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BENDING OF CLT BY THE LATTICE HINGE METHOD

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ABSTRACT: This study provides an overview of ongoing research on cross-laminated timber (CLT) panels bent with the lattice hinge method: a system that has been explored by ArtBuild and Ney & Partners WOW for two temporary structures. First, the parameters that define the lattice hinge cutting process are described and exposed at the scale of CLT panels. Second, the results of a series of experimental tests will be investigated to define the structural behaviour and properties of slotted CLT panels. Finally, the two projects that were built will be presented in terms of architecture and structural details. The first one is a pavilion built for the Libramont Fair in 2019, and the second one, is an ephemeral auditorium that has been set up in the ephemeral Grand Palais in Paris for the International Wooden Construction Forum (Forum Bois Construction) in 2021.

KEYWORDS: CLT, lattice hinge, bending method, CNC manufacturing

1 INTRODUCTION

Traditional methods for wood bending can be classified into four categories:

(1) In-plane cutting of curved piece

The easiest way to obtain a curved piece of wood is to cut it out of a larger raw element. The advantage of this technique is that it is very simple and does not generate internal stresses in the piece of wood. However, it generates large losses of material and is not feasible for large elements and thicknesses. In addition, the wood grain of the curved element is interrupted by the cut-outs and reduces its bearing capacity.

(2) Hot bending

When the moisture content of wood increased it becomes softer and easier to bend. The hot bending process consists of immersing wood in hot water or subjecting it to steam (usually under pressure). Then, it is placed in a bending mould while it dries. Once dry, the wood will keep the curvature that was imposed by the mould. This method requires a lot of time and specific equipment.

(3) Gluing of lamellas

The technique commonly used for glued laminated timber offers the ability to easily create curved beams. The standard lamellas of 40 mm thick have a low rigidity and are easy to bend. The successive gluing of lamellas can be done by a hydraulic press or mould in order to shape the beam with the required curvature.

(4) Notching of wood

The purpose of the notches is to reduce the stiffness of the wooden piece by removing some parts of the material.
The advantage of this method is to be reversible because the curvature can be maintained by mechanical fasteners instead of glue. It is commonly used for the realization of musical instruments such as violin and sees its success growing the last few years with the arrival of laser cutters which allow to multiply the number of possible cutting patterns. The lattice hinge method enters in this category.

All these techniques can be applied to solid wood and glulam beams, but it is more complicated for large timber panels such as CLT. Therefore, this study aims to provide a bending technique for CLT panels in order to explore a new architectural typology.

2 LATTICE HINGE : DEFINITION AND PARAMETERS

2.1 DEFINITION

The ‘lattice hinge’ is formed by an array of parallel overlapping cuts in a flat wooden panel. By dividing the panel into a set of thin columns, each column can twist on its own axis and rotate. The length of these so called “torsion legs” drives the overall curvature radius of the panel. The longer the leg, the more flexible the panel. The piece of CLT that links two torsion legs are considered as planar surfaces and have no influence on the overall curvature of the panel.

2.2 GEOMETRICAL PARAMETERS

2.2.1 Panel dimensions

The external dimensions of the CLT panel are determined by its length *L*, width *W* and thickness *h*.

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2.2.2 Lattice hinge pattern dimensions

The cutting pattern of the lattice hinge is defined by the number of torsion legs required across the width n and height N_{div} of the panel, as well as the width b of the legs.

2.2.3 Panel curvature

The bending curvature of the panel is defined by the radius of curvature R. It is also possible to calculate the sag f of the panel once bent, the final reduced width (or chord of the arc C) and the global angle of rotation of the panel φ with the following equations:

$$f = R \cdot \left(1 - \cos\left(\frac{\varphi}{2}\right)\right) \tag{1}$$

$$C = 2 \cdot R \cdot \sin\left(\frac{\varphi}{2}\right) \tag{2}$$

$$\varphi = \frac{W}{R} \tag{3}$$

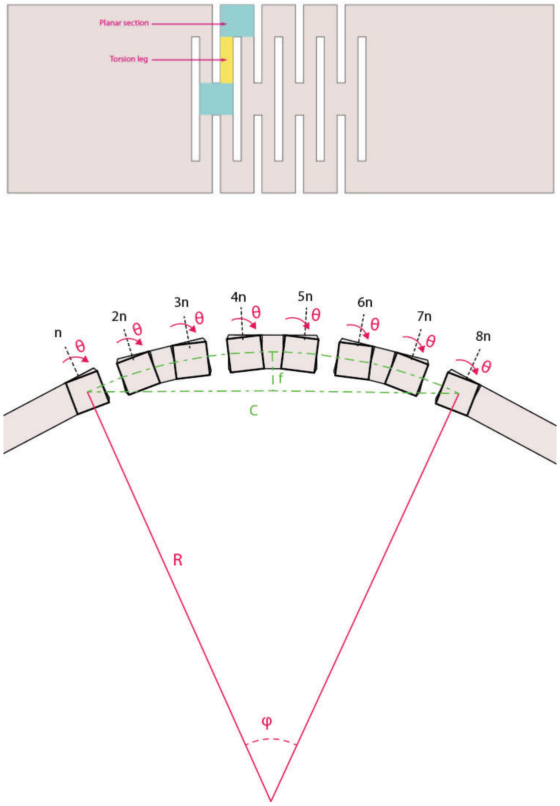

Figure 1: Geometric parameters of lattice hinge [3] [6]

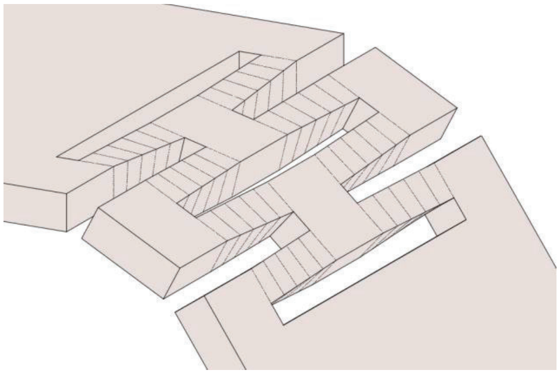

Figure 2: 3D view of twisting mechanism by lattice hinge [3][6]

2.3 DESIGN OF TORSION LEGS

To bend a CLT panel, each torsion leg rotates around its own axis, with an angle:

$$\theta = \frac{\varphi}{n} \tag{4}$$

The torsion legs are submitted to shear stresses due to a torsion moment. The torsion moment in a square wooden element can be expressed by two formulas [10] - depending on the angle of rotation of the torsion leg (5) or depending on the shear stress (6):

$$T = \frac{G_{eq} \cdot \theta \cdot J}{l} \tag{5}$$

$$T = \tau \cdot \alpha \cdot h \cdot b^2 \tag{6}$$

By combining the two formulas, we can define the expression of the minimal required length for torsion legs in function of the desired curvature and the maximum shear stress allowed $\tau = \tau_{max} = f_{v,d}$:

$$l_{min} = \frac{G_{eq} \cdot \theta \cdot J}{f_{v,d} \cdot \alpha \cdot h \cdot b^2} \tag{7}$$

where:

- G_{eq} is the equivalent shear modulus of a torsion leg that has been defined by a series of tests. The resulting value is given in the table below as well as the standard values for shear modulus of CLT for comparison.

Table 1: Standard shear modulus value for CLT

		Design values	
Shear modulus CLT	$G_{0,mean}$	690	N/mm²
Rolling shear modulus CLT	G_R	50	N/mm²
Equivalent shear modulus	G_{eq}	210	N/mm²

− $f_{v,d}$ is the shear resistance capacity of CLT. Bending is applied as a permanent loading, therefore we assume $k_{mod} = 0.6$ and $\gamma_M = 1.25$ for CLT.

$$f_{v,d} = f_{v,k} \times \frac{k_{mod}}{\gamma_M} \tag{8}$$

$$f_{v,d} = 1.68\ N/mm^2$$

- J is the torsional inertia of a rectangular cross-section. As CLT is made of several cross layers of wood, rolling shear probably has an influence on the J value. This interaction will be studied by a series of experimental torsion tests on CLT.

$$J = \beta \cdot h \cdot b^3 \tag{9}$$

− α and β are form coefficients defined with empirical values from the table below.

Table 2: *Form coefficients for torsional inertia [12]*

h/b	1	1,5	2	3	6	10
$\boldsymbol{\alpha}$	0,208	0,231	0,246	0,267	0,299	0,313
$\boldsymbol{\beta}$	0,141	0,196	0,229	0,263	0,299	0,313

2.4 PARAMETRIC MODELLING

All parameters and formulas listed in the previous section have been implemented in a parametric model with Grasshopper/Rhino. The input data are the panel dimensions and the required radius of curvature. The lattice hinge pattern dimensions are given as output and drawn on any given developable surface.

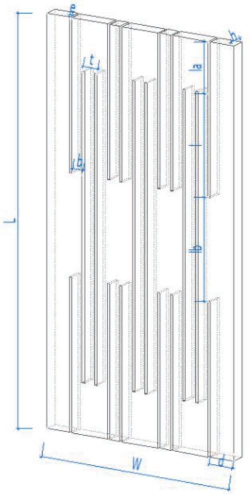

Figure 3: *Axonometric view of slotted CLT panel and dimension parameters*

3 EXPERIMENTAL TESTS

The aim is to define the structural behaviour of a slotted CLT panel for each loading types and directions. A total of 5 different load tests have been realised :

- Torsion test
- Transversal bending test
- Longitudinal bending test
- Axial tension test
- Axial compression test

The results of those tests helped to quantify the loss of stiffness due to the slots in the CLT panels.

First, the torsion test will be described in order to find the equivalent shear modulus value that is needed to define the length of the torsion legs for the cutting pattern. Then, only transversal bending test is described in this paper as it has the biggest impact on the loss of stiffness for the CLT panel. All test results can be found in [7].

3.1 TORSION TEST

Since torsion tests are rarely performed on wood and the partner laboratory (ECAM[5]) does not have a machine specifically dedicated to torsion tests, an experimental system was designed and implemented on a test bench to allow testing of CLT samples.

A total of 8 samples have been tested in CLT 60 3s:

- 4 samples of 20 mm wide and 800 mm long
- 4 samples of 30 mm wide and 800 mm long

The loading system is composed of a lever arm fixed to the sample by a bolted connection and a rod allowing the placement of weights at the other end. Measures of deflections are taken in the centre and at both supports in order to retrieve the relative rotation angle of the sample. The torsional moment is determined by multiplying the load applied at the end of the lever arm by the distance to the sample.

Figure 4: *Torsion test system*

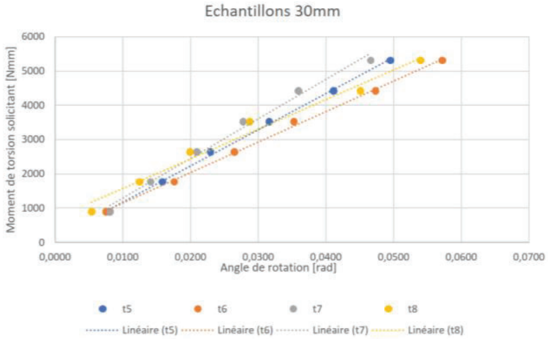

Figure 5: *Rotations* $\boldsymbol{\theta}$ *of the sample in function of the torsional moment* $\boldsymbol{T}$ *applied*

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The value of the equivalent shear modulus can be deducted from equation (5), considering that the values J and l are constant for a given cross section. The mean result for all samples is: $G_{eq} = 210\ N/mm^2$.

3.2 TRANSVERSAL BENDING TEST

A 3-point bending test was performed on slotted CLT panel. The loading was done by sand bags.3 samples have been tested in CLT 60 3s with a span of 715 mm.

Figure 6: *Transversal bending test system*

The parameter EI governing the transverse bending stiffness of the panel can be expressed using the deflection formula for a bi-supported beam subjected to point loading as follows:

$$u = \frac{q \cdot L^3}{48 \cdot E \cdot I} \quad \rightarrow \quad EI_{eq} = \frac{q \cdot L^3}{48 \cdot u} \qquad (10)$$

where u = deflection at the centre of the panel, E = modulus of elasticity, I = inertia, q = load and L = span.

Table 3: *Values of deflections for maximum load of 3,125 kNm/m*

Samples	1	2	3	Mean value	CLT (no slot)
u [mm]	33	28	39	33.50	0.32

For CLT, the transversal stiffness is given by the coefficient D_{22} in the stiffness matrix. For a 3-layer CLT panel of 60 mm: $D_{22} = 7{,}733\ kNm^2$. The tests gives a value of $D_{22,eq} = EI_{eq} = 0.071\ kNm^2$. Therefore, the loss of stiffness of a slotted CLT panel compared to a full CLT in transverse direction is about 99%. The panel loses most of its bending capacity, so an external system must be put in place to maintain it in the transverse direction. This was achieved in two different ways for the two projects where curved CLT was used (see section 5).

4 CLT PANEL PROPERTIES FOR NUMERICAL ANALYSIS

Thanks to the test results, we were able to define an equivalent stiffness matrix for a slotted CLT panel. This stiffness matrix is then used in a Finite Element software (SCIA) in order to define a simplified calculation model that is used to check the global behaviour of a structure with slotted CLT panels.

Table 4: *Stiffness matrix for slotted CLT panel*

CLT	60-3s
D11 [MNm]	$2{,}088 \cdot 10^{-1}$
D22 [MNm]	$7{,}100 \cdot 10^{-5}$
D12 [MNm]	0
D33 [MNm]	$6{,}732 \cdot 10^{-3}$
D44 [MN/m]	4,423
D55 [MN/m]	13,800
D66 [MN/m]	480,000
D77 [MN/m]	240,000
D67 [MN/m]	0
D88 [MN/m]	25,969

5 CASE STUDY

5.1 NAUTILE SYLVESTRE

5.1.1 Project background

Commissioned for the 85th edition on the occasion of Demo Forest, an event that follows the Libramont Fair, the wooden pavilion named “Nautile Sylvestre” was conceived by ArtBuild Architects, Saïse Design and Ney & Partners WOW as a totem for forestry and timber trades. It is the first structural use of bent CLT panels.

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Figure 7: *General view of the pavilion*

5.1.2 Architectural design

Inspired from the bio-structure of the banana stem, a double revolution staircase gives access to a central elevated platform at 4.5 m above ground level. The upper and lower side of the staircase offer respectively, a point of view and an exhibition gallery. Visitors can wander easily by following the curvature of the walls and crossing the pavilion from one side to the other.

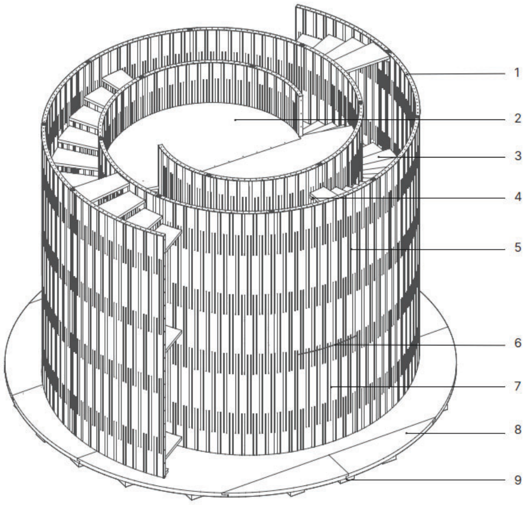

Figure 8: *Axonometric view of the Nautile Sylvestre pavilion – 1. Metal plate at the head of CLT walls assembled with splice joints / 2. Slab with CLT 60 mm assembled by lap joints / 3.Stair steps with CLT 60 mm / 4.Supporting joist for steps / 5.Bent walls with CLT 60 mm / 6. Curved door in metal frame / 7. Invisible locksmithing elements / 8. Base plate with CLT 90 mm / 9. Support wedges 300 x 300 mm*

5.1.3 Connection system of multiple slotted CLT panels

We studied several options to maintain the panels curvature and we retained a combination of three options adapted to each part of the panels. At the base, the panels are inserted into a notch that has been milled in the platform following the spiral geometry. At the top edge, an 8 mm steel plate has been added in order to not only maintain the curvature but also act as protection against rain water. Since the panels are 5.50 m high, we also defined a minimum of two intermediate lateral supports to ensure a constant curvature over the height and serving as supports preventing buckling of the panels. The staircase steps, that are laterally screwed to the CLT walls, are fulfilling this role. The whole structure gains in structural efficiency thanks to the multi-layered shell created by the successive walls of bent CLT-panels connected together : a static diagram that accurately reproduces the functioning of the banana stem.

Figure 9: *Interior view of the staircase*

5.1.4 Mounting process & reuse

For the milling process, a CNC machine was used to make the cuts in the panels. A 10 mm wide saw was chosen over milling to save production time.

Once milled with lattice hinge pattern, the prefabricated panels can be transported flat to the site. This suggests a significant economy in terms of transport costs.

On-site, the panels were curved, erected and assembled by carpentry students in a few days. First, the steel plates were screwed to the top flange and wooden pieces screwed to the bottom flange of the CLT panel to give it the right curvature. Then, the panels were lifted with a mobile crane to move them to their final position. The construction started from the centre and extended symmetrically to the outer edges of the pavilion.

After the fair, the structure was dismantled and the panels returned to their original flat condition. They were stored in a workshop waiting to be reused for the next fair.

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Figure 10: Lifting of curved CLT panel

5.2 EPHEMERAL AUDITORIUM

5.2.1 Project background

On the occasion of the 10th edition of the "Forum International Bois Construction" in Paris, the ephemeral auditorium stands in the centre of the ephemeral Grand Palais. A total amount of 64 CLT panels are bended and assembled together to create the plenary room for conferences. This temporary structure is easily dismantled and is intended to be reused for other events.

Figure 11: Interior view of the auditorium

5.2.2 Architectural design

The auditorium is a rectangular room with seating for 350 people. The perimeter walls cover an area of 29 m x 19 m with a modular construction made of bent CLT panels connected by steel bracings. This wooden curtain provides privacy but it also allows for some subtle transparency. The notches in the wood act as a sound trap and provide an acoustic barrier for the auditorium.

A single panel has a dimension of 2,40 m x 5,25 m and weigh about 300 kg. In order to stand as a stable structure, a minimum of three panels must be connected to each other. This project is made of three different constructive modules : linear walls, doors and angles. They can be inter-connected in many configurations to be able to adapt to the future needs.

The CLT panels are made of Douglas fir wood, a natural durable species. This maximizes the potential for reuse of the structure as it enables it to be used as an outdoor structure (if covered and protected from rain).

Figure 12: Wooden curtain of CLT

5.2.3 Connection system of multiple slotted CLT panels

The curvature of the panels is maintained by a post-tensioning system developed specifically for the project. Custom-made cast iron pieces are inserted into the slots and tensioned by a steel rod at each end. The geometry has been defined according to the curvature of the panel. Holes are integrated on both sides to integrate a steel rod that acts as post-tension to maintain the panel in its curved position.

All these parts can be disassembled to put the panels back flat and facilitate transport.

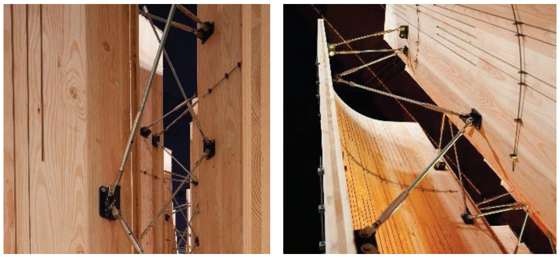

Figure 13: Connection detail between curved CLT panels

6 CONCLUSIONS

Interest in lattice hinge has been revived thanks to the growth of digital tools. This study shows how it has been implemented in CLT panels at a structural scale.

Bending by the lattice hinge method implies that wood is submitted to local torsion. As a multi-layered material, CLT does not behave like solid wood in torsion and the formulas found in the literature to calculate shear stresses due to torsion turned out to be invalid. Therefore, the torsion of CLT has been studied through a series of test to define an equivalent shear modulus that can be used for torsion calculations. Moreover, the global analysis of the projects was performed by using an equivalent stiffness matrix for CLT based on the tests results.

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The first application was to create curved bearing walls for a temporary pavilion. In the future, bent CLT panels could be used in buildings for walls or facades. Studies are still on-going to define new developments and potentials for curved CLT panels.

REFERENCES

[1] Artbuild, Nautile Sylvestre - Welcome Pavilion, 2019, [online], accessed on February 7, 2022, https://www.artbuild.com/lab/nautilus-tlc-exploration

[2] Artbuild, OSA - The ephemeral auditorium, Paris - France, 2021, [online], accessed on February 7, 2022, https://www.artbuild.com/lab/osa-the-ephemeral-auditorium-paris-france

[3] Bitoun S., Le potentiel architectural du bois plié, ENSAPM - Département transitions, 2016, [mémoire], 30 p.

[4] Deferred Procrastination, Latice Hinges Design - choosing torsional stress, [online], accessed on February 8, 2022, https://www.defproc.co.uk/analysis/lattice-hinge-design-choosing-torsional-stress/

[5] Deferred Procrastination, Latice Hinges Design - minimum bend radius, [online], accessed on February 8,2022, https://www.defproc.co.uk/analysis/lattice-hinge-design-minimum-bend-radius/

[6] Deguine L., Lattice Hinge, développement d'une méthode générique, ENSAPM, 2016, [mémoire], 82p.

[7] Malache Y., CLT cintré par la méthode du Lattice Hinge : les prémisses d'une utilisation structurelle, ECAM, Brussels, 2022, [mémoire], 110p.

[8] Ney and Partners WOW, Nautile Sylvestre pavilion, 2019, [online], accessed on March 1, 2023, https://wow.timber-engineering.partners/projects/totem-foire-de-libramont/

[9] Ney and Partners WOW, Nautile Sylvestre pavilion, 2019, [online], accessed on March 1, 2023, https://wow.timber-engineering.partners/projects/ephemeral-auditorium/

[10] PUECH V., CLT, du panneau plan au mur courbe, Ecole Nationale des Ponts et Chaussées, Paris, 2017, [mémoire], 120 p.

[11] Pro Holz, Cross Laminated Timber structural design, Basic design and engineering principles according to Eurocode, 2014, 191 p.

[12] SCIA Engineer, Calcul des caractéristiques de base du profil, [online], accessed on November 26, 2022, https://help.scia.net/17.0/fr/rb/crosssections/calculatin_of_sectional_characteristics.htm

https://doi.org/10.52202/069179-0481