Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology № 88, 2014: 61-64
(Ann. WULS - SGGW, For. and Wood Technol. 88, 2014)

Numerical modeling of textile inspired three-dimensional woven timber structures.

IWONA DUSZYK
MARTA SITEK
Department of Building Construction, Faculty of Civil Engineering, Warsaw University of Technology

Abstract: *Numerical modeling of textile inspired three-dimensional woven timber structures.* The paper presents the numerical analysis of textile inspired three-dimensional woven timber structures. The numerical model built in ABAQUS 6.11 software simulated the possible behaviour of the structures under loading.

Keywords: woven timber, numerical modeling, ABAQUS, textile structures.

INTRODUCTION

The potential of woven timber structures are gaining on popularity in scientific research. The aim of the investigation is to consider a possibility of application of such structures on a building scale. Apart from the obvious fact that architects can be easily attracted to woven structures because of their aesthetic reasons, they present all excellent properties that timber posses like the ease in shaping or high strength to weight ratio. As a sustainable resource they are also environmentally friendly.

In the previous work of the authors the two-dimensional woven structures were investigated. The results of this analysis will be helpful to continue the research on three-dimensional structures.

TEXTILE STRUCTURES

Textiles are structures formed in a process which may include weaving, knitting, felting etc. Yarns are used in various ways to produce different weave effects. Simple and complex fabric design is produced by three basic weave structures for fabric manufacturing: plain weave, twill weave and satin weave. Their combination, or varying the type of yarns, twist levels, etc. may result in an almost unlimited variety of constructions [1]. Great advantage of textiles is that the structure components work cooperatively together as one entity. In the case of failure of the weakest element this will not provoke the collapse of the structure as a whole, since the load of the weakest element will be carried by those adjacent to it. What is more, textile structures have an advantageous ability to adapt to subjected load. While the load increases, the structure undergoes large deformation, but due to its elasticity it avoids destruction [2]. Of course the possible combinations of textile structures based not only on differentiating the basic weave modules but also applying various yarn materials pose a wide range of possibilities for structures, waiting for investigation and optimization.

SHAPE ASSUMPTIONS

The shape of three-dimensional woven timber structure was chosen on the basis of several criteria. The structure should have a rectangular plan and a cylinder shape. Its public-oriented function like opera or theatre requires dimensions which result from the angle of visual perception of a viewer and a good visibility from all seats. The assumed dimensions of the structure are 20m by 35m in plan and height of 10m. The numerical model includes the part of the structure based on circular sector of 45 degrees and 10m length.

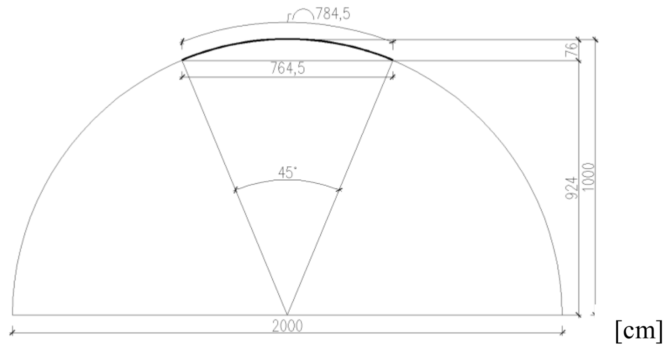

Figure 1. Cross section of the structure with analysed module of circular sector of 45 degrees.

DESIGN

On the basis of previous work some assumptions were made in order to continue the research:

- WEAVING PATTERN, MATERIAL AND NUMERICAL MODEL CHOICE

From three most popular weaving patterns, shown in Figure 2, the twill pattern appeared to be the stiffest [4].

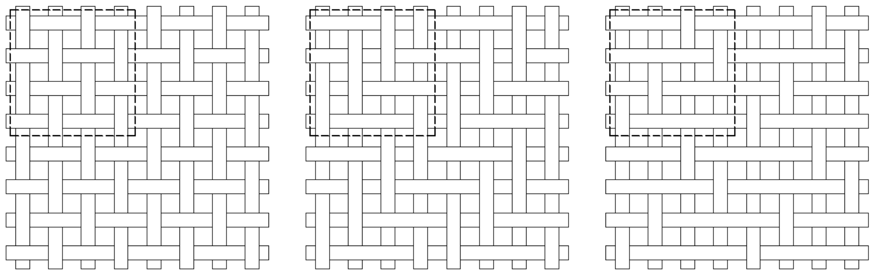

Figure 2. Main weave structures: plain, twill and satin weave; basic module is marked.

Three types of timber were investigated: pine, larch and fir [3]. Among them larch represented the stiffest material. Twill weave is a simple weave structure where the weft floats over and under specified number of warps, creating a diagonal pattern. The numerical model created by choosing mesh size of 0,025 by 0,025m and element type S4 gave the most reliable results in the fastest computational time [3]. The model was loaded with self-weight and pressure of $0{,}4\frac{kN}{m^2}$. Mechanical properties of larch (C30 strength class) in dry moisture conditions are given in Table 2.

Table 2. Properties of wood according to [4]

	$f_{m,k}$ [MPa]	$f_{t,0,k}$ [MPa]	$f_{t,90,k}$ [MPa]	$f_{c,0,k}$ [MPa]	$f_{c,90,k}$ [MPa]	$f_{v,k}$ [MPa]	$E_{0,mean}$ [GPa]	r_k [kg/m^3]
Larch	30	18	0,4	23	2,7	4,0	12	380

Choosing wood for textile techniques has its reasons. Wood is composed of cellulose fibres, which are flexible and allow for respectively elastic deformation. In this paper wood is described as a continuous and homogenous linear elastic orthotropic material with three planes of symmetry. Average values of material properties, which vary between species and even within them and also depend on moisture content and specific gravity [5], are presented in Table 3.

Table 3. Properties of wood at approximately 12% moisture content (Source: [5])

	E_L [GPa]	E_R [GPa]	E_T [GPa]	$n_{LR}=n_{RL}$	$n_{RT}=n_{TR}$	$n_{LT}=n_{TL}$	G_{RT} [GPa]	G_{RL} [GPa]	G_{TL} [GPa]
Larch	12,90	1,01	0,84	0,355	0,371	0,276	0,09	0,81	0,89

- FINITE ELEMENT MODEL

The basic module of a 3-D woven panel (Fig. 3) composed of 3 by 3 boards is considered. Boards have a 3,5mm by 350mm cross section. Straight boards are 10.0m long and the arc shaped boards are 7.845m long. Distances between the components are 2.05m along the arc and 2.3m along the cylinder slant height.

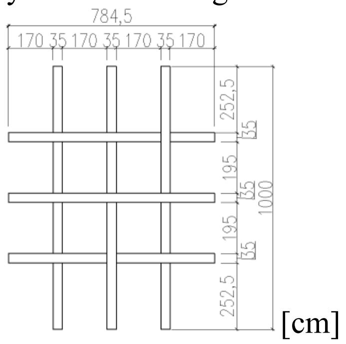

Figure 3. Dimensions of flattened basic investigated woven structure (twill weave)

The numerical model of the module was built in the FE software ABAQUS 6.11. The S4 element used for meshing is a general-purpose four-node finite elements with full integration. It provides accurate solutions in all loading conditions for shell problems. They allow transverse shear deformation and use thick shell theory as the shell thickness increases and become discrete Kirchhoff thin shell elements as the thickness decreases.
The boundary conditions shall resemble the natural behaviour of woven boards in a much bigger structure and therefore: $u_1=u_2=u_3=R_3=0$, where u_i is a displacement component and R_i is the rotation component in the local i-axis direction. The model was loaded with self-weight and pressure of $0{,}4\frac{kN}{m^2}$ (which correspond with some technical equipment attached to such structure, like lighting). The density values were taken for each case according to Table 2.

Each board in a module was modeled as a separate part in ABAQUS/CAE. Then they were assembled into one model. To simulate interlacing of boards, contact interaction should be created between them. It was defined as a small-sliding interaction between two deformable surfaces. One of them acts as a "master" surface and the other as a "slave" surface. A kinematic constraint does not allow the slave surface nodes to penetrate the master surface [6]. Because there is an initial gap between the straight boards interlacing the arc shaped one, the suitable measures for reducing it were undertaken. In the sequence of procedures a separate analysis step was introduced where a small displacement (slightly greater than the gap) was applied. For the contact pressure definition, ‘hard contact’ was chosen. Penalty contact algorithm was assumed for tangential behavior. As the friction coefficient for wood varies between 0,25 and 0,5 mean value of 0,375 was chosen for the analysis [3]. In the model each interaction is defined separately. Only after defining the contact between "master" and "slave" surface the boards interlace themselves. In the figure 4 the model has introduced four interactions in the numbered positions from 1 to 4. It can be observed that interlacing occurs in the numbered positions.

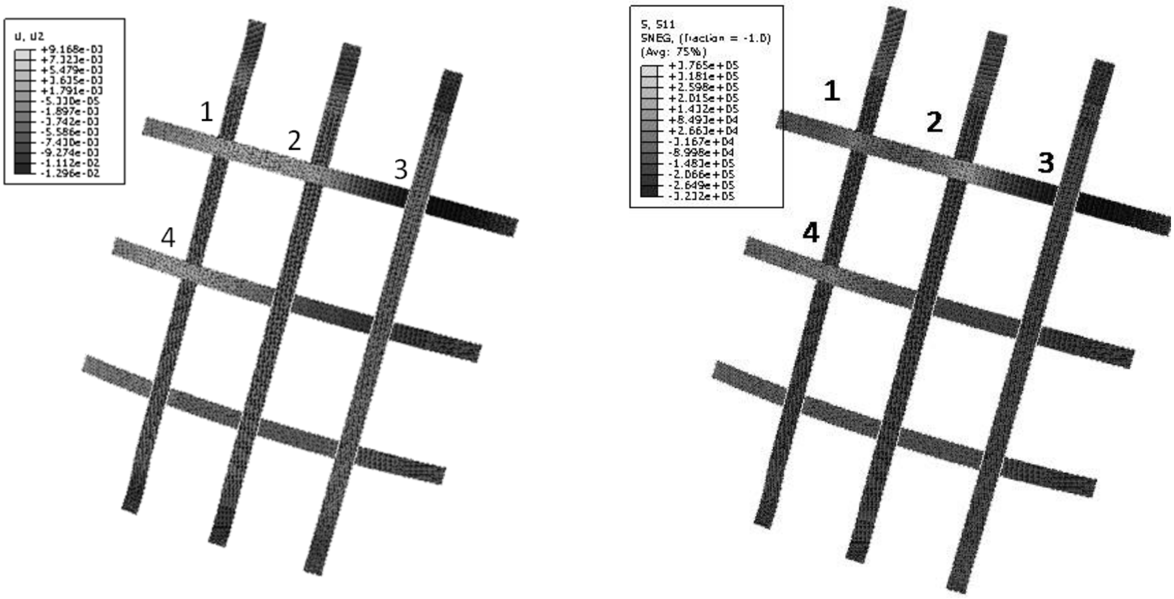

Figure 4. Deflection and S11 stress in a model with four interactions introduced.

The research shows the possibility to explore new kinds of timber structures based on weaving, which provide qualities of construction that only textiles can offer like being flexible, semi-transparent and after all interesting from the structural point of view.

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Streszczenie: *Numeryczne modelowanie trójwymiarowych struktur plecionych z drewna.* W artykule przedstawiono sposób modelowania trójwymiarowych struktur plecionych z drewna. Na podstawie analiz przeprowadzonych na płaskich strukturach wybrano materiał, rodzaj elementu skończonego i rodzaj splecenia. Opracowano model numeryczny w programie ABAQUS 6.11 struktury trójwymiarowej o kształcie półwalca i pokazano symulację pracy modelu pod działaniem odpowiednich obciążeń i podczas zadawania interakcji w poszczególnych obszarach.

Corresponding authors:

Iwona Duszyk,
Zespół Konstrukcji Drewnianych,
Wydział Inżynierii Lądowej,
ul. Armii Ludowej 16,
00-637 Warszawa