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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. We study the architectural design process from parametric modelling, through CNC machining and assembly operations to production. We explore the relationship between the design of a 3D digital model, building of an experimental pavilion by simulation and the manufacturing processes. 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 the "digital production line" approach have opened up new perspectives for the building industry in creating prefabricated wooden structures. In this article, we offer to characterize the digital chain congenial to the development of non-standard folded structures which consist of wood panels by way of a full-scale application case study. We present a digital model which describes and creates a structural and architectural folded shape by configuring the different database parameters. This model can be used as a gateway between architectural and engineering disciplines.*

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

1. Introduction

The term "fold" as used in the field of architecture (Zaha Hadid, Rem Koolhaas, Daniel Libeskind, GregLynn...) shows a shift in the designs and vocabularies of contemporary forms. It is partly based on the theoretical foundations of the philosopher Gilles Deleuze, where 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 designed architectural object, takes place in an evolutionary continuum where the parameter variation replaces the constant laws. The "event object" with vast potentials and modulation possibilities is replacing the traditional "fixed monument object". Hence forth, the fold is becoming a conceptual tool to address the realm of contexts and perspectives in architecture.

The practices of digital technology as developed today in the field of architectural design and manufacture have instrumented the idea of a continuous development of the shape. This practice has even 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. Folding, the philosophical concept operating as architectural concept becomes a productive concept which can be explored. The emergence of new materials or new components and their relating technicalities makes possible this continuum of shape (de)formation and virtualization on the basis of potential variabilities of the production tools.

It is under such broad terms of changing practices and evolution of architectural and production concepts that we have developed our work. It aims to, albeit to a limited extent, focus on the fold with respect to its morpho-geometrical dimension and its ability to respond to a fluctuation of contexts and uses. We want to bring a fresh look on the integration of the structural dimension as a modulation factor. We also address the fold in its digital dimension via a parametric approach allowing adaptative modeling within the design-manufacturing continuum. Finally, we report on an experiment leading to the production of a folded structural envelope made of laminated wood panels.

2. The fold

2.1. THE FOLD : A MORPHO-STUCTURAL SYSTEM

In nature the fold can adapt to local stresses and external forces which will lead to a deformation of the material. The fold can suffer a deformation as in the case of geological folds characterized by orogenesis. In architecture the fold provides many morphological but also structural possibilities. It brings good stiffness 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 openness 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 material, folding can give rise to stresses specific to each material.

- **Fold obtained by molding:** Viscous materials such as concrete, pose the problem of molding. On the one hand, the mold defines a surface condition and on the other hand, the form is subject to the technical characteristics of mold release (molding undercuts, molding voids, ...).
- **Fold obtained by material deformation:** The fold is commonly associated with the deformation of a thin material surface with a small bend radius in relation to the thickness of the material (metal foil, paper, fabrics ...). The fold can be the result of an action such as folding or creasing. It is estimated that the tangents at a point of the surface are continuous in all directions. In that case, we can define a minimum acceptable bend radius before the material breaks. However, the disadvantage of this technique lies in its inability to produce big structures.
- **Fold obtained by assembly:** 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 be appropriate to the material used. This third method interests us with respect to the use of industrial wood panels.

3. Fold model made of wood panels

Our research turns to the use of flat industrial panels for the development of folded wood structures. Currently, an insufficient mastery of the physical wood behavior laws to make panels deformable has not yet allowed an easy use of the material. Hence, we orientate our work towards a technology of assembled folds.

3.1. STUDY CORPUS

Two highly experimental achievements have demonstrated the high potentials of wood to create particularly inventive architectural design: the temporary pavilion in Osaka realized by the architectural firm RAA Ryuichi Ashizawa Architects (Ashizawa, 2010) and the Chapel of St Loup in Pompaples (Figure 1). Indeed, a series of folds, oriented mono-directionally, will considerably rigidify a thin surface. The scope is thus enlarged and the material is saved. Structurally, these constructions function as a series of portal frames. The Japanese pavilion is equipped with a primary skeleton creating peaks, ridges and valleys. The introduction of panels by triangulation serves as wind bracing for the various portal frames. The chapel in turn frees itself from a primary structure. Prefabricated 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. It appears that each pleated construction finds its balance between shape parameters and structure.

Figure 1. The Chapel of St Loup (left) and The Temporary Pavilion (right).

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 modelling. The use of flat panels leads the creation of break lines during the generation of the folded envelope. These break lines discretize the support skin in planar surfaces matching with the curvilinear morphology of initial envelope. The fold is then oriented in relation to the normal of the envelope surfaces. It is controlled regularly or irregularly by the frequency and amplitude parameters. 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 nature, 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 stability (modifying the break lines, assembly stiffness). The manufacturing imposes geometric constraints as a result of Numerical-Control tool parameter setting, such as angular cuts and maximum panel size (weight and size management). Finally, it makes sense to set up a management system monitoring the kinematic impact to verify the feasibility and accuracy of the assembly parameters. 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 2) consists of a parametric design phase of morpho-structural envelopes associated to a robotics manufacturing phase.

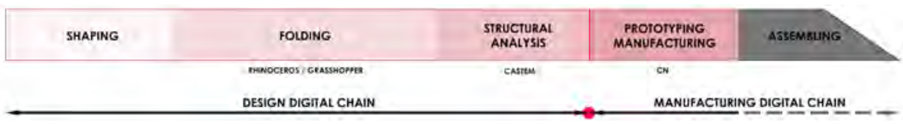

Figure 2. This is the progress of digital chain.

The digital design environment is composed of 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.

5.1. PARAMETRIC DESIGN

The digital continuum is ensured by the creation of clusters so as to generate different command codes (figure 3). This digital model does not define an optimal solution but is sufficient. Parameters allowing architectural folded shapes to match as much as possible the satisfactory structural features, without deviating from the morphology of the initial envelope.

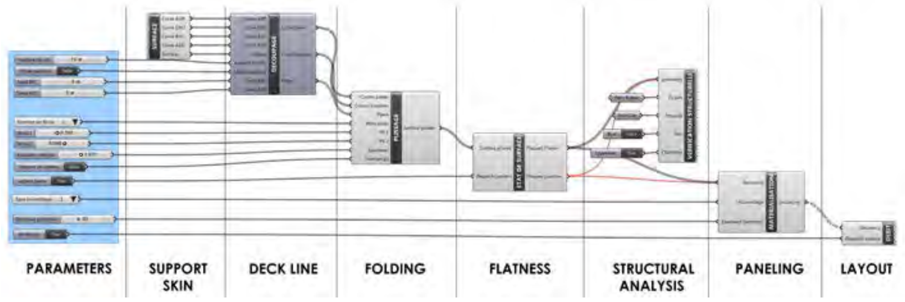

Figure 3. Digital device of design.

- **Shape Parameters :** The envelope support is defined by a Nurbs typed curvilinear surface. It can be built in the Grasshopper environment as a parametric envelope or imported by another software. These envelopes are characterized by two directions. The first enables a discretization of the initial envelope in configurable breaklines number, and the second corresponds to the folding orientation. The folding algorithm determines a regular or an irregular grid. From the normal of the faces created by the grid, alternated positively or negatively, the algorithm of the fold can manage the amplitude. 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. VBnet script programming allows the determination of surface flatness with a variable degree of precision. The structure thus adapts to the deformation capacity of the material.
- **Assembly parameters:** On the one hand, they concern the structural aspect and on the other hand the manufacturing and assembling aspect. 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 (mortise and tenon 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 mechanics principles of the fold are considered to be the evaluation criteria for structural envelopes. Nevertheless, the structural analysis has not yet led to automatic modifications effected on the envelope morphology. The data are to be interpreted manually which act on the different parameters set out in the morphological modeler.

4.3. DIGITAL MANUFACTURING

The implementation of machining and materials 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 (size of admissible panels, maximal value of angular cutting, characteristics of cutting tools, methodology of clamping system…) and of the material (nature of the material, initial size of raw particle boards, …). 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 chips and wood grains to achieve structural optimization. To do this, the model integrates an algorithm which 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 of parameters implemented in the design phase and also the correctness of the implementation. The experiment 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. The created folded structure serves as the " welcome pavilion” of the exhibition (figure 4b).

5.1. PROPOSAL

The revolving form as envelope support was modeled according to architectural criteria. These criteria were defined by the location and the specifications suitable for the exhibition. 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) and those of the CNC machine tool (5 axes CNC Güdel machine, figure 4a) put at our disposal as well as parameters set out from the structural analysis. A finger, joint connect system, for wood was chosen for the folding edges processing, a tongue-and-groove system adopted for the purpose of joining the panels along the break lines.

To increase the stability of the pavilion, a compression ring was added. Drilling an oculus in the center brings light inside and increases the lightness of the panel. This type of piece is modeled by hand within the design environment. The digital manufacturing environment put at our disposal required three changes in file formats to ensure a data continuity between the design and the production processes. The different data exchange formats (.STEP; .BTL; .ISO) all pose risks of breakdown in the continuity of the digital chain. The production process encompassed the cutting and machining of 57 wood pieces. A pre-assembly at the workshop allowed the validation of installation kinematics and the play during assemblies.

Figure 4. a: Digital device of manufacturing. b: Assembled structure.

5.2. MORPHOLOGICAL AND STRUCTURAL VALIDATION

The morphological analysis is done in two steps. Firstly, the morphological analysis is to validate the lasergrammetry of the work piece after machining giving us information about the dimensional error in percentage between the numerically modeled piece, and the processing panel piece (5%) (figure 5a). This error is due to a lack of precision in the robot's movements and also the positioning of the tool holder. Secondly, the analysis is to validate the assembling methodology with the complete use of lasergrammetry for structure assembly, so as to analyze the morpho-structural impact of dimensional deviations on each assembled element (average precision 1/1000). These errors are a result of incomplete imaging linked to the scanner, manual cleaning of specks and spots, scanner precision and hygrometrical behavior of the material used. On examining the tolerances in traditional wood construction, we find this to be an exceptionally low value. This precision fulfills the required condition and sufficient such that the machining precision can 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 5b). 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 the different assembly typologies and technologies (connectors, gluing, etc.), the stability of structures can be increased.

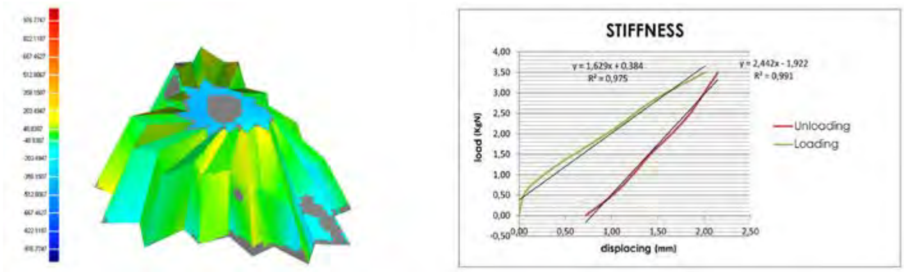

Figure 5. a: Morphological difference analysis. b: Experimental stiffness graph.

5. 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 tooling 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.

6. Acknowledgements

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