Parametric design as a feature for structural improvement

A modular timber structure

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The presented reciprocal frame structure is a modular composition of timber folded panels. The overall geometry is driven from a folded plate base module which is then spatially multiplied in using Euclidean isometries. The intersection of consecutive modules, impose the slide-cut geometry which ensures the local and global stability of structure. Embedded inside a CAD environment, the three-dimensional geometry is parameterized according to the base module and by using a Finite Element non-linear analysis, it is demonstrated that the structural performance can be improved with a more interlaced configuration of parameters. A prototype based on this geometric principal has been fabricated and assembled to explore feasibility of the concept in the building scale.

Keywords: Timber space structure; reciprocal frame structure; structural system improvement; Finite Elements analysis; parametric design

The Folding Concept

The structure presented in this paper has been initially designed during an architectural workshop, „The Atelier Weinand" at IBOIS-EPFL, turning around the discrete architectural geometry.

A V-form base module is fabricated connecting two mirrored timber panels through the mirror plan. Each module is equipped with four U-shape cuts which enhance the connection between consecutive elements. These modules are then slipped consecutively along their U-shape cuts, to form an arch which is extended transversally. The geometry of U-shape cuts implies 5 axis machining.

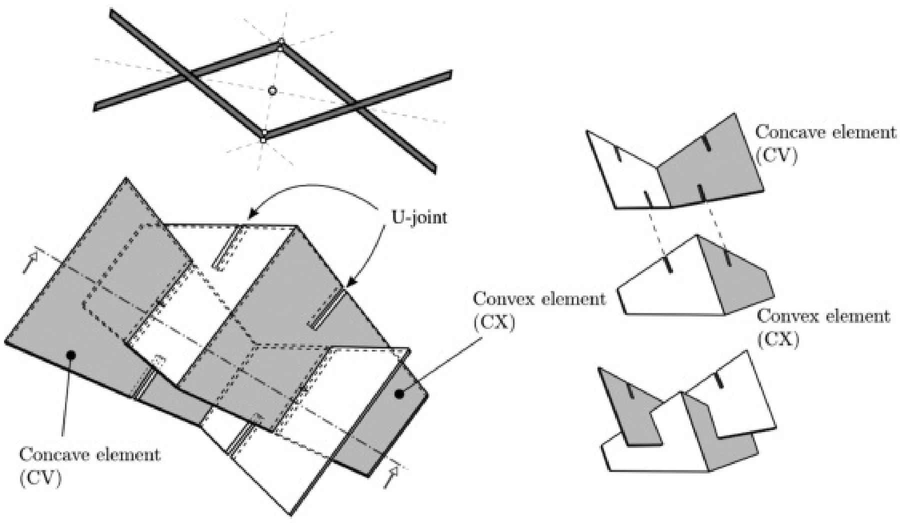


Fig. 1: Base module.

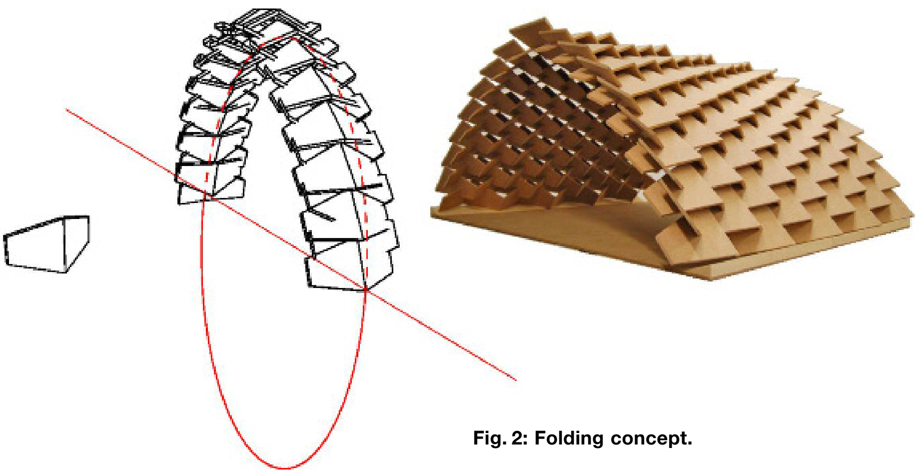


Fig. 2: Folding concept.

Prototype Realization

A prototype of this structure has been realized at EPFL in order to test the structural feasibility of the concept as well as to investigate the architectural ambiance.

The project included development of relative NC codes for 5-axis machining, as well as designing constructive details and fabrication of the structure for exposition. All V-form folded modules have been manufactured from 21 mm thick three-layer cross-laminated panels and cut by means of CNC machines.

Structural Analysis

A Finite Element 3D model has been established to study the structural behavior of the modular arch. Based on these observations, improvements are proposed in the following part.

Results for the global deformation field and the stress driven from a static non-linear analysis of a single arch under its self weight load case are shown in Fig. 4. It can be seen that the geometric configuration of the assembled modules leads to a concentrated distribution of stress at the location of slide cuts. This mainly happens because of bending behavior of the structure around U-cuts. Moreover, a modal dynamic analysis has been realized to have a first estimation of structural rigidity in lateral and transversal loading conditions by comparing natural frequency values: the first global mode is a lateral one and it has a relatively small natural frequency of 0.59 Hz, comparing to practical guidelines, which advices a minimum natural frequency ranging between 1 to 4 Hz.

Propositions for structural system improvement

Based on our findings, we proceed on this section with two goals: first, to obtain a more uniformed stress distribution in panels and to reduce the stress concentration in U-joints; Second, to increase structural rigidity, measured by means of natural frequency of the first global mode.

Fig. 3: Prototype realization at EPFL © Alain Herzog

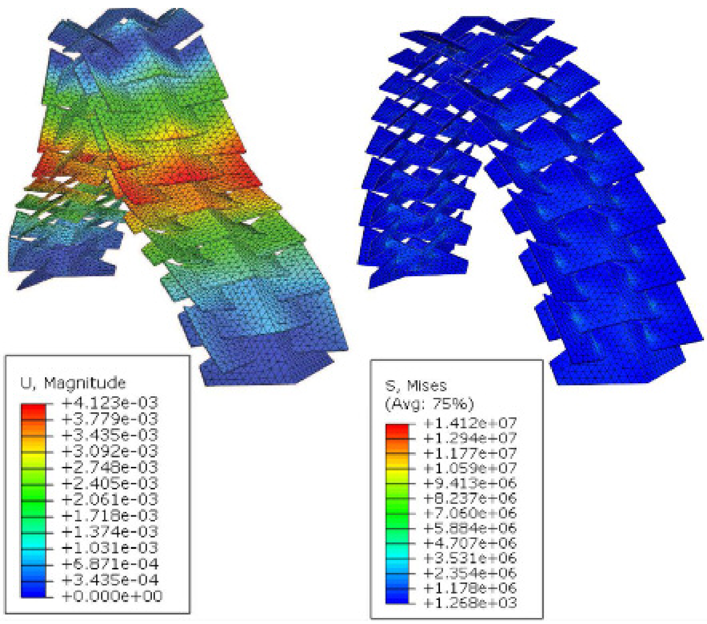


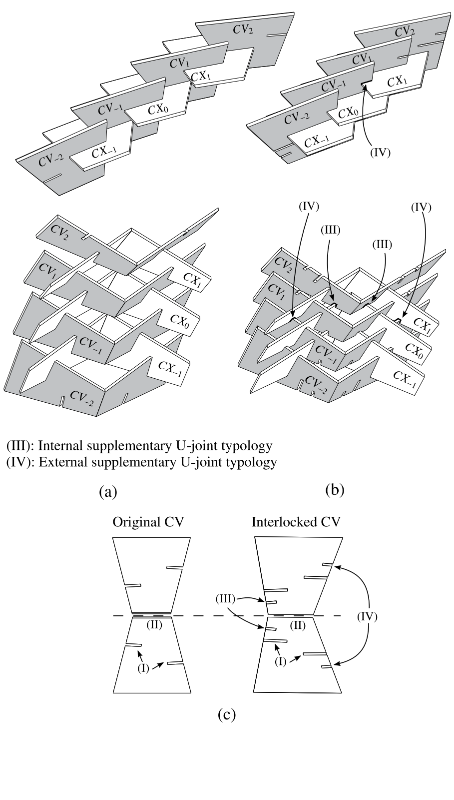
Fig. 4: Global deformation field and von-Mises stress in single isolated arc model.

Increasing panel inter-locking effect

If we consider a CX module, picked deliberately from the arch, the neighborhood of this module will be as in Eq.1. (Fig. 5a) According to geometric principal, CX_1 is connected to CV_1 and CV_2 across two U-joints for each. The idea is to increase the length of these current U-joints to make CX_1 meet CV_{-1}. (Fig. 5b) The two intersection cubes are then removed from CV_{-1} and it ends up with two extra U-joints on external part of the panels. Consequently, CV_1, connected currently with CX_0 and CX_1, in his place, intersects with CX_{-1}. Removing the two new intersection cubes from CV_{-1} provides two more extra U-joints connection, placed this time, in internal part of CV module.

$$CV_{-2} - CX_{-1} - CV_{-1} - CX_0 - CV_1 - CX_1 - CV_2 \quad (1)$$

If we resume, the general idea is to keep the cut-pattern for CX module unchanged, although for CV module there would be 4 more U-cuts: two internal and two external. (Fig. 5c)



To achieve this objective, the original geometrical concept has been implemented within a parametric computer-aided design interface. The important parameters determining the geometry of each typology of modules in the original design have been identified. Then, the geometrical configuration for the assembly of the Base modules is set respectfully to the height and total span of the original structure.

Increasing the slide length, while keeping constant total span and height of the structure, will increase the number of modules. The original design is consisted of 33 slipped modules. In fact, by increasing length of joint by 103 mm to create two more U-joints between panels, 53 modules of nearly the same size is needed to respect the same height and span as the original design. Therefore, it follows that the inter-locked version will be 53 / 33 ~ 1.7 times heavier than the original one. By multiplying number of slide joints and distributing their position across the all length of panel, we expect a more uniform load transfer between modules. Indeed, the results for von Mises stress, came from an elastic nonlinear analysis, confirms this idea. The maximum von Mises stress for self-weight load case, reduces to 1.15 Mpa for maximum total deformation of 1.3 mm, which is still acceptable. This is true even though the interlocked configuration is 1.7 times heavier than the original one. The main gain is on the structural rigidity, where the minimum natural frequency, calculated from a modal dynamic analysis is estimated to be 5.99 Hz. Using the values of natural frequency (f) and total mass (m) for the original configuration (marked with subscript 0 in Eq.3) and the improved inter-locked version (marked with subscript 2), one may compare the relative equivalent structural stiffness (k) between these configurations as represented in Eq.3, concluding that the new slide locks make the original structure 165 times stiffer.

$$\frac{k_2}{k_0} = \frac{m_2}{m_0}\left(\frac{f_2}{f_0}\right)^2 \cong 165 \quad (3)$$

Fig. 5: Increasing panel interlocking effect: two geometric configurations (a) Original (b) Interlocked (c) Comparing geometric modification brought to CV module as well as its connection typology.

Conclusion and Further work

The structure presented in this article shows an example for the design practice when the final form is driven by the connection technology, where complex modular global forms are proposed by means of mutually supported simple folded panels. The proposed slide connection scheme inspires a new family of reciprocal frames, where instead of linear members (beam or bar), planar (folded or elastically deformed) members are mutually supported. The connection between mutually supported members in this concept is integrated within the geometry of members, unlike the traditional reciprocal frame system where the connector members are employed.

As a further work, the same concept is employed where instead of folded panels curved thin deformed panels are used. The mutual supportiveness scheme of panels rests unchanged but the slide connection geometry needs to be determined based on a form-generation relaxation analysis. Moreover on such prototype, instead of single folded modules, continuous thin flat panels will be used where connections are milled and fabrication is realized by elastically deforming panels and sliding. As a consequence, transversal extension of the structure will be straightforward.

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