Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Fold and Snap - Flatpacking a wooden Beam

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Abstract

The adaption of curved folding strategies in timber construction applied to thin wooden plates is the topic of ongoing research. In the actual context the authors develop the strategy further with the aim of an introduction of the strategy in the AEC. For this purpose, demonstrators in various scales and materials were developed [1] [2]. While curved folding has been proven to be a potential game-changer in timber construction, using a flat packed beam in combination with a snapping bistable mechanism assembled to a bridge-like structure has not yet been demonstrated.

In this paper the authors will present a demonstrator consisting of two identical beams assembled flat and actuated manually using a snapping mechanism to keep the final folded geometry in a stable state.

Keywords: Structural Origami, Structural Morphology, Curved folding, timber construction, innovative manufacturing

1. Introduction

The application and adaptation of folding techniques to generate statically sound structures, also known as structural origami, has enabled new fabrication strategies in various fields. In timber construction it could allow for the use of thin wooden CLT-plates, assembled to deployable structures, folded in final state, and further used as structurally valid building parts. Ongoing investigations [2] proof that the use of these plates for structural parts instead of classical use as cladding or parts of timber stud walls is a valid strategy for timber construction.

The fact that a similar approach was shown by Soyskap et al. [3] for satellite parts underlines this theory, as space travel is dependent on resource efficiency and lightweight structures.

Demonstrations in various scales have proven that this idea has potential not only for smaller scales, such as the packaging industry or design-objects but also for the building industry, particularly in timber construction.

In this paper the authors will discuss the design and development of a curved folded beam with a hollow cross-section that snaps into its final state. The mechanism comprises two identical curved folded mechanisms that are connected along their outer edges. This forces the structure to snap into a stable position after being actuated into a certain state.

The focus of this paper is the discussion of this strategy, its general constraints and the development of a large-scale demonstrator spanning 10 meters. Therefore, the authors will discuss the relation of curved folding and wood, in particular the geometric, material and structural constraints that need to be considered during the process. The authors will show how the hinges need to be detailed and applied to a thick material like wooden plates. Finally, the bridge will be discussed in detail. From the general design to the fabrication and assembly process, the authors will give a detailed description. The demonstrator consists of multiple elements that were assembled to two large sheets, and then folded into rectangular flat multilayer packages. Each package was manually actuated until it snapped into its final position and then assembled into a bridge-like structure.

Figure 1: the bridge on site

2. Curved Folded Wood

Folding and timber construction has already largely been described and investigated. The focus here is mainly on straight fold-lines and rigid plates [4]. Curved fold-lines and therefore the introduction to curved folding [5] and wood results in a more complex result, as active bending [6] needs to be considered. The necessity of considering of material thickness leads to in thick folding [7]. This creates an additional level of complexity to the entire process when it comes to hinge detailing for example.

2.1. Materialization

Early studies show that curved folding in wood requires a holistic approach, adding additional constraints to the thick folding [7] problematic. The design is informed by the material properties as e.g.: available wood quality, sheet size or bending behavior, the folding mechanism and its degrees of freedom, the hinge material and its detailing and finally the actuation method.

Depending on the available sheet size and the folding mechanism, especially its valley and mountain assignment, we can differentiate between single-sheet and multi-sheet constructions. Single sheet constructions consist of one single layer of material for each foldable patch. As shown with the application of the lens tessellation, a single sheet construction with identical fold assignments is a valid solution if the foldable patches are not exceeding the sheet size.

If the foldable patches exceed the available sheet size, a multi-sheet construction needs to be used, that allows also for the generation of large sheets with tangent continuous curvature in bent state, through overlapping plates. Another reason for this solution can of course be structural needs, that require a higher plate thickness as provided by a supplier.

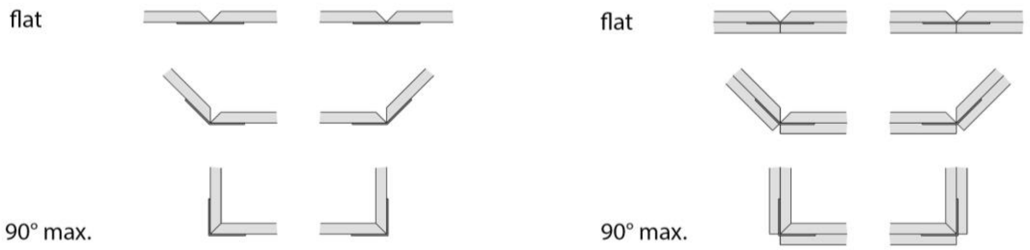

Figure 2: single (left) and multi-sheet(right) construction and its consequences for hinge position

Depending on the entire material thickness, the maximum bending radius needs to be defined to avoid structural failure. Adapted from the glulam fabrication the authors applied a minimum bending radius above 200 times the material thickness. In some cases, like e.g. OSB-plates, a value of 150 is possible, but weakens the final strength of the entire folded configuration.

During the design process of structurally foldable configurations, the authors propose two approaches for choosing the of cross sections. When starting from a certain given material thickness, it is advantageous to consider the maximum radius already during the geometry generation. Therefore, approaches that allow for the direct control of the bent-folded state are advantageous. Mirror reflection of a given surface, based on a 2Dplanar curve allows this control to a certain level, but is sometimes limiting in the designs that can be achieved. If the design should have less constraints the isometry enforcement [8] approach can be used, that requires always the monitoring of all surface patches concerning their bending radii. Using the Lotus [9] approach, starting from one surface with a pre-defined curvature always requires monitoring of the second generated patch, and is therefore a good compromise in the design stage.

2.2. Hinge Detailing

Dealing with large foldable structures the hinge detailing is key to success. As already shown by Tachi [7], the plate thickness in relation to location of the “zero-thickness” plane and therefore the hinge location is of utmost importance for a deployable mechanism.

In contrast to rigid panels, bent panels experience bending strains at their upper and lower boundary surface. Depending on their bending direction, either the top or bottom layer shrinks or elongates. As folding along curved creases causes in neighboring patches opposite bending strains. Thus, the lengths changes of the bottom and top layer along the fold-lines add up. These length changes cause stress peaks at the fold-line’s ends.

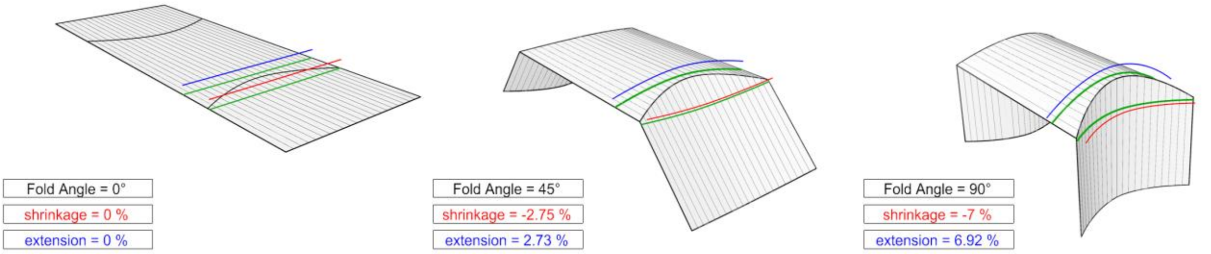

Figure 3: the length change along a curved fold-line during motion. The section-curves normal to the rulings (green) and the related extension(blue) and shrinking (red) related to the offset.

These effects have a direct influence on the hinge detailing and the material. Previous experiments proved, that a textile hinge from silkscreen-printing textile is a good solution if mounted properly. The textile hinge can either be used for single-sheet constructions mounted on one outer layer of the wooden sheets, or it can be mounted between two sheets. Ideally the textile is located on the side of the structure where tension forces appear.

In multi-layer constructions the textile can easily be integrated between two glued sheets of material in the “zero-thickness” layer. Mounting the textile requires a good strategy, as the textile should be fixed as close as possible to the hinge zone at the fold-line, but glue must be avoided to reach the hinge itself, as it would then break the hardened fibers of the textile during folding motion. Breaking the textile locally in most cases initiates the disintegration of the entire textile hinge. Based on the pattern the structural failure of one single fold-line can result in the failure of the entire structure.

To solve this problem, the authors tried two different solutions for the bridge beams, consisting of thin metal that is cold deformed during the folding process. The sheets were either mechanically fixed through pressure or glued directly to the material.

3. Snapping Bridge

During the investigation, the authors decided to build a demonstrator, that allows to explicitly show the potential of curved folding in timber plates, with a classical building element, namely a bridge beam. Explicitly the authors show with this construction, the advantages of multi-sheet fabrication, prefabrication, cold deformed metal hinges, and the structural performance of the entire building element.

3.1. Design

The design of the bridge foresees a span of 10 meters and the developed overlapped pattern was thus larger than the available sheet size of 5 meters. The bridge beam consisted of two identical beam geometries, to be able to compare the performance of the hinge details. In section the bridge changed its structural height from a small cross section near the supports to a large one in mid-spam. The geometry featured a maximum curvature based on the glulam cross section depth to curvature relation, and finally showed a potential solution to the unfolding problem of the mechanism.

The bridge was developed with the above-described isometry method, where a surface based on a curve is mirrored with a series of planes, generating the fold-lines. The curve is controlled in the section of the entire bridge. The generating curve, and therefore all curved fold-lines, has two inflection points. It starts at the supports horizontally and then changes slowly into an arch to change into horizontal direction again. This surface was then folded 90 degrees in vertical direction on both sides, and then mirrored along a xy-plane to form a closed loop. This closed loop is globally developable, if opened at a seamline.

Since the demonstrator was built at the end of the Covid19 pandemic, the only available and financially viable material was OSB. So the bridge is fabricated from two layers of 19mm OSB-plates, and had therefore a maximum bending radius of 7600mm.

Foldable mechanisms have always the problem that they can not only be folded in a three-dimensional form, but also tend to unfold to their original flat state again. From the manifold solutions, the authors decided to not use a mechanical solution that is applied to the folded beam but develop a folding mechanism that will stay in its final configuration for geometric reasons. This can be achieved with this geometry, by adding two straight fold-lines to the mechanism. These straight lines are located exactly in the xy-plane that is also used for the mirroring process. As shown in Figure 4 these two additional foldlines allow for the flat-foldability of the mechanism.

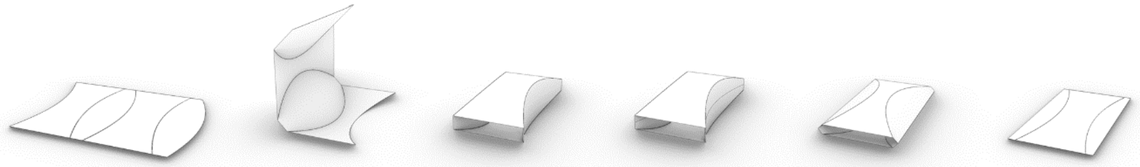

Figure 4: from rigid developable (left) to folded state(mid) to flat folded closed loop state with additional fold-lines (right)

As straight and curved fold-lines in this configuration generate high stresses during folding motion, the mechanism now snaps between two states: The flat-folded and the targeted original state. It is no longer a rigid foldable mechanism, but a bi-stable one, that activates during motion not only the bending moments, but also torsional moments. Especially in the middle section of the beam the geometric length problem causes high stresses. Besides the advantage of snap through after actuation, the beam is now also a rectangular flat-packed package, that can be efficiently transported or stored in this state.

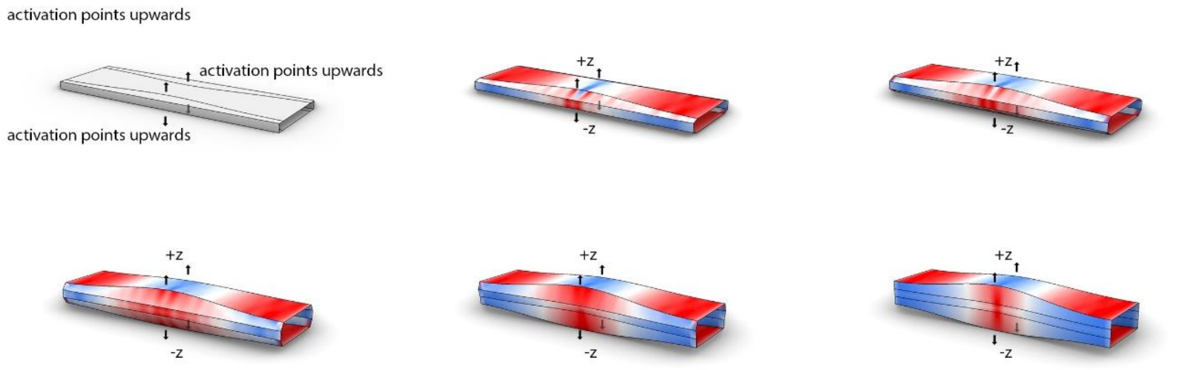

Figure 5: Curvature Analysis during motion showing the torsion before the final folded state, actuated by pointwise forces, here the mean curvature of the different surfaces is shown, red shows convex curvature and blue concave curvature.

The downside is that the mechanism now has in flat folded state two fold-lines whereas the patches have a fold-angle of 180 degrees. This is not a problem for a paper model, but interpreted as thick folding, with the hinge between two plates this becomes a technical problem [10]. In this case the authors decided to divide the 180 angle into two 90 degree angles, with an offset of 20 cm. As the hinge is materialized form metal plates, that are deformed during motion, a reduction of deformation caused by folding is advantageous, to reduce the risk of breaking.

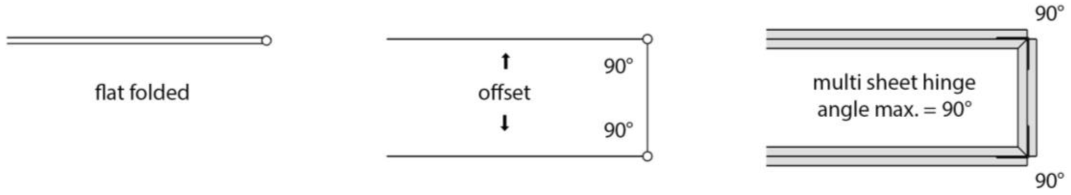

Figure 6: Solution for the flat folded state with material thickness by dividing a 180° in half

From a structural point of view, the beam offers a hollow cross section with a changing height towards the center of the bridge beam similar to a fish-bellied-beam. This classical beam concept allows for spans of 10 meters by OSB plates only.

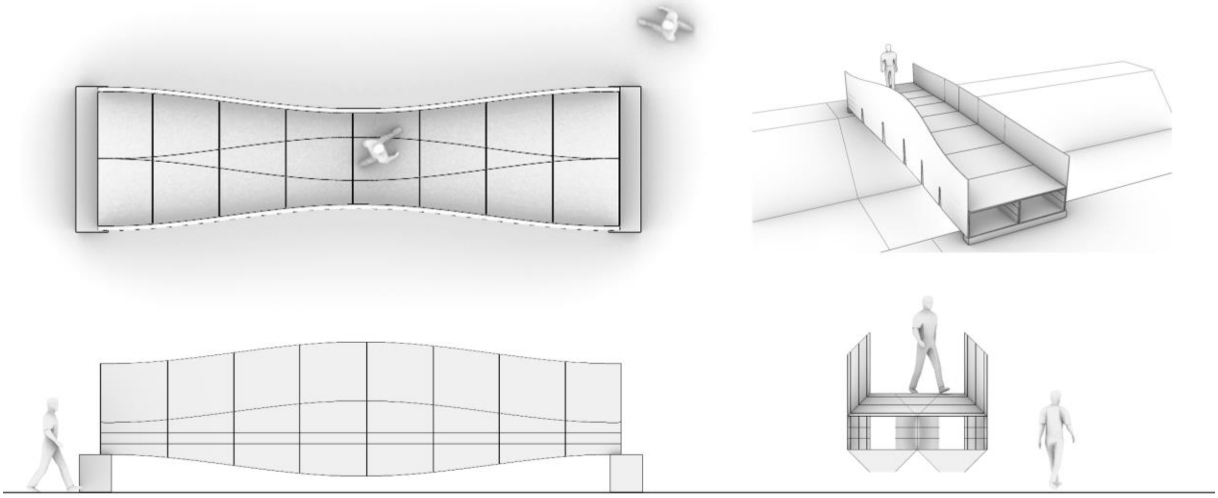

Figure 7: the final bridge design in top-, side- front- and perspective view

3.2. Fabrication and Assembly

The milling of the flat plates was relatively fast, as the miter joints were reduced to four curved and four straight fold-lines of the inner layer. All outer plates and curves have been milled orthogonal to the milling plane. Along the fold-lines positioning holes were drilled, that allowed for a fast positioning of the parts and in case of the “Gripmetal” hinge a mechanical local pressure plate, that can be screwed from both sides to impress the plates. The milling process took 24 hours in total.

Figure 8: the folding process of one beam from developed to folded state (from left to right)

The milled pieces were then assembled to one large wooden sheet of 1000 by 400 centimeters. The individual patches had overlaps of 40 cm so they can form a single surface, that has no kink in bent state. After laying out the first layer of material, the hinges were laid out in place and fixed by the second layer of wooden plates. While the “Gripmetal” hinges were individually pressed in with special metal parts, the thin sheet-metal was just glued between the two sheets of material. The final plate was then glued under pressure overnight.

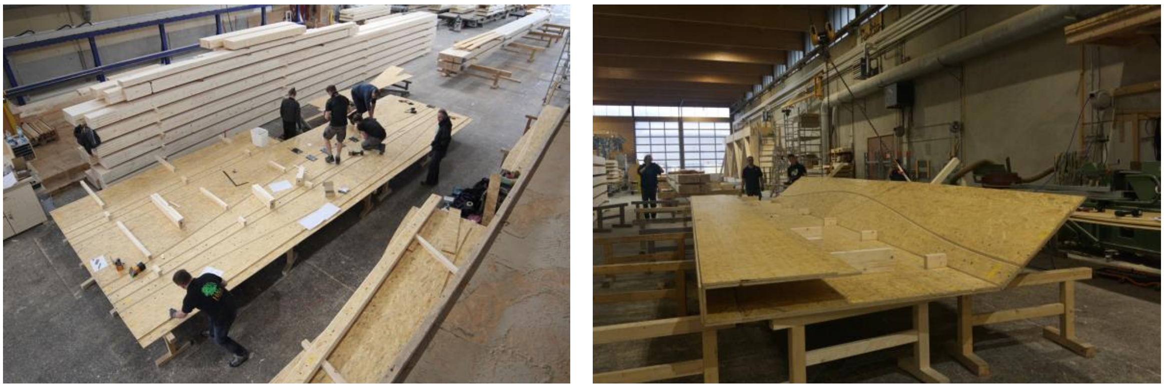

Figure 9: the assembly of the plates to one large “sheet(left) and
the folding process to form a closed cross section (right)

After the planar sheets were finally ready, they were folded with the help of a crane to form the rectangular hollow sandwich. To avoid bending in this state, the wooden elements were fixed in the unfolded state in a way, that they form a support in rectangular state. The height of the stick elements was half the height of the rectangular piece that separated the 180-degree fold. The seamlines of the plates, was executed with an overlap and also glued under pressure.

3.3. Actuation

After unsuccessful tests with simple levers fixed on the sides of the beams, the actuation process was executed with long threaded bars. The bars were situated in the parallel rectangular distance parts of the rectangular package. Introducing a force, by shortening the distance between the two parts was actuating the mechanism. The bolt nuts were manually tightened, to have haptic feedback to estimate when the snapping might appear. The threaded bars were guided through a wooden piece in the beam, so the snapping energy would be blocked in final folded state by this rigid part, to avoid the hinge's failure through the dynamic snapping process.

After the effort of screwing started to become less and less, the beam finally snapped in its final form. This strategy worked for both identical beams. Although the snapping process was planned, the exact moment of the snapping motion was unpredictable, and therefore surprising for the workers.

Figure 10: One beam in flat state, and on in folded state in the back (left)
and the beam during actuation (right)

The two beams were finally assembled together and the gap was closed with one single layer of OSB-plates as walkway. A handrail from OSB-plates was also attached to the structure, so it could be used as a pedestrian bridge. As the exact location of the final object was not yet known during fabrication, the process was executed in the workshop of the industrial partner Holzbau Saurer.

Figure 11: One final beam element (left) and the bridge consisting of two beams during construction (right)

4. Snapping Bridge

Figure 12: The final bridge spanning over a small river

The assembled bridge was brought on site close to the community of Reutte. The bridge was temporarily placed over a small river bed spanning 9.80 meters. It was strong enough to hold more than 20 persons. The entire assembly time after milling was less than one day.

Mechanical testing of the bridge allowed for a point-load of more than 35 KN per beam. For the testing of structural performance, a more detailed work is currently in progress.

4. Conclusion

The authors showed and explained, how a curved folded wooden bridge demonstrator was developed, fabricated and built. This demonstrator, lead to profound insights that allow for the implementation of curved folding in timber construction. The Demonstrator showed that snapping mechanisms are one potential approach for blocking a folding mechanism in final state at a scale of several meter.

5. Outlook

The implementation of curved folded mechanisms is an interesting field of research that might “soonish” be applied to AEC. However, the demonstrator shows that manual actuation is possible but not a potential strategy for industrial applications.

The design freedom, especially for architects, needs obviously more investigations, but for the detailed development the simplification of geometries is a necessity.

In future research the authors will not only focus on the geometry and application, but also on the hinge geometry itself. The difficulty of the hinge detail lies in the forces it must transfer during motion and in final state. Snapping leads to higher stresses that require a durable structural joint solution. Cold deformed metal hinges cannot be applied in case of repeated unfolding and refolding due to fatigue.

Acknowledgements

The authors would like to thank to the partners of the research project “Plates2Structures-THINK.WOOD.Innovation” (FFG No.: 907048) - Funding Association of Austria (FFG) and our partner “Holzbau Saurer” from Reutte, Tyrol.

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