Geometrical description and structural analysis of a modular timber structure

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Summary

The ambitious goal of the ongoing research at IBOIS, the Laboratory of timber constructions at the Ecole Polytechnique Fédérale de Lausanne (EPFL) is to develop a next generation of timber constructions made out of innovative timber-derived products, through applying textile principles on the building scale. The presented structure is a modular composition of timber folded panels, notably demonstrates an example of applying the geometric techniques used to produce modular patterns and lattices to timber construction context. Effectively, it is shown that complex space structures can be designed using simple connection technology between elements. Moreover, by taking advantage of advanced CAM process, complex planar timber elements are cut in large scale and assembled with high precision as for the prototype of the structure presented in this paper. The folding concept corresponds to a planar reciprocal frame structure. The basic module is consisted of two mutually supporting timber folded panels which are slipped in, consecutively, along their cuts, to build up an arch. The inter-module connection's stability is provided by contact boundary condition over the slide joints. The fundamental mechanical properties of the structure are examined using Finite Element Method and considering the non-linear contact boundary condition. The static behavior is studied under the self-weight load case as well as the modal dynamic response. According to analysis results, and by aid of a CAD parametric model, structural and geometrical alternatives are proposed to improve the structural performance. 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

1. Introduction

1.1 IBOIS, the re-interpretation of timber construction

In recent years, the necessity of using renewable and sustainable resources in the building sector has become obvious, and interest in timber as a building material has revived. [3-5]Novel timber-derived products, such as massif block panels, have emerged and the use of such products is spreading. [6, 7] The ambitious purpose of the ongoing research at IBOIS, the Laboratory of timber constructions at the Ecole Polytechnique Fédérale de Lausanne is to develop a next generation of timber constructions made out of innovative timber-derived products, through applying textile principles on a building scale. [4, 9] It aims at the unprecedented exploration and study of timber related structures and their structural analysis within a framework integrating the mechanical and structural principles of textiles. Since timber can be viewed as a fiber-derived product, it follows that the analogy between micro scale fiber structures and timber-derived wooden structures can be explored at micro and macro-scale. The key to our approach is the underlying notion that timber's fibrous nature, historically perceived as a liability for a construction material, is in fact a precious feature that should be exploited to increase both the material's functional and aesthetic value. Its inherent flexibility permits it to be folded into robust, lightweight structures that use material very sparingly. The concise observation of existing textile techniques and fabrication methods, notably here the geometric techniques used to produce modular patterns (as in [11]), combined with investigation lines such as the modular structure presented here, will lead to a new family of timber constructions based on the logic and principles of textile fabrics.

1.2 Geometry of space structures: a survey on "form-element" realationship

During the recent decade, four main directions dealing with the geometry of the space structures have been recognized and resumed in fig 1 with an example of a related publication on the subject. These approaches are described and analyzed below.

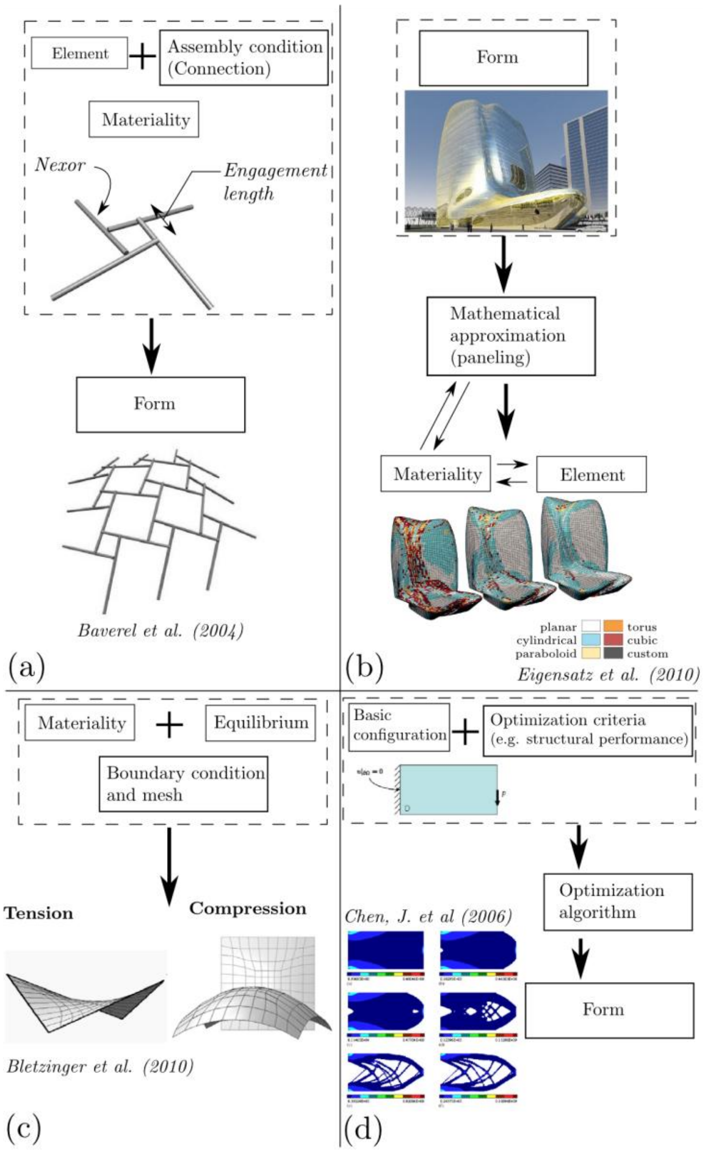

Fig. 1: Forms for space structures: (a) Reciprocal frame structures [1](b) Free-form design and panelling approximation [2](c) Equilibrium forms either in tension or compression[8](d) Free-form obtained from a topology optimization process [10]

- **Reciprocal frame structures:** this family of modular space structure, are consisted of interlaced linear elements, where the final form is a result of a basic module as well as a connection technology. [1, 12-14] (fig 1a)

- **Free-form design:** here the free form design surface as the input and by means of geometric-mathematical models, approximates the surface into a uniform (or typologically uniform) planar mesh. The mesh generation is clearly constrained by tolerances of the approximation problem as well as the economical sensibility analysis. The supporting structure follows closely this approximated mesh and thus its spatial form is indeed less influenced from materiality and robust mechanical reflections on the equilibrium and the mechanical governing laws. The materiality and the connection technology come clearly next to the free-form design surface. [2, 15, 16] (fig 1b)

- **From-finding practice:** it deals principally with tensile membranes or vaulted masonry construction in order to determine a tensile or compressive geometry. Here the final form is the direct result of equilibrium and is influenced intensively by the materiality and the boundary condition applied. [8, 17, 18] (fig 1c)

- **Topology optimization:** The last stream can be resumed under topology and shape optimization problems. These methods combined with evolutionary algorithms, often result in free-form spatial objects, which although have been generated based on a structural criteria, fall into the first category, where they are geometrically approximated in order to be built.

In fact, according to the free-form design, it starts generally with a "complex form" which ends up with multiple typologies of elements in a top-bottom process, and "complex connection technologies", where structural elements follow offsets of the external form. Indeed, we ask the question whether the same free-form practice should be followed in context of timber construction. This is the reason to take the materiality and the complexity of the connection technology, as an important feature here, in order to distinct above approaches. The core idea which follows in coming lines is an investigation on families of space structures, where the focus, rather than on an irregular surface approximation, lays on materiality and related connection technology. According to this approach, the final form is a result of the geometry of connected members as well as the employed connection technology. In the context of timber engineering, we focus on use of CAM facilities to cut complex geometries from timber thin panels and slender beams, while the connections are kept simple as it is implied from the wooden materiality.

The modular structure proposed in this paper comes from such exploration on form-element relationship. It is not only geometrically treated, but also from mechanical point of view it is demonstrated that its structural behavior is understood. Moreover a prototype is realized to complete the investigation.

2. Presentation of structure

2.1 The folding concept

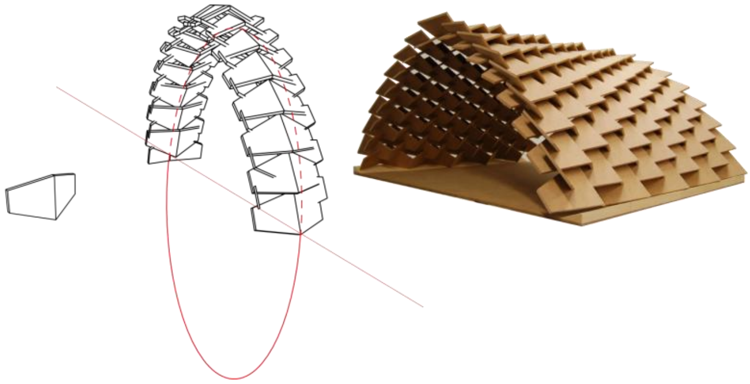

Fig. 2: Folding concept for the modular structure designed in the Atelier Weinand workshop © Bastien Thorel

The folding concept presented in this paper has been initially examined, during an architectural workshop, "The Atelier Weinand" at IBOIS-EPFL, turning around the discrete architectural geometry under the supervision of Y.Weinand. A V-form basic module is fabricated connecting two timber panels and is then spatially multiplied using consecutive spatial rotations and translations to form an arch. (fig 2)

The structure can be decomposed into four principal typologies each consisted of two mirrored timber panels, joined together as a V-form module, through the bisector plan, by means of two hard wood dowels. They are placed in the middle as shear keys and two oval head screws inserted nearer to the borders in order to avoid relative translation and rotation. Fasteners are inserted in direction of the normal to the plan of reflection. These modules are then slided consecutively along their U shape cuts, to form an arch. The inter-panel stability is provided by roto-rigidity of slide connection and axial contact of reciprocal panels.

2.2 Geometric and parametric decomposition of global form

A trapezoidal plate is introduced to be the generator member of the form, noted as $\mathscr{B}_1$ and referred to as the "Base panel". In general, this single panel is transformed by means of two classes of operators in order to give shape to the global form. The first operations are the set of Boolean operators, representing the machining, connecting and assembling process. Whereas the second type of operators, referred to as Geometrical operators, introduce rigid body movements and consist of congruent maps, employed to place the object in the space. Among Boolean operations, union, intersection and remove are used. While among Geometrical operators, we may enumerate rotation around a space vector, reflection against a plan, inversion against a spatial point or translation in direction of a space vector as examples of simple isomorphisms.

The geometric transformation permitting to determine the slide cuts between two consecutive modules is illustrated in fig 3. The manuscript letters ($\mathscr{B}$, $\mathscr{M}$, etc) stand for geometric objects and bold capital letters as (**S**, **R**, **T**, etc) symbolize isomorphisms, respectively the symmetry, rotation and translations. Boolean operations are represented by their mathematical symbols of union, etc.

By repeating the same geometric transformation, a double cut module is obtained shown in fig 4, called the “Base module”, which is the base brick of the modular structure.

As a result of the implementation of the geometric transformation described above in a CAD environment, a parametric model of the modular structure is obtained where the geometry is controlled by means of a set of meaningful scalars.

2.3 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. A selection of photos illustrating the project is shown in fig 5. 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 at EPFL.

3. Structural analysis

Here the objective is to understand the structural system considering the geometric non-linearity by the aid of appropriate numerical models and to improve it. The diagnostics about the structural system is consisted of the linear static analysis under the self-weight and the modal dynamic analysis, in order to examine the rigidity. Based on these observations, improvements are proposed in §4.

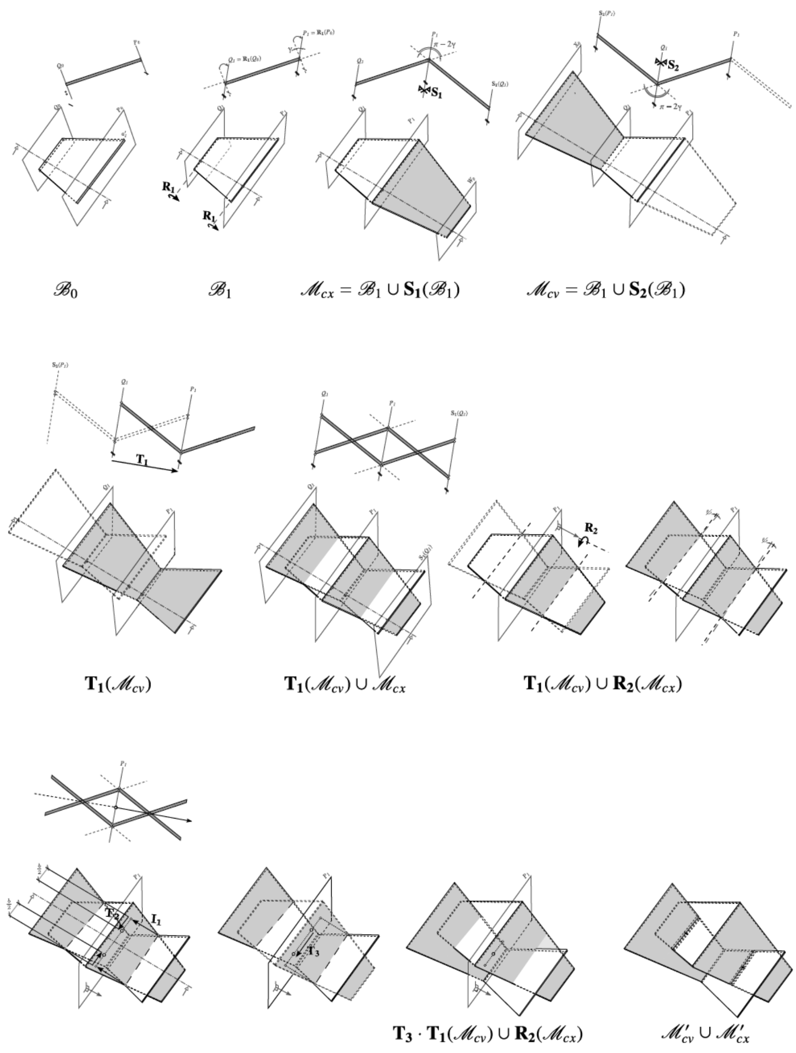

Fig. 3: Geometric transformation of basic trapezoidal panel ($\mathscr{B}_0$) into two slided V-form modules ($\mathscr{M}_{cv} \cup \mathscr{M}_{cx}$)

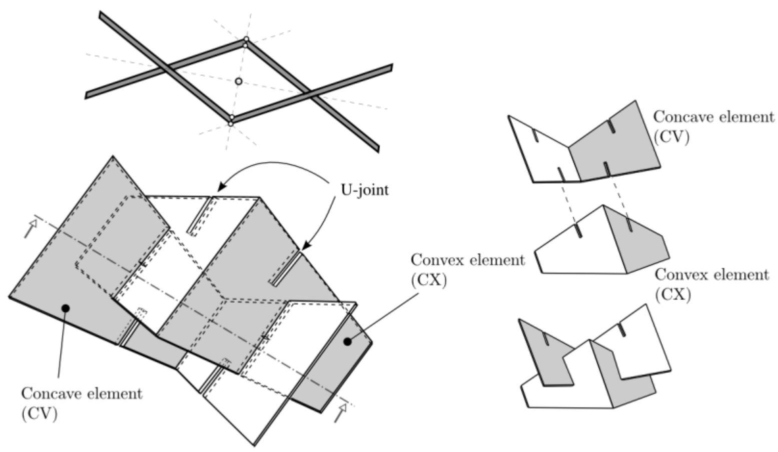

Fig. 4: Base module

3.1 Modeling hypothesis and local boundary condition analysis

Fig. 5: Prototype realization at EPFL © Alain Herzog

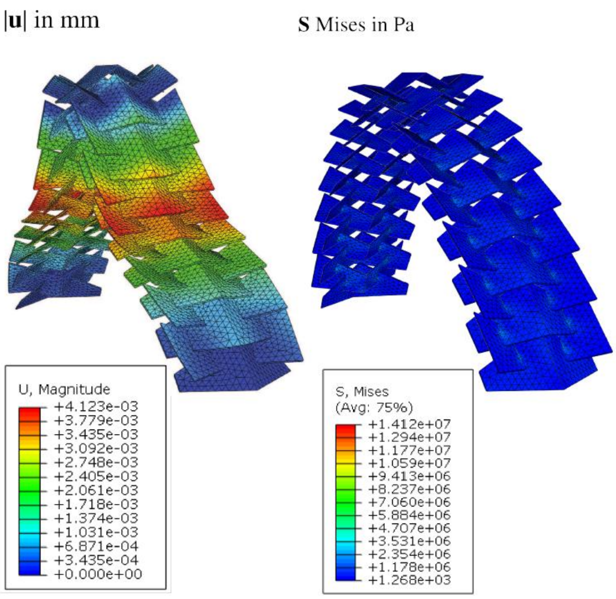

Fig. 6: Global deformation field and von Mises stress in single isolated arc model

According to the adapted modeling approach, the thickness of panels enters in the reality of modeling, permitting to model the slide connection as it is defined from the geometric configuration. For each slide connection, five normal contacts are defined between two pair of surfaces as master and slave surface. Contact property is considered to be frictionless. The contact boundary condition has to be satisfied along slide joints underlying finite deformations. A 10-node modified quadratic tetrahedron element is chosen to mesh the continuum model, referred to as C310DM ABAQUS® solid element.

The timber is considered to be an elastic homogeneous material throughout the whole thickness. The Young Modulus, $E = 8000\ Mpa$, Poisson's ratio, $\upsilon = 0.3$ and material density, $\rho = 500\ \mathrm{kg/m^3}$ are concluded from documentation disposed by the industrial provider of cross-laminated panels. [7]

3.2 Structural analysis of a single arch

Results for the global deformation field and the Von mises stress driven from a static non-linear analysis of a single arch under its self weight load case are shown in fig 6. It can be seen that the geometric configuration of the slided together modules leads to a concentrated distribution of stress at the location of slide cuts. This mainly happens because of bending behavior of the structure. Moreover, a modal dynamic analysis for the isolated modular arch 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. [19]

4. Propositions for structural system improvement

Based on our findings in 3.4, 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.

4.1 Toward a truss system

While having already a geometric superposition concept, one immediate remark would be to change the current beam-like system with a more truss-like one. Two main directions are tracked, as follows.

- Addition of intermediate elements: this could be realized by help of additional intermediate elements which are inserted properly at mid-plan of the arch to connect consecutive CX-CX and CV-CV modules between each other.
- Opening the U-joint: in the initial geometric configuration, each module's stability is provided by the locking effect of panels across the U-joints. In a truss system with additional intermediate panels, fixed between them and fixed to the slided modules, it would be possible to open the angle of U-joints. This will help to reduce the concentrated stresses. (fig 7a) Applying these two main modifications on the original structure, the maximum von Mises stress under the self weight load case is reduced from 14.1 Mpa for original configuration, to 1.66 Mpa, keeping the same order of magnitude of maximum total deformation. Furthermore, the stress has been led to intermediate elements rather than panels and consequently, the concentrated pattern of stress on panels has been resolved. The natural frequency for the first global mode of the structure is increased up to 0.98 Hz.

4.2 Increasing panel inter-locking effect

Let's consider a CX module, picked deliberately from the arch. The neighborhood of this module is as in (2). (fig 8.a) According to geometric principal exposed in fig 4, 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 8b) The whole 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.

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-form cuts: two internal and two external. (fig 8c)

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 montage of the Base modules is set respectfully to the height and total span of the original structure.

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

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 slided modules. In fact, by increasing length of joint by 103mm 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 $53/33 \sim 1.7$ 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 (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 (3), concluding that the new slide locks make the original structure 165 times stiffer.

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

5. Conclusion and Further work

A modular structural concept consisted of folded planar timber elements, is presented in this article. It is shown that the form of the space structure is determined by the geometry of its base module and the connection geometry between panels. It indeed represents a novel family of space structures which can be interpreted as planar reciprocal frames. The parametric implementation of concept is brought out and it is established that this parametric model can be used to propose structural improvements, notably here by increasing the inter-locking effect of connections. Further research will look at a generalization of this work based on mathematical exploration on modular structural shapes suitable for timber construction.

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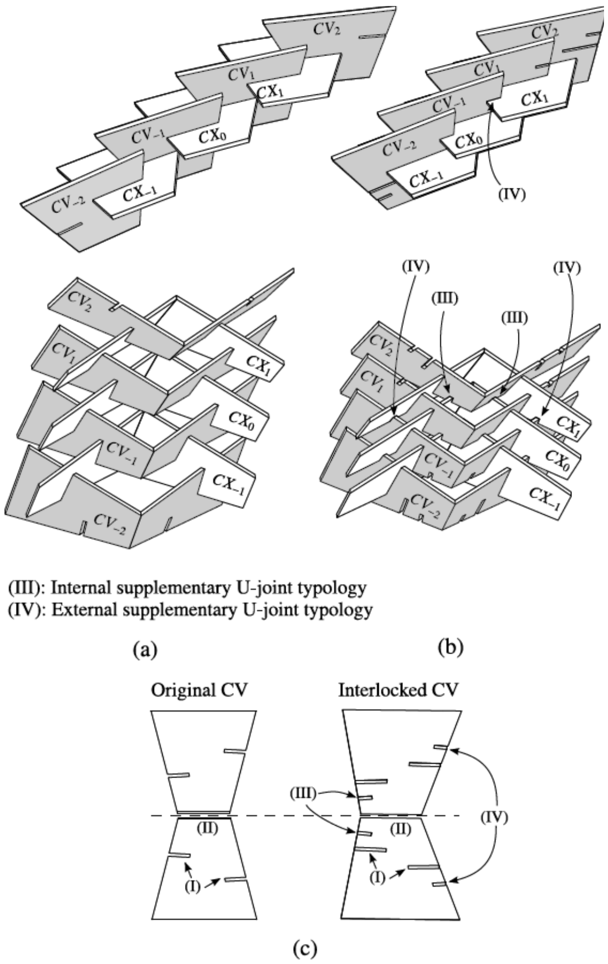

Fig. 8: Increasing panel interlocking effect: two geometric configurations (a) Original (b) Interlocked (c) Comparing geometric modification brought to CV module as well as its connection typology

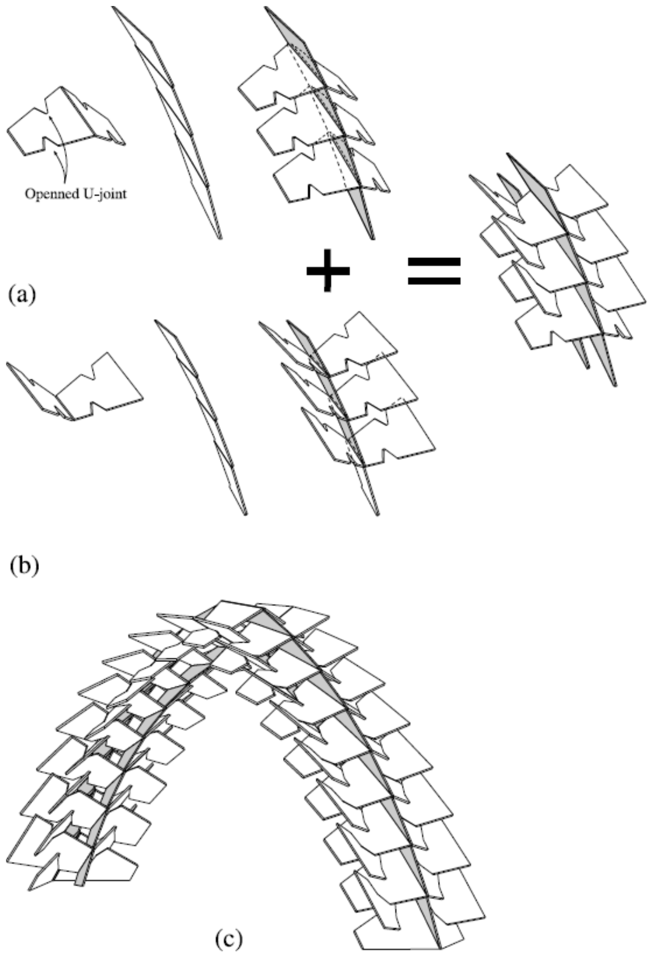

Fig. 7: Toward a truss behaviour (a) CX module modification and intermediate panels (b) CV module modification and intermediate panels (c) Isolated arch reinforced with intermediate panels on top and bottom fibbers

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