Abstract

How about fastening a knot? not with ropes... but with timber panels. Timber Fabric Structures (TFS) originate from such an inspiration. An architectural reinterpretation of fabric techniques (mainly braiding) using building scale timber panels to design lightweight timber spatial structures. TFS design raises challenges on both geometrical and structural facets: we would like to predict their relaxed deformed shape based on design pattern, but also the stress state introduced through the assembly, in order to be able to size panels and connections. The three-dimensional geometry of TFS is behavior-based: it is the equilibrium state of its flexible structural components actively curved under the overlap order constraints. Panels bend, twist and buckle to meet the interlacing pattern and in braided configurations contact might also occur between panels over the cross section and/or faces. Our form-finding tool is expected to meet three requirements: (a) come with an interpretation for interlacing as coupling constraints to be applied on flexible bodies which represent panels (b) implement a flexible body kinematics which enhances twist degrees of freedom and (c) take into account the panel intersection detection and handling.

We cross two avenues toward structural form-finding of TFS. We first investigate use of FEM techniques, suitable to handle finite rotation regime and complex contacts occurring while interlacing panels. We demonstrate the possibility, yet complexity, of reproducing the geometry of panel interlaced structures using a pseudo-dynamic framework with nonlinear shell Finite Elements. Such expensive bespoke simulation, yet precise, limits generative exploration of TFS morphology, while besides it would be necessary to know the exact interlacing sequence in order to reproduce it. In search for form-exploration freedom, in the second avenue we inspire from physically-based modeling in Computer Graphics for our structural form-finding purpose. We are interested in physics-based models to simulate flexible thin panels in order to propose an approximative but efficient simulation alternative to FEM. The current physics-based frameworks used in architectural form-finding are mostly particle-based modeling engines which can hardly manipulate twisted flexible objects, neither correctly reproduce out-of plane bending behavior of thin shell bodies. Two flexible body models derived from Discrete Differential Geometry, are extended and employed in our study: a discrete Kirchhoff rod model based on a curve-angle kinematic with twist and bending degrees of freedom and a discrete elastic shell model for deformable triangular mesh surface manipulation with membrane and flexural energies. We exploit the rod model in a nonlinear static framework in order to virtually buckle, twist and interlace an initially flat set of panels of given length and span. The deformed configuration result of the static simulation is not however always intersection free, depending on design parameter inputs. The intersection resolving is performed in a dynamic framework with panels now simulated as thin shells and with the help of a surface intersection contour minimization algorithm for mesh surfaces.

In terms of contributions, (a) we propose a formulation for Adaptive Dynamic Relaxation method as a fictitious viscous elastic material model for pseudo-transient dynamic simulation of thin shells and use it to reproduce the deformed geometry of some TFS (b) we reformulate the inextensible discrete Kirchhoff rod model to use in a static framework by solving a constrained optimization problem with interlacing pattern overlaps formulated as proximity and alignment constraints (c) we revisit the discrete elastic shell model with an insight on the thin shell continuum mechanics, give the correspondence between kinematics in both theories and propose to extend the physics-based model with second-order energy terms, we use it to design actively bent timber load-bearing concept modules (d) we concert the static rod and dynamic shell engines with intersection handling feature as a physics-based simulation pipeline for TFS and demonstrate some concept structures to highlight the design potential of twisting and interlacing as form-giving forces. Our core contribution remains to bring and extend efficient physics-based flexible body models with rich kinematics for structural form-finding of actively bent structures into the architectural geometry context. Both rod and shell solvers are implemented as components for Grasshopper®, the popular graphical algorithm editor used for generative architectural 3D modeling.

Keywords: Timber fabric structures, elastic rods, thin shells, nonlinear, physics-based simulation, Finite Element Analysis, Dynamic Relaxation method