woven fabric development [5 - 8]. Researchers in the field have mostly been oriented towards the application of algorithms related to colour order and their representation, thus solving designer's problems only [9-13]. What is more, some models based on weave symmetry have been researched and developed [14, 15].

Investigations presented in this paper are based on the most common mathematical representation of weave draft – binary matrices. The goal of the investigations is the development of new algorithms for advancing specific procedures which still require manual editing in woven fabric construction, along with the implementation of the algorithms in order to verify the correctness and possibility of integration into CAD/CAM systems. It could be said that this paper is an extension of investigations presented in existing papers (considering fundamentals), but it also presents a solution for weave reinforcement, contour thickening in motifs and a shading effect for the design and construction of new woven fabrics.

Mathematical representation of woven structure

Mathematical representation of a woven fabric is based on the fact that a woven structure is composed of vertical (warp) and horizontal (weft) sets of threads that are perpendicular. These sets, on an imaginary intersection of each thread from the first set with each thread from the second set, form warp intersection points if the thread from the first set (warp) is

Table 1. *The results of Boolean operators.*

A	B	$A \wedge B$	$A \vee B$
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	1

positioned above the thread from the second set (weft), or they form weft intersection points if the thread from the second set (weft) is positioned above the thread from the first set (warp).

In textile tradition, intersections are represented by fields of black and white squares. Due to their binary nature, the information on woven fabric design can easily be transferred to a computer through Boolean algebra, in which black squares denote "TRUE" (or number 1) and white squares "FALSE" (or number 0). Furthermore, we shall use two basic logic operators: logical and logical OR [16, 17]. Results for these operators are given in ***Table 1***. The operator AND is represented by the symbol $\wedge$ and the operator OR by $\vee$.

Mathematical representation of a woven design

Black squares (warp thread over weft thread) are represented by 1, and white squares (weft thread over warp thread) by 0. The structure of black and white squares is equivalent to the table structure, hence the matrix definition can be applied to it [18, 19]. The structure mentioned can also be represented by two sets of ordered pairs: the set of weft intersection points, where the matrix element (*i,j*) equals zero, and the set of warp intersection points, where the matrix element (*i,j*) equals one.

In order to introduce a mathematical model for the computation of matrices in a woven design, we shall define *m* as the number of rows and *n* as the number of columns in the binary matrix **M**, which will represent the graphic structure $m \times n$.

The matrix elements are:

$$m_{i,j} = \begin{cases} 0, \textbf{if} \text{ square } (i,j) \textbf{ is} \text{ white square} \\ 1, \textbf{if} \text{ square } (i,j) \textbf{ is} \text{ black square} \end{cases} \quad (1)$$

The graphic structure shown in ***Figure 1*** is composed of 3 rows and 4 columns, which means that the corresponding matrix **M** must contain 3 rows and 4 columns, and for the example given the matrix is:

$$\mathbf{M} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Now we shall introduce the transpose $\mathbf{M}^T$ of matrix **M**. The transpose $\mathbf{M}^T$ has *n* rows and *m* columns, with the values defined in the following equation:

$$m^T_{j,i} = m_{i,j} \qquad \forall i \in [1, m], \forall j \in [1, n] \quad (3)$$

In order to perform the operations on binary matrices from the woven design, we shall define the matrix operator * (which would be matrix multiplication for matrices composed of real or complex numbers), considering the following:

- Binary matrix **A** has *m* rows and *n* columns; its element is $a_{i,k}$.
- Binary matrix **B** has *n* rows and *p* columns and its element is $b_{k,j}$.
- Binary matrix **C** = **A** * **B** consequently contains *m* rows and *p* columns (like in the case of matrix multiplication). The elements of **C** are defined in the following way:

$$c_{i,j} = (a_{i,1} \wedge b_{1,j}) \vee (a_{i,2} \wedge b_{2,j}) \vee \ldots$$
$$\ldots \vee (a_{i,k} \wedge b_{k,j}) \vee \ldots \vee (a_{i,n} \wedge b_{n,j}) \quad (4)$$
$$\forall i \in [1, m], \forall j \in [1, p]$$

The woven design consists of four parts, each of which can be represented as a binary matrix. In the lower left segment of the woven design there is a weave draft representing matrix **W**, and to the right of it there is a treadling draft representing matrix **V**. The threading draft representing matrix **H** is shown in the upper left segment, and finally in the upper right segment there is a tie-up draft defined by binary matrix **E**.

The requirement that each thread in the weave be stitched in at least one intersection point means that matrix **W** has to have at least one "1" and one "0" in each row and each column. Otherwise, such thread would remain free unintegrated in the woven fabric construction. This requirement is fulfilled in our example, which will later be used for demonstration of the weave reinforcement algorithm.

Equation (5) is a matrix representation of the weave draft from ***Figure 3***.

$$\mathbf{W} = \begin{bmatrix} 0&0&1&0&1&0&0&0&1&0&0&0&1&0 \\ 0&1&0&0&0&1&0&0&0&1&0&1&0&0 \\ 0&0&1&0&1&0&0&0&1&0&0&0&1&0 \\ 0&0&0&1&0&0&0&1&0&0&0&0&0&1 \\ 1&0&0&0&0&0&1&0&0&0&1&0&0&0 \\ 0&1&0&0&0&1&0&0&0&1&0&1&0&0 \\ 0&0&1&0&1&0&0&0&1&0&0&0&1&0 \\ 0&0&0&1&0&0&0&1&0&0&0&0&0&1 \end{bmatrix} \quad (5)$$

Only one warp thread can pass through one shaft in the loom, which means that binary matrix **H** in each column must have exactly one "1". Of course, there can be more "1"s in a row of matrix **H**, the number depending on the number of equal columns of **W**. The threading draft of the weave draft shown in ***Figure 3***, is shown in ***Figure 4***.

Binary matrix **H,** which represents the threading draft from ***Figure 4***, is shown in Equation (6):

$$\mathbf{H} = \begin{bmatrix} 1&0&0&0&0&0&1&0&0&0&1&0&0&0 \\ 0&1&0&0&0&1&0&0&0&1&0&1&0&0 \\ 0&0&1&0&1&0&0&0&1&0&0&0&1&0 \\ 0&0&0&1&0&0&0&1&0&0&0&0&0&1 \end{bmatrix} \quad (6)$$

A simple algorithm for the construction of matrix **H** is given.

The number of rows in **H** equals a distinctive column count from **W**, and all the values in matrix **H** at the beginning will be "0". For the first column of **W,** we shall put "1" in position (1,1) of matrix

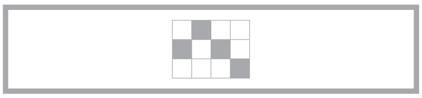

Figure 1. *Graphic representation of a woven structure.*

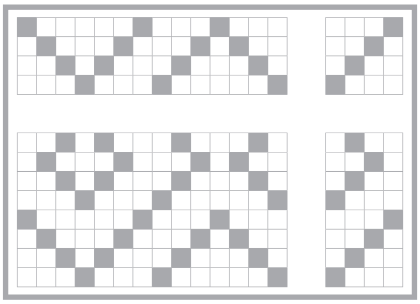

Figure 2. *Woven design.*

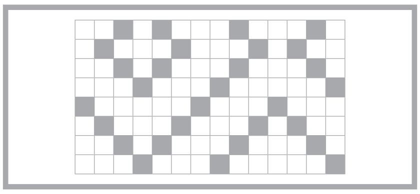

Figure 3. *Weave draft.*

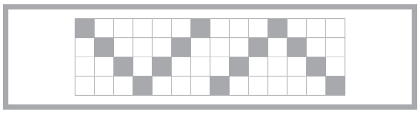

Figure 4. *Threading draft.*

$$\mathbf{V} = \begin{bmatrix} 0&0&1&0&1&0&0&0&1&0&0&0&1&0 \\ 0&1&0&0&0&1&0&0&0&1&0&1&0&0 \\ 0&0&1&0&1&0&0&0&1&0&0&0&1&0 \\ 0&0&0&1&0&0&0&1&0&0&0&0&0&1 \\ 1&0&0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&1&0&0&0&1&0&1&0&0 \\ 0&0&1&0&1&0&0&0&1&0&1&0&1&0 \\ 0&0&0&1&0&0&0&1&0&0&0&0&0&1 \end{bmatrix} * \begin{bmatrix} 0&0&0&1 \\ 0&0&1&0 \\ 0&1&0&0 \\ 1&0&0&0 \\ 0&1&0&0 \\ 0&0&1&0 \\ 0&0&0&1 \\ 1&0&0&0 \\ 0&1&0&0 \\ 0&0&1&0 \\ 0&0&0&1 \\ 0&0&1&0 \\ 0&1&0&0 \\ 1&0&0&0 \end{bmatrix} * \begin{bmatrix} 0&0&0&1 \\ 0&0&1&0 \\ 0&1&0&0 \\ 1&0&0&0 \end{bmatrix} = \begin{bmatrix} 0&1&0&0 \\ 0&0&1&0 \\ 0&1&0&0 \\ 1&0&0&0 \\ 0&0&0&1 \\ 0&0&1&0 \\ 0&1&0&0 \\ 1&0&0&0 \end{bmatrix} \quad (9)$$

$$\mathbf{V_e} = \left(\begin{bmatrix} 0&0&1&1 \\ 0&1&1&0 \\ 1&1&0&0 \\ 1&0&0&1 \end{bmatrix} * \begin{bmatrix} 0&0&0&1 \\ 0&0&1&0 \\ 0&1&0&0 \\ 1&0&0&0 \end{bmatrix} * \begin{bmatrix} 0&0&0&0&1&0&0&0 \\ 0&1&0&0&0&1&0&0 \\ 1&0&1&0&0&0&1&0 \\ 0&0&0&1&0&0&0&1 \end{bmatrix} \right)^{\mathbf{T}} = \begin{bmatrix} 1&1&0&0 \\ 0&1&1&0 \\ 1&1&0&0 \\ 1&0&0&1 \\ 0&0&1&1 \\ 0&1&1&0 \\ 1&1&0&0 \\ 1&0&0&1 \end{bmatrix} \quad (13)$$

Equations 9, 13.

H. For each next i-th column in matrix W, we will compare it to each prior j-th column; if the i-th column is equal to the j-th column, then matrix H in position (j,i) will contain the value "1", and if the i-th column is not equal to any prior column, we put "1" in the i-th column in the first free row of binary matrix **H**. The expression "first free row in **H**" means the first row in **H** contains only "0" values. It is important to mention that comparison of column equality in matrix **W** always starts from the first column.

The harness lifting draft, which is a part of a woven design, is represented by binary matrix V. Harnesses that are lifted participate in the creation of woven fabric. Number 1 in i-th row and j-th column of matrix V represents the lifting of the j-th harness in i-th row of a weave draft. Thus it is possible with known W and H to determine V. This appears simple if matrix E is an exchange matrix.

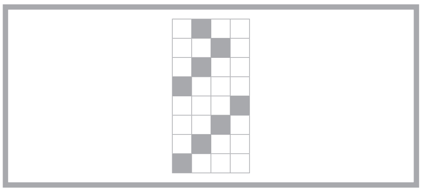

Figure 5. *Treadling draft.*

Figure 6. *a) original picture; b) picture after the reinforcement.*

Generally, matrix **V** is computed by performing operation * on matrices **W**, **H** and **E** according to Equation (7) [20].

$$\mathbf{V} = \mathbf{W} * \mathbf{H}^{\mathbf{T}} * \mathbf{E} \quad (7)$$

Equation (8) is used for calculation of the weave draft (W) from the threading, treadling and tie-up draft.

$$\mathbf{W} = \mathbf{V} * \mathbf{E} * \mathbf{H} \quad (8)$$

Binary matrix **V,** obtained by entering matrices **W**, **E** and **H** from our example into Equation (7), is computed in Equation (9).

The graphic representation of matrix **V** is a treadling draft, given in our example in ***Figure 5***.

Binary matrix **E** is actually an exchange matrix, which is a special case amongst permutation matrices; in other words, it is a row-reversed version of an identity matrix.

Importance of weave reinforcement in woven fabric construction

Reinforced weave is formed by adding warp intersection points to the weave draft with a weft effect, the weave draft size remaining the same. Adding warp intersection points can be done on any side (left, right, up, down) of the existing warp intersection point, but it has to be uniform throughout the weave draft. The reinforcement process may continue while there are at least two weft intersection points for each weft thread. If there is only one weft intersection point for the weft thread, the result is a warp effect weave. The process of weave reinforcement is mostly used in weave shadowing, in other words in a gradient transition from the weft effect to the warp effect and vice versa. Weave reinforcement is used not only in weave design but also for making lines thicker for one or more pixels in the process of drawing motifs. An example is shown in ***Figure 6***, where the original picture is on the left, and the reinforcement of contours made with ReinforcedWeave software is on the right.

This procedure not only preserves line continuity and connectivity but also closed areas. Closed areas in a motif are usually filled with colour in the process of weave design, and by ensuring that closed areas are preserved after the reinforcement, the problem of flooding other areas is solved. The reinforcement procedure also enables continuous and correct work with multicoloured shading, i.e. step transition from the weft to warp effect and vice versa. The fineness of continuous transitions from a light to dark effect and vice versa has a significant impact on the aesthetic value of woven fabrics. Such effects are rarely used in textile engineering since the manual editing of a weave draft is inevitable. The weave reinforcement algorithm presented solves

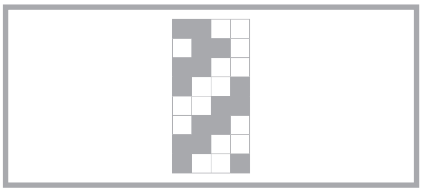

Figure 7. *Reinforced treadling draft.*

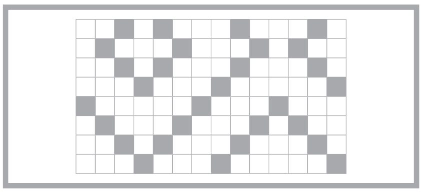

Figure 8. *Reinforced weave draft.*

the problem of human intervention in weave draft design mentioned.

Weave reinforcement algorithm with example

A mathematical algorithm for weave reinforcement is presented in this paper. In order to describe the algorithm, we shall firstly name the binary matrices used later.

- **W** is a matrix representing the initial weave draft
- **H** is a matrix representing the threading draft
- **V** is a matrix representing the initial treadling draft
- $\mathbf{W_e}$ is a matrix representing the final (ending) weave draft
- $\mathbf{V_e}$ is a matrix representing the treadling draft of the final weave
- **E** is an exchange binary matrix $N \times N$ (where N is the row count of **H**), representing the tie-up draft
- **S** is a reinforced $N \times N$ binary matrix where N is the row count of **H**

The matrix **S** is constructed from exchange matrix **E**, according to Equation (10).

$$s_{i,j} = \begin{cases} 1, \text{ if } (e_{i,j} = 1 \ (\forall i,j \in [1,N])) \vee \\ \vee (e_{i,j} = 1,\ k = i \bmod N + 1, \\ \forall i,j \in [1,N]) \\ 0, \text{ otherwise} \end{cases} \tag{10}$$

In order to perform the reinforcement, we shall continue with the computation of $\mathbf{V_e}$, according to the following equation:

$$\mathbf{V_e} = \left(\mathbf{S} * \mathbf{E} * \mathbf{V}^{\mathbf{T}}\right)^{\mathbf{T}} \tag{11}$$

In our example, matrices **E** and **S**, according to the Equation (12), are:

$$\mathbf{E} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \mathbf{S} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

By entering matrices **E** and **S** into Equation (11), binary matrix $\mathbf{V_e}$ is obtained, as shown in Equation (13).

The graphic representation of the computed matrix $\mathbf{V_e}$ can be found in ***Figure 7***.

By using Equation (8) and replacing the matrix names (matrix **V** is replaced by the new matrix $\mathbf{V_e}$), we get Equation (14).

$$\mathbf{W_e} = \mathbf{V_e} * \mathbf{E} * \mathbf{H} \tag{14}$$

The result of weave reinforcement is a final weave draft, represented by matrix $\mathbf{W_e}$, Equation (15) being an example.

A graphic representation of the reinforced weave draft is shown in ***Figure 8***.

The algorithm for weave reinforcement described can be expressed in a simpler way, as seen in Equation (16):

$$\mathbf{W}_e = \mathbf{W} * \mathbf{H}^{\mathbf{T}} * \mathbf{S}^{\mathbf{T}} * \mathbf{E} * \mathbf{H} \tag{16}$$

Equation (16), which describes the weave reinforcement algorithm, transformed into pseudo code is shown in ***Figure 9***. Note that simple operations like matrix transposition are not presented here in a form of pseudo code.

Weave reinforcement can be performed with a moderate number of reinforced intersection points (**M**), while there are at least two weft intersection points in each weft thread. If this is the case, we need to redefine the values for the elements of matrix **S**, as in Equation (17):

$$s_{i,j} = \begin{cases} 1, \text{ if } (e_{k,j} = 1, k = (i + \\ + m - 1) \bmod N + 1, \forall i,j \in [1,N]) \\ \forall m \in [0, M - 1] \\ 0, \text{ otherwise} \end{cases} \tag{17}$$

Software implementation of the matrix model

Weave draft representation in the form of a binary matrix is appropriate for storage and efficient computations, which

```
ReinforcementAlgorithm(W)
{
 /* input: W; output: We; */
 BinaryMatrix
W,H,HT,S,ST,E,H,We,Temp;
 H = CalculateH(W);
 HT = Transpose(H);
 E = ExchangeMatrix;
 S = Reinforce(E);
 ST = Transpose(S);
 We = OpAsterisk(W, OpAsterisk(HT,
OpAsterisk(ST, OpAsterisk(E, H))));
 return We;
}


Reinforce(E)
{
 /* input: E; output: S; */
 BinaryMatrix S;
 S = NullMatrix;
 N = rows(E);
 for i = 1 to N
 for j = 1 to N
 k = (i MOD N) + 1;
 if (E[i,j] == 1) OR (E[k,j] == 1)
 then S[i,j] = 1;
 else S[i,j] = 0;
 return S;
}


OpAsterisk(A,B)
{
 /* input: A,B; output: C; */
 BinaryMatrix C = NullMatrix;
 for i = 1 to rows(A)
 for j = 1 to columns(B)
 for k = 1 to columns(A)
 C[i,j] = C[i,j] OR
(A[i,k] AND B[k,j]);
 return C
}
```

Figure 9. *Listing 1 - pseudo code for the weave reinforcement algorithm.*

was implemented in the demonstration software ReinforcedWeave. This program was modularly implemented in the C# language (under .NET framework), hence it offers easy further development, upgrades and implementation of other weave draft alteration actions, with a minimal time loss for the adaptation of existing modules [21, 22]. Current implementation is limited only by the weave draft size to be used; however, it can be easily extended to the full formats used in the textile industry. Also, the input

$$\mathbf{W_e} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \tag{15}$$

Equation 15.

and output formats for storing the weave draft and the whole woven design can be expanded with industrial standards. The initial window of the ReinforcedWeave program is presented in ***Figure 10***, along with the sample weave draft.

Below is a list of matrix representations in the Tie-up mode:

- top left: threading draft representing matrix **H**
- top right: representation of matrix **E** or matrix **S** (with the Reinforcement enabled)
- bottom left: representation of matrix **W** (weave draft) or matrix $\mathbf{W_e}$ (reinforced weave draft)
- bottom right: representation of matrix **V** (treadling draft) or matrix $\mathbf{V_e}$ (reinforced treadling draft)

Below is a list of the options in the program:

- The number of wefts: the number of weft threads – the number of rows in matrix **W**
- The number of warps: the number of warp threads – the number of columns in matrix **W**
- The number of reinforcements: the number of reinforced points (1 – no reinforcement)
- Show reinforced: enable/disable reinforcement
- Pegplan / Tie-up: working mode selection (reinforcement demonstration can be performed using the Tie-up mode)

In order to create a reinforced weave draft with the ReinforcedWeave software, we have to start by choosing New from the File menu. After that, we need to enter the weave draft size in the boxes Weft threads and Warp threads, plus draw the weave draft in the corresponding area. A screenshot after making and drawing a new weave draft is shown in ***Figure 10***. If we already have a weave draft in the windows bitmap file, we can select Import from the File menu and choose that file instead of the procedure previously described.

The reinforcement process is enabled by checking the Show reinforced option and by choosing the reinforcement size in the box Number of reinforcements. The reinforced weave draft is presented in the place where the original weave draft was. The blue squares represent warp intersection points present both in the original and reinforced weave draft;

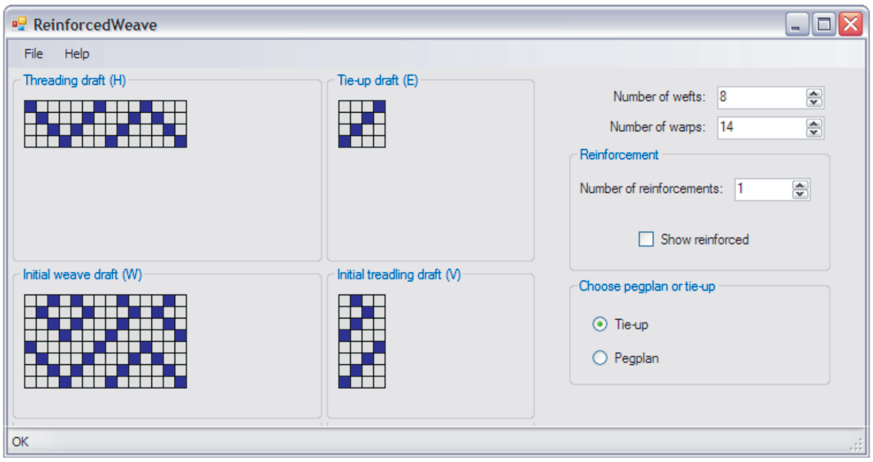

Figure 10. *A new woven design entered into the ReinforcedWeave software.*

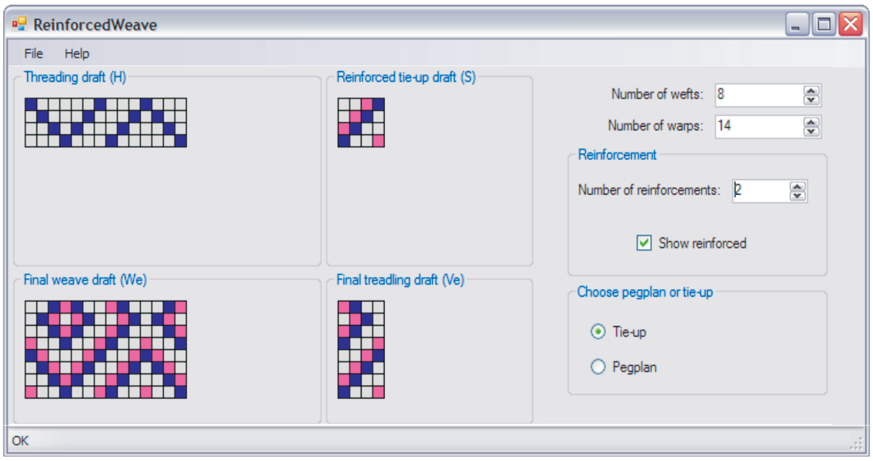

Figure 11. *Weave draft in the software after reinforcement.*

the pink squares represent warp intersection points in the reinforced weave draft, which were weft intersection points in the original weave draft, and the light grey squares represent weft intersection points in both the original and reinforced weave draft. The example shown in ***Figure 10*** was reinforced using the software, and a screenshot of the reinforced weave is shown in ***Figure 11***. We can save the reinforced weave draft to the windows bitmap file by choosing Export from the File menu.

We can perform changes to the intersection points in the weave draft with a left mouse click on a square in the weave draft, which toggles intersection points from the warp to the weft intersection point and vice versa. Changes to matrices **E** and **S** are performed in the same way.

The options Open, Save and Save As from the File menu can be used to load and store the complete woven design to the file. The example from this paper has been included in the examples the ReinforcedWeave originally came with.

Additional possibilities and the Pegplan mode are described in the program help, which can be obtained by choosing Contents from the Help menu. In the status bar at the bottom of the window, we can see a message whether the weave draft currently shown in the screen is valid or not. The ReinforcedWeave software has a limit for the weave draft size – the maximal size is up to 300 × 300 intersection points. However, we consider it adequate for demonstration purposes.

Conclusion

- in the mathematical model (one of many possible) presented in this paper, binary matrices are used which have an equivalent structure to the traditional graphical woven structures, enabling easier application of the model,

- automated weave reinforcement with a moderate number of reinforcements shortens the development time and reduces expenses in the woven fabric construction process,
- through the development of the model and the CAD software prototype ReinforcedWeave, the simplicity of automated weave reinforcement is shown; the software can easily be used in industry with minor adjustments,
- the model presented enables simple and efficient application in the further development of CAD software packages for the analysis and construction of simple and complex multilayered woven fabrics,
- the reinforcement process described can be applied to computer graphics, where the weave draft containing warp and weft intersection points should be replaced by pictures containing black and white or colour pixels,
- the ReinforcedWeave software can be downloaded at http://www.ttf.hr/~zpenava/ReinforcedWeave.zip,
- the weave reinforcement procedure in textile engineering simplifies weave design as well as the making of closed contours in motifs.

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