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GENERATIVE DESIGN FOR FOLDED TIMBER STRUCTURES

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Abstract. Folding structures belong to the group of lightweight structural systems, which often consist of polygonal elements like triangles or quadrangles. Folding structures whose construction is made out of cross-laminated timber (CLT) panels represent an innovative step in the timber industry, which has many advantages. CLT panels can be used simultaneously as supporting elements and as finishing building envelopes. There are many prefabrication possibilities, high efficient material consumption, low production and assembly costs, and it has environmental advantages over conventional materials used for folding structure like concrete, metal or glass. CLT folding structures are not sufficiently explored. One of the reasons may lie in the fact of limited design possibilities, which includes the specificity of CLT capacity. Another reason is maybe the inability to use standard wooden connectors to transfer the forces along the thin linear edges where the panels are supported. The aim of this paper is to present design possibilities through parametric modelling using the characteristics of CLT. Using the example of a wooden theatre stage we will present results of our research.

Keywords: Parametric modelling; folding structures; cross-laminated timber.

1. Introduction

Folding structures are one the most cost-effective building constructions, due to the economical material usage because of their high stiffness (Piano 2008).

At the beginning of the twentieth century along with the development of reinforced concrete, folding structures were introduces into architecture. After the first prejudice, that this type of construction can be performed only in concrete, in the second half of the twentieth century, folded structures were made of other materials such as steel, wood, polyester resin, glass and their combination. Most of the structures which were built at that time were symmetrical and in form of cylinders or rotational surfaces. Today's usage of digital tools in the production of building elements - such as cross-laminated timber (CLT) - opens a new formal freedom in designing free-form folding structures (Buri, 2010; EPFL 2013; Hassis 2008). This gives new spatial experience and simultaneously the advantages of an excellent static system.

The purpose of our research is to transfer the possibilities of small scale paper folding models into buildable architecture in real scale. We will both introduce theoretical considerations and the whole workflow of a real scale architectural building that is ready to build. In our previous work, we investigated the geometry and behaviour of folded structures using an endless number of paper models and parametric computer models, see for instance Stavric and Wiltsche 2013, Stavric and Wiltsche 2014, Wiltsche and Stavric 2014.

In the following chapters, we will discuss architectural design, geometry, parametric design and static behaviour of folding structures, particularly with regard to standard building material of a certain thickness, especially CLT. At the end of the paper, we will present an elaborated real scale architectural project based on the theoretical chapters written before.

2. Architectural Folding Design

There exist some very interesting architectural examples which demonstrates the potential of folding structures like the Folded-Plate Hut in Osaka by Ryuichi Ashizawa Architects, United States Air Force Academy – Cadet Chapel by Leo A. Daly, Inc. and Henningson and the Chapele St. Loup in Switzerland by Danilo Mondada.

Folding structures can also be found in different fields like industrial design, fashion, interior design, etc. Gregory Epps fabricated an interesting design example for Zaha Hadid at the Biennale in Venice (see Epps, 2012).

3. Mechanical properties and behaviour

The mechanical behaviour of spatial structures is significantly improved by using folding techniques. A folding structure can cover a large span without bending of the individual plates, since they act primarily like membranes. This means that three internal forces - two normal forces n_x, n_y and one shear force n_{xy} - take over the complete loads. Diaphragms and bracings are required to enable the described mechanical model. The thickness T of the different parts is very small in relation to the length L and width W (figure 1). The structural characteristics of the different folding types can be categorized mainly into prismatic and general structures.

3.1. PRISMATIC FOLDED PLATE STRUCTURES

Prismatic folded plate structures - as shown in figure 1 - are relatively easy to handle regarding analytical computations. They can be generated geometrically by moving a cross section area (in fig. 1 in yz-plane) along a line orthogonal (x-axis) to the section.

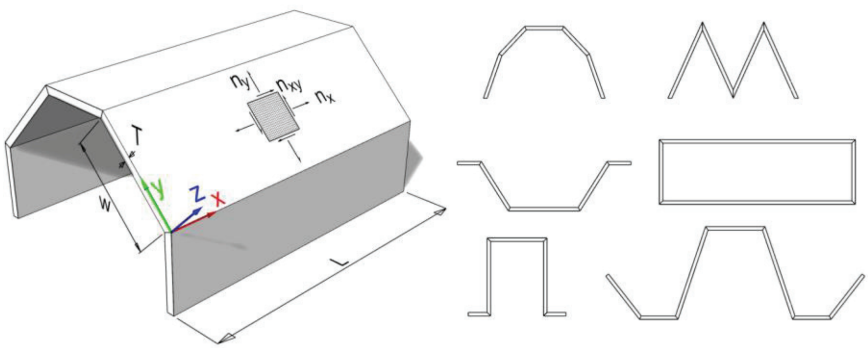

Figure 1. Prismatic folded plate structure (left) and different cross sections (right).

The membrane forces along the common edges of the adjacent parts must be transferred by an appropriate connection system. The orthogonal membrane forces parallel to the edges can be neglected, but the orthogonal forces orthogonal to the edges and the shear forces are of importance. If the deformations of the edges are very small in comparison to the deformations of the plates (figure 2 left) the usage of the elementary folding theory is quite appropriate (Flügge, 1973; Timoshenko, 1959).

In addition to the internal forces bending moments are developed. The bending moments parallel to the edges can be neglected, but the bending moments transverse to the edges and the torsional moments are responsible to transfer the forces for a rigid connection. To find an analytical solution Fourier series can be used. This theory is an enhanced one and should be used when the deformations of the plates and the edges are similar (figure 2 right).

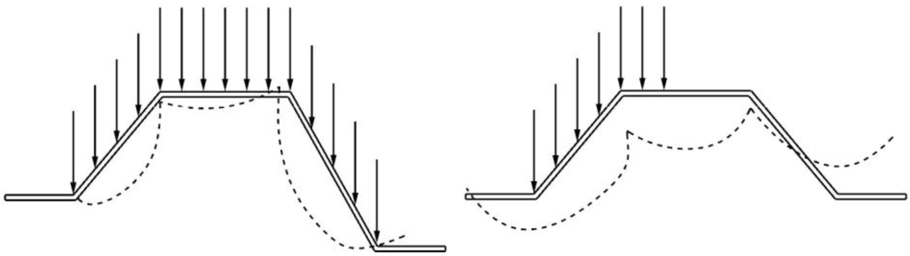

Figure 2. Deformations (dashed lines) of the plates.

3.2. GENERAL FOLDED PLATE STRUCTURES

For general folded plate structures, an analytical solution for the computation of the internal forces is no more feasible. For this case, it is justified to develop numerical methods like FEM.

4. Geometry

4.1. FOLDING

One of the main aspects in our work is the geometry of folding. As in previous works elaborated (Stavric and Wiltsche, 2014; Wiltsche and Stavric, 2014) we developed a detailed geometric approach to the design of folding structures that can mainly be used for architectural design. One of our initial points is always to work out and compare paper folded with CAD-driven parametric models. Paper models can lead very often to a main design. As paper is bendable these models can be very often misinterpreted in terms of geometry. Parametric CAD models must be geometrically precise and yield hundreds of alternatives. However, both approaches complement each other.

Usually we can distinguish between rigid linear and curved folding. As we are interested in working with standard plane material, we focus in rigid linear folding. We call rigid linear folding that kind of folding which produces straight folding edges and every polygon part in between the edges stays flat throughout the complete folding process (figure 3). However, there exist already very interesting projects using curved folding in architectural scale as mentioned in Verma et al. (2013) or the curved CLT panels of EPFL (2013).

For a designer the form is always essential (Jackson, 2011). As we are interested in buildable folding structures, we concentrate more in geometrical shapes than in figurative folded origami (human or animal forms). We deduce our forms from geometric basic shapes. These are especially planes, cylinders, cones, loft surfaces, developable surfaces or complex surfaces based on the combination of the basic forms. Figure 3 shows some of these forms.

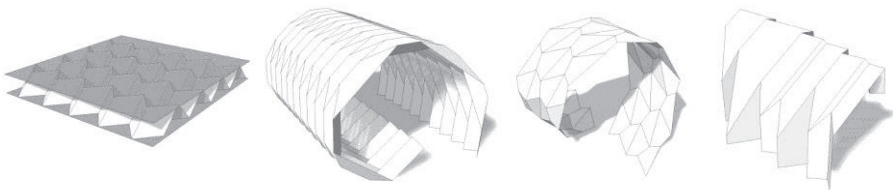

Figure 3. Different linear folding shapes (flat, cylindrical, screwed and lofted).

4.2. OFFSET

Not every folding structure is an appropriate design for building purposes. Since a folding structure is also a building envelope it is of great importance to develop a clear and detailed connection system for the elements. This is valid for both sides of the folding structure. On the outside it is important for rain protection and to prevent water accumulation in pockets and in the inside due to esthetical reasons.

The connection of four or five plane parts meeting in one knot is for practical work a very complex challenge. If the parts are additionally of a certain thickness, a nice architectural solution is more or less impossible. Therefore, we prefer using forms where at most four parts meet in one knot. If material of a certain thickness (more than 1 inch) is used an offset problem becomes crucial. For a precise connection in the knots the outer and inner faces of the adjacent panels have to meet in one point, respectively (see figure 4). Two neighbouring panels have to meet along their mitre cut (i.e. symmetry plane) to get a correct and proper solution. The geometric version to guarantee appropriate offset can be found in Wang et al. (2007), where the opposite angles a_1, a_2 and b_1,b_2 in a knot must sum up to the same result: $a_1 + a_2 = b_1 + b_2$. Moreover, if $a_1 + a_2 = 180°$ the structure is folded and developed from a plane sheet of paper without a cut.

Usually a butt joint is the typical connection principle when connecting rectangle panels orthogonally. However, as we use arbitrary angles between adjacent parts this procedure has to be adapted.

4.3. NESTING

Since folding structures are often developed from a sheet of paper, the nesting of the parts for the production process in real architectural scale is given almost automatically and material efficiently. For the cutting process of panels with thickness, the nesting has to be adapted, since the CNC machines need a certain space.

Figure 4. For the precise connection of four panels with thickness the opposite angles in a knot has to sum up to the same result $a_1+a_2=b_1+b_2$ and the panels have to be mitred along their symmetry planes.

5. Parametric Approach

At the beginning, we always choose an overall geometry, and then we select the appropriate folding-net. Since we control the geometry of our folding structures, we always produce geometrical precise parametric CAD-models, mainly with the software Rhinoceros and Grasshopper. We can integrate constraints, which are necessary to work out a project in architectural scale: panel size, angles between panels, panel thickness and edge length. In addition, we can animate all different positions during the folding process until we come to the desired design (figure 5).

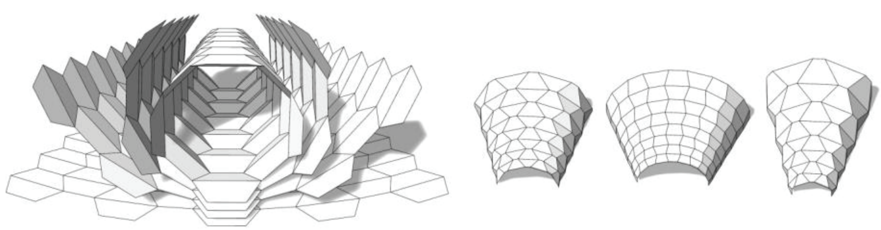

Figure 5. Different positions of the folding process of a conical shape (left) and different kinds of panel geometry (right), all parametrically controlled.

6. Project Open stage theatre

In order to proof our folding concept we applied and implemented our theoretical approach in form of a stand-alone (plug and play) contemporary stage theatre where a folding structure was an appropriate structural and formal concept. This so-called “Origami Theatre” in the city of Novi Sad (Serbia) is the outcome of a strong collaboration between theatre stage designers, light designers, geometricians, structural engineers and architects. It shows that the integration of wood as building material with a lightweight load-bearing structural system offers a great potential.

6.1. PROJECT CONSTRAINTS

The theatre stage was planned for a music and theatre festival as a temporary building, which should be reassembled up to three times and adaptable for three different locations in the city of Novi Sad. The three locations have different conditions and constrains that influenced the choice of the structural system and the design process. The theatre was planned for different kind of performances given by small alternative theatre groups as a part of art performance in the public space.

The first site is inside a fortress complex, which was built about 300 years ago. The complex that lies on a hill was used as a military, defense system in former centuries and it is tunneled with 16 km of underground tubes. To the highest part of the fortress, where the theater should be placed, leads only a narrow one-way cobbled road. This led to a limitation of both the transportation vehicles and the building elements in size and weight. The exposed position on top of the hill implicated additionally the problem of strong wind.

The second location, which is in the city park exposes the theatre to a high level of damage and vandalism and the third location, is in downtown.

6.2. PROJECT IMPLEMENTATION

The mentioned constraints led to the choice of a folding structure made of cross-laminated timber, especially because of panel size limitations, transport and the possibility to rebuild the stage several times. We chose a four sided irregular cross-section profile that defines an envelope to cover the stage area. The cross section led to an asymmetrical footprint that influences positively the acoustical properties of the structure. The platform is elevated up to 50 inches over the surrounding terrain (figure 6 left).

In accordance with the stage designers and to adapt the stage for different performances, we decided to design a shape that follows a cone. Such a shape offers a spatial experience similar to the relief perspective that is often used in conventional theatres for simulating extended space. Moreover, we chose a folding pattern, which solves the offset problem of the panels (see chapter 4.2; Stavric and Wiltsche, 2014).

In order to improve the acoustic reflection and to open the whole structure to the audience, one panel on the front and one on the backside of the stage were extended. This creates an interplay between the large and the small part of the stage and allows both the use of the front and the backside as a separated stage; and it is adaptable for children's performances.

The CAD-model was setup parametrically with the software Rhinoceros and Grasshopper, wherein we included all necessary constraints: This is the minimum and maximum length of the individual parts (due to the limited transportation and the standard CLT size), angles between the panels (for a safe connection these angles had to be between 75° and 115°) and thickness of the panels (due to the optimization of material consumption). Figure 5 shows different designs that were considered. Additionally to the geometrical model, our parametrical model calculated all building costs in real time that led to a direct review of the early stage of the design.

One very important advantage of such a conical folding structure is that the existing structure can be extended or shorted without changing static properties of the whole building.

6.3 MECHANICAL COMPUTATION

As already mentioned in chapter 3.2 a numerical model was needed for the computation of the internal forces of the stage, since the shape is a general one. This model is comparable to the elementary folding theory of chapter 3.1. Based on a FEM model the load cases of deadweight, wind and snow were investigated (figure 6 right). For the plates five layered CLT panels were chosen. The overall thickness is 3.74 inch. Based on the computed internal forces the regarded verifications were easily fulfilled. Only the extended panels at the front and the backside have to be braced, as it can be seen on the right side of figure 6.

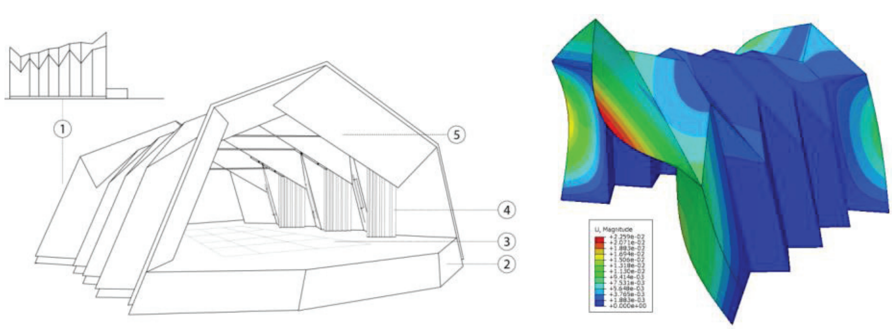

Figure 6. Left side: 1) conical shape, 2) platform, 3) moveable parts, 4) theatre streets and 5) rails for lights. Right side: FEM model with scaled deformation.

The edge forces were needed to setup the connection system. Screws which are drilled under 45° to the edge direction were considered. The highest shear forces occurred along the relatively short edges in the transmission area between the horizontal and vertical parts. For the edge with the highest forces self-tapered screws with a diameter of 0.3 inch, a length of 8 inch and a distance of 8 inch are needed.

6.4. PROTOTYP

In collaboration with a higher technical school, we produced a prototype in the scale 1:4 (Figure 7). We used three-layer laminated spruce panels with a thickness of 0.75in. The inclined mitre-cuts were manufactured by hand, since the production of the small sized panels was too time-consuming for professional CNC machines. We used screws with a length of 3in. As the prototype was very robust and rigid, we tightened the screws in a relatively great distance of about 8in (like for the original model calculated). Due to the mitre-cuts the assembly of the different parts was custom-fit and predetermined and easier to handle as for ordinary butt joints. However, the order of assembly was very important to consider so especially the last plates could be mounted.

Figure 7. The students, who built the prototype.

7. Conclusion

This paper shows a setup for buildable folding structures made from timber. We proposed the usage of cross-laminated timber (CLT) which is used more and more in the building industry, in addition to conventional material such as concrete and glass. As a natural non-carbon product, CLT it is said to become an important building material, especially with regard to sustainable architecture. As we entered the complex field of folding plate structures, which is not yet really explored in combination with CLT, it is important to collaborate with engineers to explore all the possibilities of this natural material to design new fascinating and challenging architecture.

8. Future work

Based on our current work, we would like to include more constraints like static considerations and complex geometric forms in our parametric model. The virtual model should be more flexible in terms of other materials, connection systems and design requirements. We would like to apply curved folding also for wood structures with the aim to open a new formal flexibility in wood constructions and to bring new designs and visual identities to the building. Therefore, the collaboration with civil engineers must be further increased.

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