Method of form-finding and mechanical analysis of woven timber structures: A geometrical-numerical-computer aided approach

Yves WEINAND

Laboratory for timber construction, IBOIS, ENAC, EPFL

Station 18, CH-1015 Lausanne, Switzerland

email: yves.weinand@epfl.ch

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1 Résumé

1.1 Introduction

This new concept structures originate from a macro-scale analogy between Fabric production techniques and lightweight architecture using Timber panels. The common denominator of different interlacing techniques is indeed a knot. The key to the approach is to give a particular interpretation of a knot by replacing yarns with thin timber panels and reproduce the overlap. While yarns are uni-directional slender elements with no bending resistance, using surfaces instead of yarns, add an extra dimension to the problem and introduce torsion and bending degrees of freedom which makes knot's form-finding a rather mechanical problem. The rectangular cross section (comparing to cylindrical cross section of threads) changes the three-dimensional closure between interlaced elements in space and collision detection/handeling becomes a key feature of this form-finding process. The collision has also a stabilizing effect which exploit active bending: interlacing cause panels deform and once inter-connected at ends, initial elastic curvature of panels reinforces the structure.

The importance of the mechanical form-finding is also justified by design requirements to know the initial state of the structure before applying external loads.

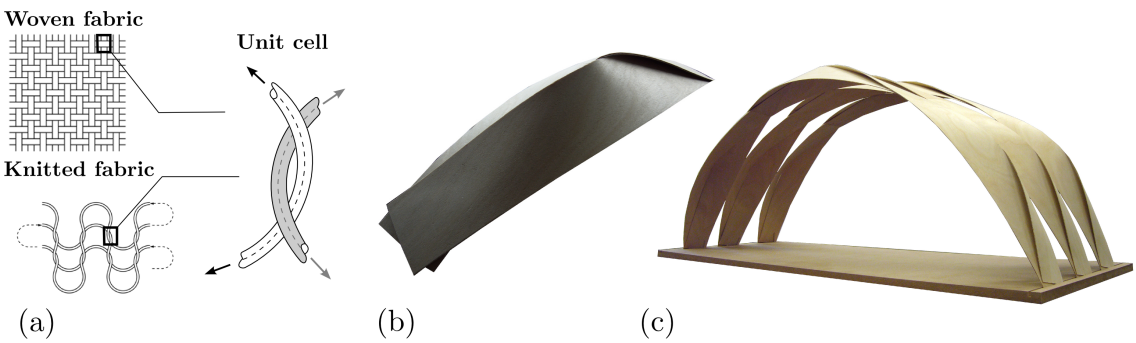

FIG. 1 The knot interpreted with timber thin panels (a) Common denominator of textile fabric (b) Knot interpreted using panels results in Timber Fabric Module (c) Timber Fabric Arch: a two strand braid interpreted with panels

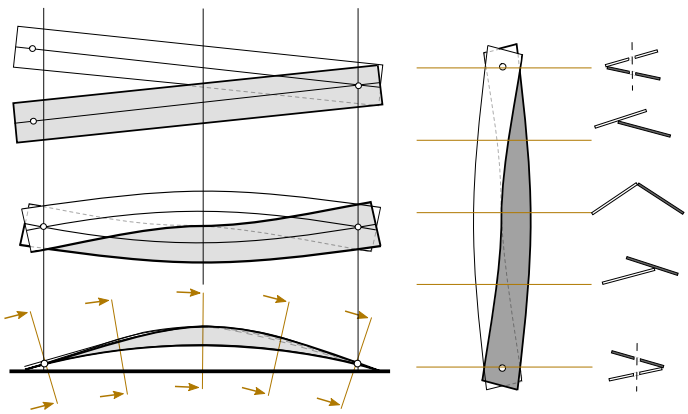

FIG. 2 Fabrication sequence and top/bottom relation of cross sections for Timber Fabric Module

Generalization of the weaving concept is straightforward. More complex knots can be formed and nodes using more than two threads can be re-interpreted with panels. (see Fig 3) In order to fully explore the field of possible forms, a compact and pertinent mechanical model should be adopted to represent panels.

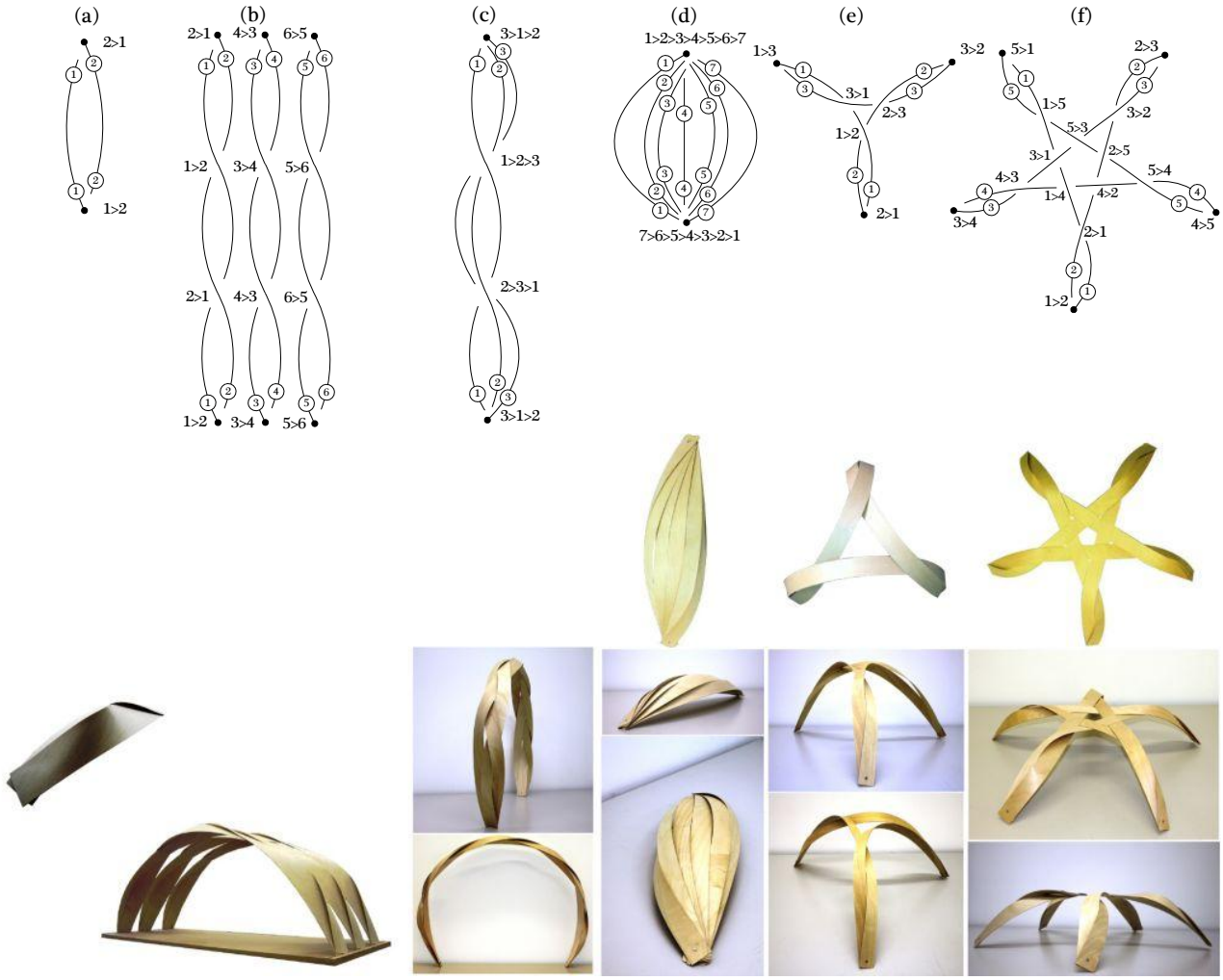

FIG. 3 2D representation of woven structures: (a) A simple two-strand knot (b) Two strand braid: Three braids put side by side (c) Three strand braid (d) Multi-strand superposition at end nodes (e) three strand fan (f) five strand fan

1.2 Methodology

The form-finding problem for a woven fabric can be split into four steps. The idea is to start form a flat configuration of panels derived from the desired weaving pattern. The boundary conditions are then imposed to this initial configuration. Boundary conditions can be the superposition order of panels in a given location as well as an explicit imposition of a given degree of freedom of a panels at a position.

Step (i) Flat elementary configuration definition: An initial flat configuration of plane curves at t=0 is defined as $\{\gamma_0^{(i)}\}$, each representing the centerline of a solid $\Omega_0^{(i)}$ at stress-free initial condition. The intersection of these curves in horizontal plan with each other defines a set containing a finite number of nodes, $\mathbf{n}_\alpha^{(j)}$, called as S_{int}, and their end curve counterparts collected in S_{ext}. The centerline curves are considered to be continuous over the $\mathbf{n}_\alpha^{(j)} \in S_{int}$. The cross section of each solid is noted as $\Gamma_0^{(k)}$.

the material properties describing the mechanical behavior are also assigned in this step. (see Fig 4)

Step (ii) Interaction definition: The desired mutual order of members at each node $\mathbf{n}_\alpha^{(i)}$ is defined by user according to the weaving pattern and $\forall \mathbf{n}_\alpha^{(j)} \in S_{ext}$ the overall boundary condition is further set.

The normal/frictional contact behavior is defined here as well as contact detection tolerances/features, depending on the collision correction method employed.

Step (iii)Imposing the boundary condition: The mutual displacement orders are imposed according to (ii) on the invol-

ving nodes and is verified at each iteration to be satisfied. the so-called overall boundary condition is also applied to support node. In this new configuration the structure is not in its static equilibrium state anymore and extra elastic energy is induced in elements due to imposed displacements and interactions, while they were initially at stress-free state.

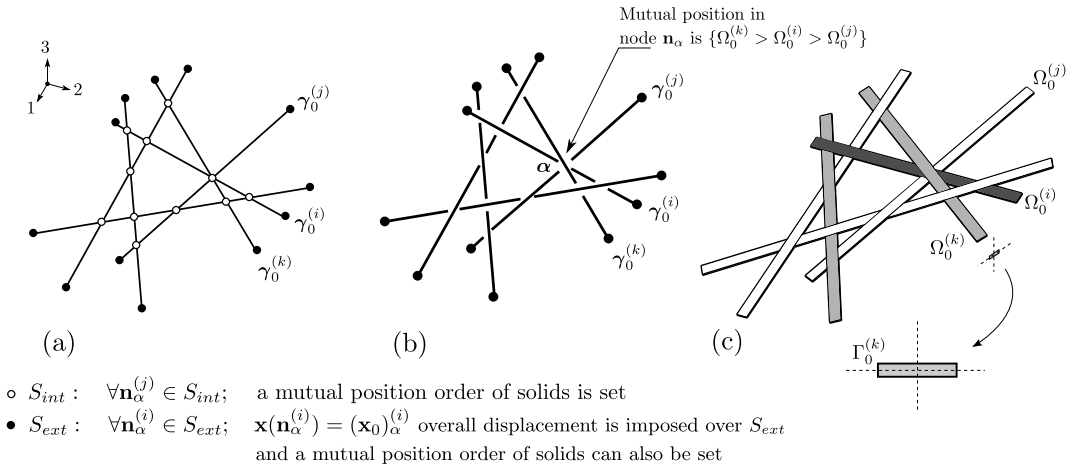

FIG. 4 Flat Elementary configuration of woven structures involving thin panels: (a) Definition of Support nodes as the set S_{int} and intersection nodes as the set S_{ext} (b) Interlacing order for superposing nodes in set S_{int} is defined (c) Solids at t=0

Step (iv)Relaxation: During this step, the position of each centerline curve $\boldsymbol{\gamma}_t^{(i)}$, of solid $\Omega^{(i)}$ is updated to a next time step until the constrained equilibrium state has been reached.

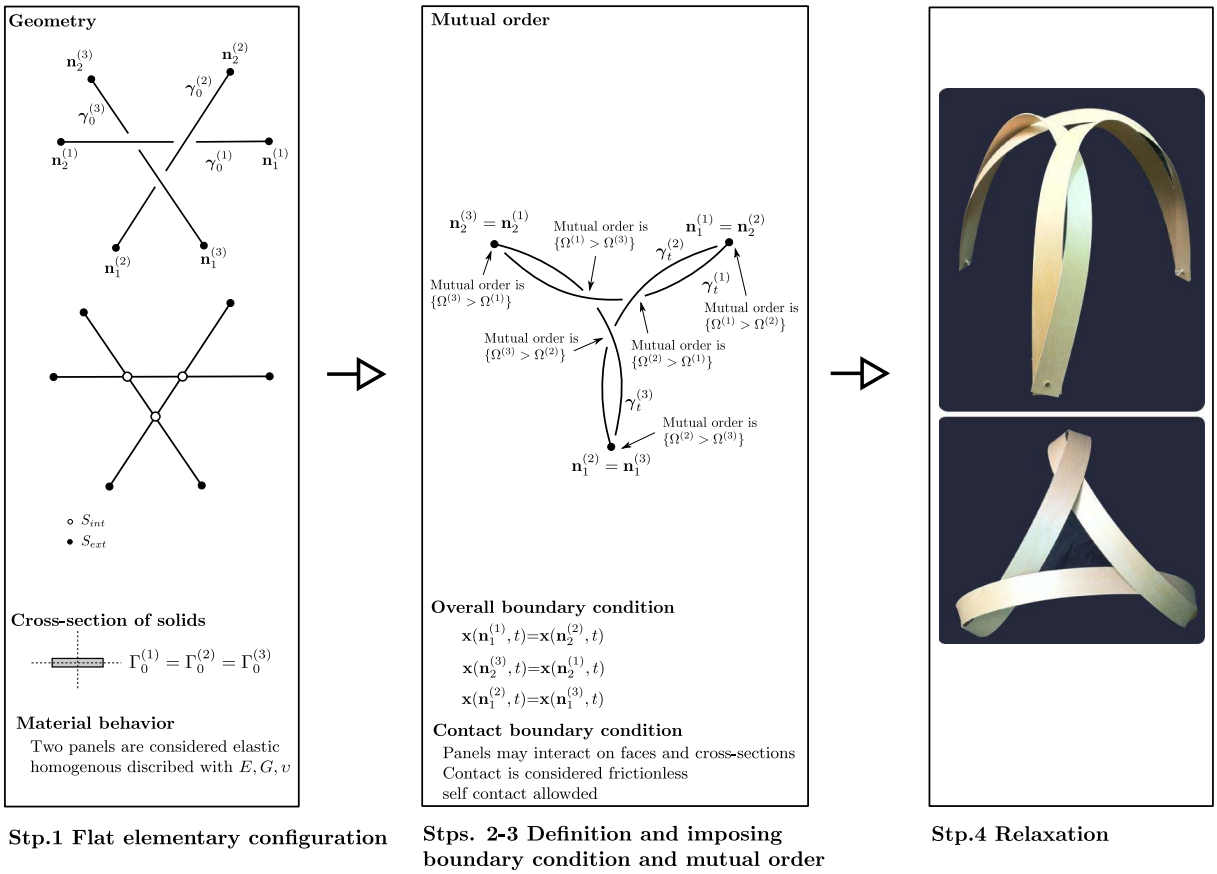

FIG. 5 Methodology illustration: From-finding a three pile woven arch

Here are two examples of simulations realized with the Explicit FEM.

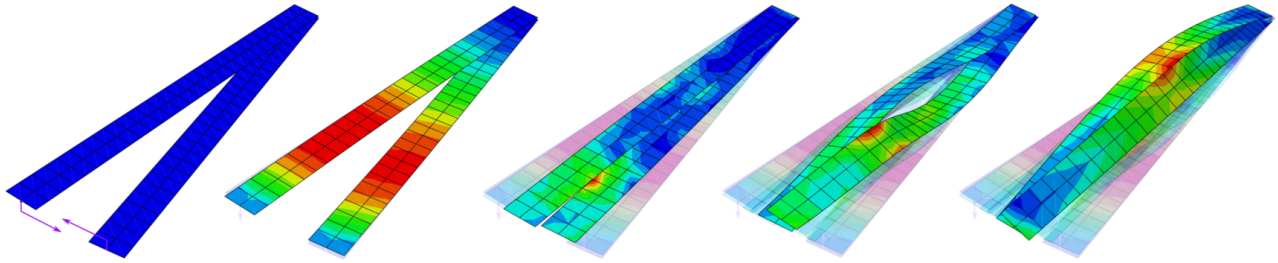

FIG. 6 Form-finding sequence for Timber Fabric Module using FEM

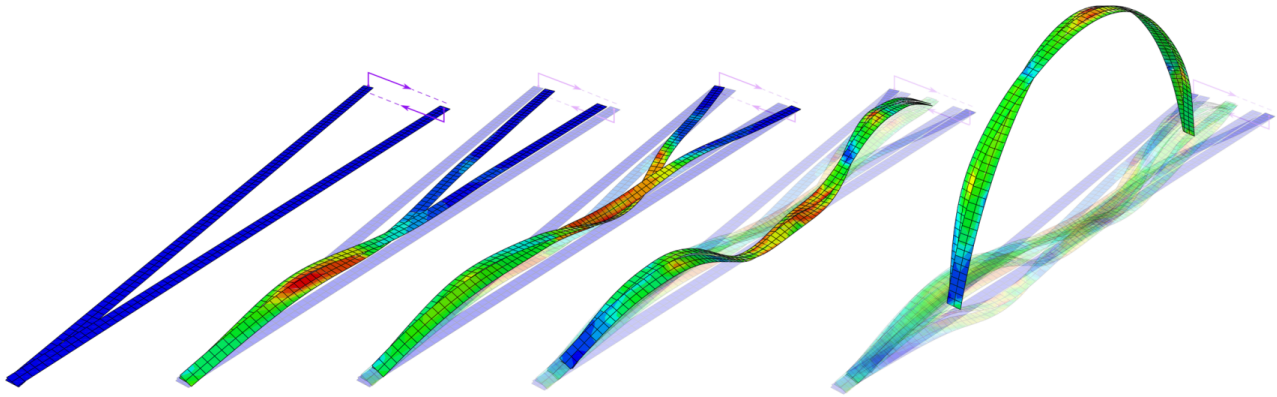

FIG. 7 Form-finding sequence for braided arch using FEM

2 Results and projected publications

Two publication project are under the process of internal reviewing for submission to relevant scientific journals. Corresponding abstracts are narrated herein.

2.1 Dynamic relaxation method revisited as a viscous fictitious material model

A modified Dynamic Relaxation method is proposed combining linear elastic material behavior and the fictitious damping effect, into a fictitious viscous material model. The procedure is mainly used to find the numerical solution of a geometrically non-linear shell problem via a pseudo-transient dynamic analysis with the Explicit finite element method. It can be shown that under the assumption of a stiffness proportional damping matrix, the critical damping coefficient is related to the minimum stable time-step of the problem. This is particularly useful in case of an existing Explicit FEM framework, where in most of the case a time-step estimation algorithm is already implemented. The approach has been implemented as an ABAQUS/Explicit user subroutine VUMAT and the overall accuracy of the numerical results has been studied for a number of geometrically non-linear shell benchmark problems.

2.2 Form-finding of a Timber Fabric Module using the dynamic relaxation method

Timber Fabric structures initiate from a correspondance between textile principles and recent industrial developments in producing cross-laminated timber panels. several individual slender-thin panels are interlaced according to a pattern and result in an innovative space structure. The obtained three-dimensional geometry can be regarded as the relaxed

configuration of panels under the imposed boundary conditions, which can be reproduced as the steady state of a pseudo-transient dynamic procedure. The assembly process for a Timber Fabric module is simulated using the a modified dynamic relaxation method and the geometry of the mid-surface of panels are extracted. These surfaces are compared with a 3D processed surface-mesh obtained from scanning a built-in prototype with non-contact Laser scanner arm. Mesh parametrization techniques are used to map both surfaces on the same 2D domain and their discrete curvature properties are compared and commented and show a satisfactory commitment.

3 Collaboration and News

A collaboration has been approached with Dr. Basile Audoly, Associate professor in the UPMC Paris VI university, with the objective of applying rod simulation techniques inspired from discrete differential geometry into our particular case of panel simulation.

An exchange visit is also planned to happen with the Columbia Computer Graphics Group at the Computer Science department of the Columbia University in the city of New York. PhD candidate Seyed Sina Nabaei has been invited to visit Dr. Eitan Grinspun's lab during Feb-March 2013 with the main goal of introduction to the discrete shell simulation technique developed at Columbia.