COMPUTER DESIGN AND DIGITAL MANUFACTURING OF FOLDED ARCHITECTURAL STRUCTURES COMPOSED OF WOOD PANELS

Testing and validation of the proposed digital approach

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Abstract. The research presented in this paper revolves around the experimental development of the morpho-structural potential of folded architectural structures made of wood. The aims are to develop an innovative system for timber used in sustainable construction and to increase the inventory of wood architectural tectonics. Laminated timber panels associated with "digital production line" approach have opened up new perspectives for the building industry in creating prefabricated wooden structures. This article provides a characterization of the digital chain associated to the development of non-standard folded structures which consist of wood panels by way of a full-scale experimental pavilion. The purpose is the study of architectural design process from parametric modeling (through CNC machining) and assembly operations to production. Towards the completion of the pavilion, a number of analytical experiments have been performed.

Keywords. Architecture; folded structure; robotic fabrication; computational design; parametric modeling; wood panels.

1. Introduction

The term “fold” as used in the field of architecture shows a shift in the designs and vocabularies of contemporary forms. For example, Peter Eisenman has used, for the Rebstockpark project, the fold as a concept of changing forms continuously through time (Eisenman, 2003) or even Rem Koolhaas...
for his work on the "trajectory" where folds generate more singularities (Koolhaas, 1995). The fold is partly based on the theoretical foundations of the philosopher Gilles Deleuze, in which the traditional form and material relation as a spatial mold, has given way to "a continuous variation of matter as a continuous development of form" (Deleuze, 2003). The practices of digital technology as developed today in the field of architectural design and manufacture have instrumented the idea of an uninterrupted development of the shape. This practice has frequently spread the idea of fold to the production process. The chronological chain, from design to manufacturing, is no longer linear but becomes a series of simultaneous developments and possible variations. The emergence of new materials or new components and their relating technicalities makes possible this continuum of shape (de)formation and virtualization on a basis of potential variations of the production tools. It aims, albeit to a limited extent, to focus on the fold with respect to its morpho-geometrical dimension and its ability to respond to a fluctuation of contexts and uses. The fold brings a fresh look on the integration of the structural dimension as a modulation factor and allows adaptive modeling within the design-manufacturing continuum.

2. The fold

2.1. THE FOLD : A MORPHO-STUCTURAL SYSTEM

In architecture the fold provides many morphological but also structural possibilities. It brings rigidity and inertia required for the structural stability to architectural works adopting it. Moreover, by principle, the fold highlights an efficient relationship between the projected area and the material quantity required for the construction. The saving made on the material gives a real environmental dimension to the fold. In addition to the conceptual dimension mentioned in the introduction, the fold provides a genuine tectonics in architecture. This leads to a visual evidence superposing both the clarity of a plastic form, and veracity of a construction design (Frampton, 1995) benchmarked against the material and structural dimension of the designed shape. The characteristics of the fold define a language; a source of architectural and structural motion (Moussavi, 2009).

2.2. THE FOLDED MATERIAL

From a physical point of view, every material can theoretically be folded. But from the viscous to the rigid substance, folding can give rise to stresses specific to each matter. We can classify a fold by continuity or discontinuity of material.
• **The continuous material:** The fold is commonly associated with the deformation of a thin material surface with a small bend radius regarding the thickness of the material (metal foil, paper,...) but it can also be obtained as means of molding technologies. A bending action, which consist to roll back the material according to a determined angle, introduces internal stresses of traction/compression and causes a reduction of material thickness (Figure 1a). Mathematically, it is estimated that the tangents at a point of the surface are continuous in all directions. In that case, a minimum acceptable bend radius is defined before the material breaks; materials plastic deformation gives limits to bending radius.

• **The discontinuous material:** A fold can be accepted as a union of different surfaces. Mathematically it can be defined by the discontinuity of tangents to a point of a surface and in a given direction. The one-time change of direction in physics means an interruption of matter and thus the notion of assembly. A classification of assembly types must match the material features in order to ensure the continuity of internal forces; this method interests us regarding the use of industrial wood panels (Figure 1b).

![Figure 1. a: Continuous tangent (minimum radius of curvature) - b: Discontinuous tangent (assembly).](image)

### 3. Fold model made of wood panels

The fold is the unit element of the folding. It consists of two entities called "faces". As part of our work on folded architectural structures made of wood panels, we consider only planar faces. The combination of two faces at a common edge and to the appropriate non-zero angular value, creates geometrically a fold (Figure 2). It is characterized by the notion of amplitude (height of the fold defining its inertia) and the concept of frequency (base of the fold). The combination of several folds creates a folding.

![Figure 2. Model of fold.](image)
3.1. STUDY CORPUS

Applied initially to walls or roofs, folded structures quickly evolve towards arch, portal frame or folded shell. The first two projects present folding structures with continuous material. The UNESCO concrete building in Paris by P.L. Nervi reconnects the dialogue between form and structure. (Nervi, 1957). The architectural realization "Corogami Folding Hut" by David Penner reveals folds generated by mechanical bending action in order to obtain a sufficient rigidity (Wiebe, 2013). In the environment of wood material several experimental achievements have demonstrated the high potentials of wood assemblies to create particularly inventive architectural design. The pavilion designed by Hybrid Space Lab office in Berlin, consists of triangular plywood sheets sewn together with cable ties (Yiu, 2009). The Thannhausen Music Hall in Germany designed by architect Regina Schineis, shows regular folding ensuring a portal frame system fixed to a concrete slab (Schineis, 2003). The temporary pavilion in Osaka realized by Ryuichi Ashizawa Architects (Ashizawa, 2010) and the Chapel of St Loup in Pomparples (Localarchitecture and Mondada, 2010) attest wooden folded structures virtues by their structural and architectural qualities (Figure 3). Oriented mono-directionally folds increase the stiffness of thin surfaces. Structurally, these constructions work as a series of portal frames. The Japanese pavilion is equipped with a primary skeleton creating ridge and valley edges and covered of panels in a wind bracing way. Quite the contrary, the chapel wood panels ensure both the architectural envelope and the structural system. Folded surfaces also provide an interesting effect of lights and shadows and result in a harmonization of the architectural space.

3.2. THE FOLDING MODEL

We work on architectural typologies of continuous covering envelopes (vault) or revolving forms which interest lies in their inherent stability (dome). The shape of the envelope, as defined by architectural criteria, represents the basis of fold modeling. The use of flat panels leads the creation of break lines during the generation of the folded envelope. The support skin is discretized by the break lines in planar surfaces matching with the curvilinear morphol-
ogy of the initial envelope. The fold is then oriented in relation to the normal of the envelope surfaces; it is controlled regularly or irregularly by parameters of the frequency and amplitude. Pilot criteria based on the material, structural behavior and manufacturing techniques are associated to these parameters. The choice of material interacts with the rigidity (Young's modulus), thickness of the panels (changing the assembly type, reacting to the weight), and the dimensioning of raw panels (modifying the pattern layout and size of the panels). The structural validity is generated by an analysis software that impacts stiffness, folding inertia (controlling amplitude and frequency) and buckling stability (modifying the break lines, assembly stiffness). The manufacturing imposes geometric constraints as a result of Numerical-Control tool parameter settings, such as angular cuts and maximum panel size (weight and size management). Finally, the management of the mounting kinematic is used to verify the feasibility and accuracy of the assembly parameters from a technological point of view. The architectural validation will be established by the designer.

4. Digital fold

The current state of the digital chain as proposed in our work (figure 4) consists of a parametric design phase of morpho-structural envelopes associated to a robotics manufacturing phase. The digital design environment is composed by the modeler Rhinoceros coupled to Grasshopper (editor of graphic algorithm for parametric geometric data management) and the finite elements analysis software Cast3M for structural verification. The digital production environment is organized according to the Computer Numerical Control (CNC) machine used.

![Figure 4. This is the progress of digital chain.](image)

4.1. PARAMETRIC DESIGN

The digital continuum is ensured by the creation of clusters so as to generate different command codes (figure 5). This digital model does not define an optimal solution but is sufficient. Those parameters allow the architectural folded shapes to match as much as possible the satisfactory structural features, without deviating from the morphology of the initial envelope.
Figure 5. Digital device of design.

- **Shape Parameters**: The envelope support is defined by a Nurbs typed curvilinear surface. It can be built with the Grasshopper environment as a parametric envelope or imported from another software. These envelopes are characterized by two directions. The first enables a discretization of the initial envelope into a number of configurable break lines, and the second corresponds to the folding orientation. The folding algorithm determines a regular or an irregular grid. The algorithm, can manage the folds amplitude by using the normal vector of the faces alternated positively or negatively. The frequency and amplitude parameters are managed by a table of values. The creation of the fold generates two panels of 4 non-coplanar edges; a VBnet script allows the determination of surface flatness with a variable degree of precision. The structure thus adapts to the deformation capacity of the material which requires prestressed panels for mounting.

- **Assembly parameters**: This concerns the structural manufacturing and assembling aspects. In the application of wood structures, each panel has to be assembled. The assembly is defined by the number of degrees of freedom (lineal pivot), as well as by a specific technology (dovetail joints). The choice of the number of degrees of freedom for stability verification is imposed on us. The technological part of the assembly leads to a specific production level and assembly kinetics. Currently, kinetics of assembly in the digital continuum is not taken into account. Setting the thickness of the surface model reveals a geometric complication which leads to, in most cases, a duplication of nodes. This problem can be tackled by a local construction feature (obviously by connectors…). Nevertheless, this kind of intervention remains manual thus calling for further reflection on the design.

- **Structural analysis parameters**: The introduction of a structural evaluator using the method of shell type finite elements (Cast3M) enables the validation of stability of the structure and its dimensioning. The meshing (discretized geometry), the materials and the limited kinematic (supports) and static (loads) conditions are commanded by specific clusters (Grasshopper). The
structural fold gives inertia to the envelope, brings stiffness to big surfaces with a minimum of material, and stabilizes the structure through three-dimensional combinations. These three mechanic principles of the fold are considered to be the evaluation criteria for structural envelopes. Regardless, the structural analysis has not yet led to automatic modifications effected on the envelope morphology, thus data has to be treated manually as a means to interact with the different parameters set out in the morphological modeler.

4.2. DIGITAL MANUFACTURING

The implementation of machining and material parameters during the design phase enables the anticipation of the whole manufacturing process. The machining methodology depends directly on the characteristics of the tools used (admissible size of raw wood panels, characteristics of cutting tools, methodology of clamping system, …) and of the material (nature of the material, …). These characteristics make it possible to define the pattern layout of different elements comprising the folded structures. This layout takes into consideration the management of wood grain and off-cuts to achieve structural optimization. The model integrates an algorithm that numbers the pieces and examines the different elements from all angles by a grid pattern defined on a two-dimensional plan. At this stage, the numeric command necessitates the writing of the command line to enable the generation of tool paths in order to cut pieces according to the pattern layout made beforehand.

5. Experimental fold

The purpose of this experiment is to validate the accuracy and correctness of parameters implemented in the design phase. The pavilion takes place against the backdrop of a student exhibition, “Wood Challenges”, where the inventive capacities of wood to tackle architectural, technical, economic and environmental issues of today and tomorrow are demonstrated (figure 6).

5.1. PROPOSAL

The revolving form as envelope support was modeled according to architectural criteria. The envelope support was folded according to the morphological criteria as required by the designer and coupled to the parameters of the material (laminated wood panels 10500mm x1800mm x 40mm), those of the 5 axes Woodflex gantry robot and parameters set out from the structural analysis. Dovetail connect system was chosen for the folding edges processing and tongue-and-groove assembly was adopted for panel joining along the break lines. To increase the stability of the pavilion, a compression
ring was added. But after structural analysis, the compression ring proved to be useless. The digital manufacturing requires several data transfer formats (figure 6), a STEP standard was used in order to achieve the data transfer from Grasshopper to Lignocam; a BTL standard, provided by Lignocam, is particularly interesting since it takes into account the specifics of wooden process; for example, a half lap on a piece extremity cannot be machined in the same way as a longitudinal process. Finally the trajectories generated by Lignocam are transferred to Woodlex gantry thanks to L1E and ABB Robotstudio. The different data exchange formats (STEP, BTL, ISO and RAPID) evidence a risk of breakdown in the continuity of the digital chain. The production process included the cutting and machining of 57 wood pieces.

5.2. CHARACTERISTICS OF ASSEMBLIES

Each assembly is defined by a technological family (dovetail, tongue and groove, ...). A parametric and geometrical definition of assemblies in Grasshopper software allows the manufacturing of these assemblies (Figure 7). The assembly is modeled by its connection type (linear pivot) in a finite elements shell type software (CAST3M). Each assembly is represented by a coupling of different degrees of freedom (3 translations and 3 rotations) and is defined by the stiffness corresponding to the joint slip (1 joint slip per degree of freedom). This coupling is implemented in the finite element analysis software by a stiffness behavior associated to its technological landmark.

Figure 6. Digital device of manufacturing and Assembled structure.

Figure 7. Modelling of tongue and groove assemblies.
5.3. MORPHOLOGICAL AND STRUCTURAL VALIDATION

The morphological analysis required lasergrammetry of machined wood panels, as well as for the complete structure. These analyses validated the protocol of machining operation (precision of robot movements and positioning of the tool holder), the assembling methodology and the morphostructural impact of dimensional deviations on each assembled element (average precision 1/1000, figure 8a). The results reflect incomplete captured image, manual cleaning of specks and spots, scanner precision and hygrometrical behavior of the material used. By examining the tolerances in traditional wood construction, we find this to be an exceptionally low value. This precision fulfills the necessary and sufficient conditions for the machining precision process to be validated and the assembly protocol confirmed.

The structural verification allows, by backward reasoning, the validation of the analysis hypotheses implemented in the Cast3M software. The set up parameters concern the elastic properties of the material (Young’s modulus for dry wood) and the stiffness of the assemblies. These define a relaxation of the degrees of freedom, as well as the internal joint slip of the assemblies (relative movements between two assembled pieces). To confirm the correctness of the parameters, we compared the overall digital behavior of the structure with the results of the experiment. The elastic behavior obtained during the loading phase corresponds to a structural accommodation cycle. Analysis and experimentation thus rest on the stiffness obtained during unloading, which becomes purely elastic (figure 8b). Against the data obtained from the calculation software, the digital model of a perfect assembly is ten times superior to the experimental value found. It is therefore necessary to take assembly shifting into account. It can be stated that the assemblies correspond to a lineal pivot coupled to stiffness (Bléron, 2001). Important work on assemblies still needs to be done. By playing with different assembly typologies and technologies (connectors, gluing, etc.), the stability of structures can be increased.

Figure 8. a: Morphological difference analysis. b: Experimental stiffness graph.
6. Conclusion

In our work, we tried to outline a first numeric controlled design tool where the folded structures under study are considered to be architectural "objectiles" (Cache, 2003). Technical variables (structural analysis, manufacturing and erecting) integrate the architectural design genesis. Nevertheless, the numeric continuum is incomplete. Several actions require a manual intervention, notably in the return of results of the structural analysis, data management of the tool management and the installation phase. The experiment, as conducted, allows us to validate our digital design tool and digital manufacture of folded structures made of solid wood panels. This pushes us to further pursue our work in the automatization of geometric correctors and optimization of the digital chain. Our morphological study on the theme of fold, and its derivative towards folding, is presented as a possible solution to an architectural production assisted by digital technology, as Lynn (1995) or even Cache has conceived. The interest of the dynamic flow of morphological genesis with literally complex structures does not lie in the shape obtained, but in the technological process itself (Gramazio, 2008). This digital approach leading to new practices requires special training in order not to lose the scope of skills acquired previously.

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