THE FOLD, A TOOL OF DESIGN ARCHITECTURAL STRUCTURES: Development of a structural and formal language in wood material

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ABSTRACT
This paper deals with a research in the field of folded architectural structures. We specifically discuss the technical components of CLT (Cross Laminated Timber) panels. We suggest a digital environment which allows a pleated structure to be adjusted to an architectural form drawn by the designer, while corroborating stability and joining. Consisting of a geometric parametric modeler coupled with structural analysis software, it guides the architect designer in the research of folded forms, improves the reliability of structural proposals and provides digital files for automated manufactured panels.

Keywords: Architecture, Pleated structure, CLT (Cross Laminated Timber), Parametric modeling.

1. INTRODUCTION

Today, the wide use of the term "origami" in numerous architectural projects expresses a movement in the vocabulary of contemporary shapes towards the research of a new architectural style, indicating a new interest in the concept of folding. Nonetheless, the origami reflects a wide understanding of this concept which has eventually forgotten its roots.

This notion of fold covers both geometrical and structural aspects. It is not new as it appears in the history of art and architecture as well. In the 20's, Joseph Albers gave to regular figures (i.e. the square) a central place in the applied arts and opened up ways for composition based on geometric rules. Later, the work of DG Emmerich on morphogenesis [1], particularly exposed in his geometry lessons, will generate the idea of structural morphology. Geometry and structure are merged together in a new language of material.

The twentieth century's architecture also provides interesting examples of architectural achievements. These examples use the geometry, including pleat geometry, of their structure as a vocabulary. We will refer now to Walter Netsch's work for the United States Air Force Academy Cadet Chapel (1954) or Jorn Utzon's for the stadium project in Jeddah, Saudi Arabia (1999).

More recently, the vocabulary of forms seized structural geometries with the development of new technicalities related to robotics, with the use of new materials as well as the development of digital tools. Finally, this vocabulary gave birth to an architectural movement called R. Oxman's "New structuralism" [2].

Today, architecture and wood constructions bring a new impetus to Europe. Vocabulary has remained strongly influenced by archetypes like the log chalet, the picturesque half-timbered house or the industrial wood frame house. However, the development of new components such as Cross Laminated Timber, allow constructions to perform a new link with the structural morphology's vocabulary, particularly the language of fold and pleating. Along with plasticity, which enriches the quality of spaces and constructed forms, the pleating optimizes the structure and the necessary amount of materials according to the span.

This article aims to define the concept of pleating in the field of architecture. We will also present a model and a tool to design and create a non-standard folding structure with wood.

2. TIMBER FOLDING

2.1 Folding and technology

A few experimental projects have demonstrated the quality of wood for inventive architectures. Structural and morphological systems are closely intertwined in these previous cases. This includes, for instance, the works conducted with gridshell structures. On one hand, there is the short wood technic developed by F.Zollinger [3] in the early 20s which was used by Hugo Haring for the Garkau farm at Scharbeutz in Germany. On the other hand, Frei Otto [4] built the Mannheim's Multihall with the long wood technique in 1975.

During the last decade, several projects tried to push the material's limit in both terms of form and structure. Ville Hara's Kupla [5] Tower (2002) in Helsinki, , Edward Cullinam's Weald and Dowland Museum in Singleton (2002) and Jurgen Mayer-Hermann's Metropol parasol in Sevilla (2011) [6] are among these projects.

Research works such as the one conducted by Y. Weynand [7] at the EPFL laboratory IBOIS, explore the geometrical possibilities (structural and architectural) of pleated wood and its sustainable qualities.

Wood-skin is a new product based on the foldtex concept [8] which is a flexible membrane in the middle of two pieces of striated plywood. By using the folding concept, this product allows a new thinking in morphological design.

2.2 Folding and architecture

Two recent achievements testify the potential of fold in architecture: the temporary pavilion in Osaka by the agency Ryuichi Ashizawa Architects and St Loup's chapel in Pompaples by the group of architects Localarchitecture / Mondada [9].

Because of their structural and architectural qualities, these projects exalt the virtues of wooden pleated structures. In such cases, a series of one-way pleats is used to stiffen a thin surface. Structurally, all of these constructions operate as a series of gantries. Pleated surfaces also provide an interesting effect of lights and shadows, and result in a harmonization of the architectural space. The folds change the pattern, modify spatial parameters (light, space...) but also structural forms. It appears that each pleated construction finds its balance between shape parameters and structure.

These two structures do not have the same construction (from the technical point of view) but their design employs a similar method. Each one of these projects has a particular geometrical construction resulting from a set of folds, following, or not, the rules of origami. In both cases, the fold's geometric features are the basis for a wall's structural parameters.

These geometrical parameters define an architectural language for the fold. The architect J.M. Delarue [10] has identified four variables that generate emotion:

- The "fascination of animated" by rhythm.
- The "euphony" upper and lower ridges, peaks and valleys, positive and negative.
- The "nuances" from the light revealed.
- The "hold of line" guiding the eye.

There is therefore a strong interaction between artistic expression and the structural requirements in these two achievements. In a design tool for pleated surfaces, it is important to keep at all times the possibility of interaction within these parameters. The designer must be able to control the language of the fold throughout the design. In order to do so, he can affect a degree of relevance to the different variables which define the language of the fold.

3. THEORETICAL MODEL

We propose a model which allows describing and creating a pleated architectural structural form. The data model should be useful to develop this form, both from a geometric and a structural point of view. This common model can be used as a gateway between two disciplines: architecture and engineering.

This model will be implemented using a digital modeler, this modeler will define the fold's optimal configuration, so that there is a link between the choice of the pleated architectural form and a satisfactory structural performance. Folded structures' parametric design occurs in two stages: the first one deals with formal qualities and the second one, works with the structural aspects.

3.1 Characterization of the fold

A fold is the deformation of a material's surface which is generally thin and has more or less radius of curvature (geological formation, drape, paper...). The fold can be obtained by the means of different methods: they may be the result of an action like folding, pleating, wrinkling or any other process which leads to a formal outcome of the fold as seen in the sculpture. This distinction is essential in our conceptual approach, because it aims to generate a geometrically structural and architectural fold.

A pleated surface is composed of several plies which non-intersecting directions. In a regular pleating the axes of the fold are parallel. However, when working with an irregular pleating, those axes are not necessarily intersecting but nonetheless never parallel.

The definition of folding could be understood in two different ways (figure1). The first one is characterized by curvature, as one estimates that the tangent (first derivative of the curve) is continuous. In this case, a minimum radius of curvature (second derivative of the curve) is defined; this radius becomes the minimal bend before the material's rupture. So, we can define a fold according to the proportion between the material thickness and the radius of curvature. However, a scaling factor might be applied to the ply: in this case, we consider the ply as the relationship between the radius of curvature and the global dimension of the bent material (i.e. sheets of corrugated metal).

A second way is mathematically defined by discontinuity of the tangent. This one-point change of direction is physically reflected by an interruption of the material: an assembly is therefore produced. It is in the latter sense that we have targeted our research into folded solid wood panels. Working with wood panels influences our pleated characterization: Although wood can be bent, it is perhaps wiser to work by assembled wood planes (according to an industrial point of view).

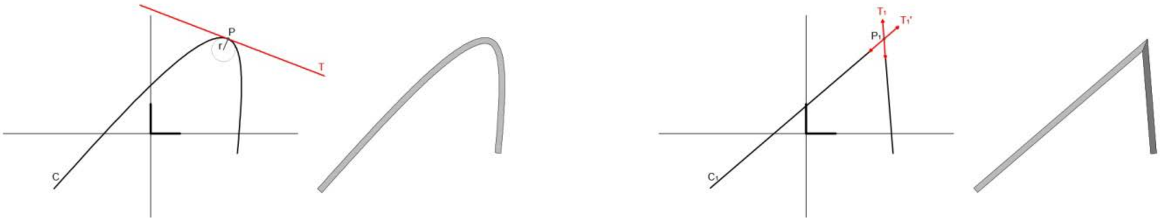

Figure 1: continuous tangent (minimum radius of curvature) discontinuous tangent (assembly material)

The fold is defined geometrically as the intersection of two planar surfaces depending on an angular value. This angle shall be defined by the number of folds regarding the distance (i.e. the frequency of the pleating) and height of the fold. The intersection of these surfaces is known as the apex line (outgoing/ bumping fold) or valley (reentrant/recessed fold). These two features are determined by an outside view of the pleated structure. We also discuss about the folded polarity in relation to each other. The turnover of the structure involves the inversion of the polarity of ply. The edge or axis indicates the direction of the fold.

Structural folding is mainly based on the idea of inertia. We talk about the amplitude of the fold. This corresponds to the throw distance between the fold line and the average plane formed by the opposing edges composing the related sides.

3.2 The morphological approach

Our approach is based on observations as a fact of architectural practices. The fact that architects work by subsequently adjusting form in order to find one or more acceptable solutions [11] is also accepted. The aim of this application is to provide creative freedom regarding shape and spatial features, by constantly allowing a series of parameters to act over the geometric modeling work: this is done by dimensioning the working area and by detailing the fold's features which are, on one side, the frequency (rhythm) and on the other side the amplitude (height of fold).

The fold can be normally applied to any surface or shape. In our work's current status, we have reduced the original form (i.e. support skin) to a tunnel shaped surface with a variable axis and profile as the interest on folded structures is their technical form and capacity to cover a large space preserving a thin section. As a matter of fact, the objective keeps on being the realization of architectural spaces capable of offering use flexibility. Of all the morphological potentialities considered in architecture, the shape of the vault was chosen (i.e. half cylinder). This shape proves to be quite useful in order to create pleating.

The pleating is constructed by a succession of folds with directions nearly perpendicular to the support skin's main axis. The selected fold's archetype has qualities such as the fact that the method is quite intuitive and allowing the constructions to become more stable. It also gives a certain rhythm which is brought by the simplicity and uniformity of the fold resulting in a good aesthetic outcome.

Cutting the support skin by plans (allowed to perform a representation of arcs) creating a path of the nodes which connects the fold lines. This method is especially robust for dynamic modeling. As a matter of fact, the modification of the original form causes an automatic adjustment on the pleating. This technique seems to be the best for producing support-skin variations.

3.3 The structural approach

The structural approach of pleating is made by using a finite elements software with shell elements to determine structural stability (under own weight) and material (buckling). It's also able to validate the dimensioning (under external loads) of the folded structure.

The concept of assembly results in a characterization of connections between different shell components. By default, we consider these connections as embedded (material continuity). But, for constructive reasons (physical discontinuity), a linear pivot development (i.e. hinges) seems to be desirable. In this case, the type of assembly becomes inadequate regarding the stability of the structure. Such situation requires the layout of the panels to be in accordance with the pleat's geometry.

3.4 Feedbacks

Feedbacks impose a change of form. They can be generated either by a calculation software regarding some fold's features being not suitable for structural conception, or by applying pleat techniques when changing the original form.

4. MODEL'S IMPLEMENTATION

In our work, the modeling process with pleated structures involves some successive morphological stages like the shaping of the support skin and folds according to geometry (profile parameters, frequency and amplitude). Geometric modeling is performed using Rhinoceros modeling tools associated with the Grasshopper parametric plug-in.

The support skin is defined by a warped surface which is specified by four splines, each one of them controlled by three points. The sequence of these points has XYZ coordinates, enabling a first shaping of the support skin. Point coordinates are editable at all times and once the initial form is defined, a pleat algorithm can be applied.

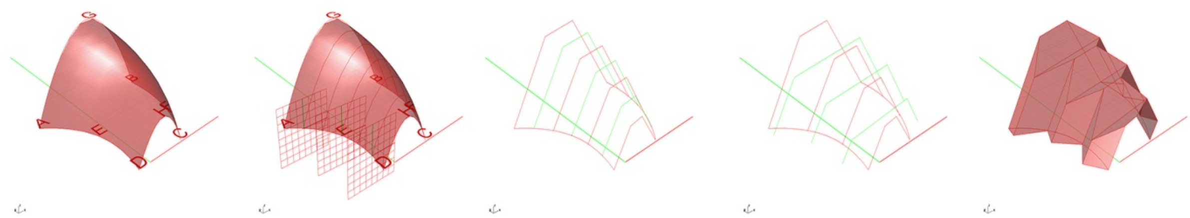

Figure 2: process of pleating

There are different geometries for the fold. In this research, we have chosen to adjust geometry to a reference surface. This meets the fold in a better way to match the initial volume. In order to achieve this, a set of polylines are built from cutting the initial shape into vertical planes aligned by normals to the main axis. Each polyline, is called a "profile" which is composed of various segments. It affects them with a random offset parametric value over a vertical plane, marking the peaks and valleys for the pleat. The profile, defined in relation to an initial surface, gives the pleat its direction. Each profile's vertex becomes a node which may have up to four common sides.

The number of segments determines the number of slants roof, that's n-1 deck line, in other words, break line for pleating. The segments making a slant must not be necessarily parallel, that's why the facets of a pleated surface are not completely planar.

In fact, the random shapes generated by modeling the initial envelope, may cause skew surfaces in the geometric construction of pleating. A surface conditioning parameter was then introduced. A script made with VBnet was used to define a flat surface with random precision degrees, this precision depends on the curvature radius the material can accept; so, the structure adapts its morphology according to the material's deformation range. The component has two inputs: surfaces (defined by their vertices) and a certain accuracy degree (the desired one). As an output, we obtain the procedure's overview, the new nodes'

coordinates which constitute facets and the remaining necessary actions that will lead to a final result. Accepting a major curvature radius over a facet, will cause a pre-stressing effort over the material, such situation will require an additional structural verification.
In order to test the wood panels' stability and dimensioning, a computer gateway is created between the pleated structure's modeler and finite element analysis software (Castem)[1]. Transient data is exported in a file format recognized by both programs. In order to allow a regular update between the two programs, an information database regarding the plated model must be considered.

First of all, this approach will have to ensure the pleated structure's dimension and stability. Thanks to the geometrical model's coordinate points (generated with Grasshopper) it will be possible to reconstruct the structure into Castem's environment. To do this, the points are classified by surfaces in a spreadsheet. To increase the calculations accuracy, these elements (which are forming the shell) are subdivided into four parts. The first stability tests are studied regarding the structure's weight (assignment of a material and thickness): the structural nodes are again considered as embedded. Actually, the results of stress and deformation represent the structure's qualitative state, which in the end, will act as the pleat's morphological markers.

5. TESTING

Two experiments have been carried out in order to validate our project. At first, the ability of both tool and model to generate a pleated shape in accordance with an existing structure has been validated. After doing so the prototype's usefulness and usability under design situations were assessed as well.

5.1 Reconstruction of the St Loup chapel of Pompaples

The St Loup chapel will be our case study. The building's morphology is based on two pleated envelops with different functions. The first one is visible from the inside of the building and it's made of engineered wood massive panels (6cm width for the roof and 4cm for vertical supports) playing a structural role. The second envelop is made of a 3 ply wood and is used to protect the bituminous sealing membrane. For this morphological experiment, all the constructive parameters have been set aside, e.g., panel width, which is the reason why only the chapel‘s interior plied surface is displayed. The aim of this experiment is to validate the support envelop model as well as the pleating model one:

A first morphological approach to the envelop allows us an approximation towards the chapel's pleated volume. Nevertheless, a gap in the curvature of the covering part was found and that can be explained because of a lack of parametric data regarding the supporting envelop processed by our generative engine's application.

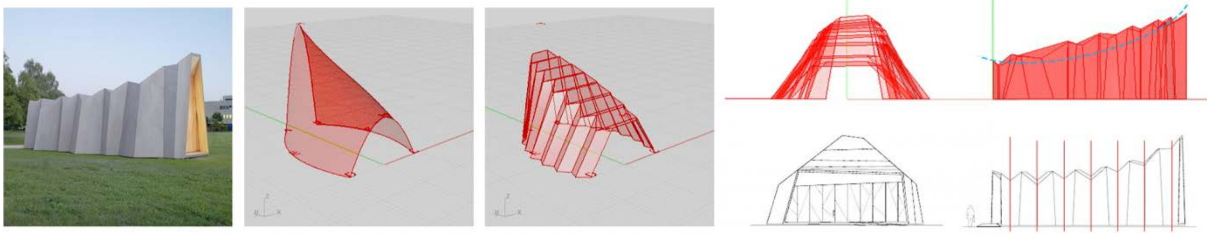

Figure 3: tests representing shape St Loup

[1] http://www-cast3m.cea.fr/

On a second morphological approach, the pleating algorithm is perfectly adapted for the initial surface. Nonetheless, the error rate from the initial surface was increasing, in some way, the gap between the initial shape and the pleated shape gets too big. A data correction has to be done in several steps. Besides, the fold's geometric construction as defined by our algorithm generates regular pleats. To respect the alternate rhythm of the chapel, it is then necessary to modify the algorithm.

5.2 Rehabilitation of the St François d'Assise's church at Vandoeuvre

This second experiment was meant to validate the design approach born from our application. Both the usefulness and the usability are evaluated in this part. The case study is the church's nave, which is actually being reconverted. The goal is to design a pleated structure as if it was in the sketch phase. The first step is the research of a general shape based on the support's envelope modeling, thus defining the structure footprint in the religious building. The second step's purpose is to execute the pleating algorithm. At this stage, the pleat parameters allow the facets' adjustment of rhythm, range, profile and curvature radius according to the designer wishes.

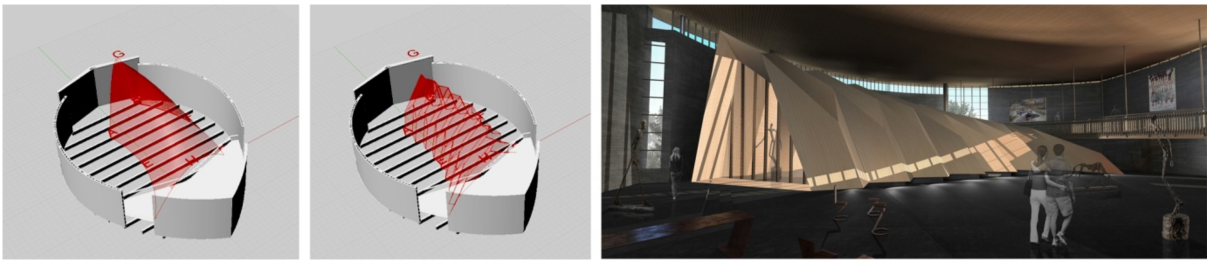

Figure 4: testing usefulness and usability of the morphological tool

The experiment begins with the evaluation of usefulness. The approach has to be robust to meet previous constraints. The model's parameters define a morphology capable of apprehending the architectural constraints of the project. Problems are concentrated in the usability of the tool. For the moment, the prototype allows us to create a project for which we can adjust dimensions and shape thanks to certain parameters. However, the final model depends on the pleat constructive geometry which cannot be adapted to some peculiarities of the project. The method is adequate for general morphological approaches but it's still not robust enough to perform accurate adjustments.

6. CONCLUSION

Today, folds or pleats are among the new design languages of architecture. A morphological research to adapt either the structural or formal qualities of folds is a source of inspiration for many designers.

In this article, we present an overview of a pleat model and its implementation with a digital tool. Research in the fields of geometry and mathematics allow us to assert that, the search of a shape, depends on the logic of the pleat process. Not only architects imagine the shape, but they also discover it.

The previous experiments highlight the pros and cons of our modeling tool. In order to meet all the constraints linked to a project and to generate relevant solutions, it is essential to manage its geometry. However, it remains impossible for our prototype to interact effectively with an architectural model. The boundaries of our morphological operator come along with the geometrical construction's process. Moreover, even if the model can be functional and receivable, the morphogenesis is characterized by a specific folding technique which restricts the boundaries of what is possible.

Many questions have been raised by the selected projects from an esthetic and structural point of view. The reality of the construction creates physical constraints. The addition of a calculating tool such as Cast3M to our morphological tool will allow formal adjustments fully respecting structural constraints.

The perspectives are various. First, the method for a parametric surface has to be improved and it's essential to perform a folding geometry refinement. Then, the integration of constructive data related to width and assembly has to be improved. Finally, the creation of structure prototypes appears to be essential for the definition of elements compatible with a constructive reality. The aim of this research is of course the study of CLT pleated structure, from design to construction.

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