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11TH HARDWOOD CONFERENCE PROCEEDINGS

Róbert Németh, Christian Hansmann, Holger Militz, Miklós Bak, Mátyás Báder

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Content

Preface to the 11TH HARDWOOD CONFERENCE

Plenary Session - Keynotes of the 11TH HARDWOOD CONFERENCE

Session I - Silvicultural aspects and forest management of hardwoods

Poster Session

Session II - Hardwood resources, product approaches, and timber trade

Session III - Surface coating and bonding characteristics of hardwoods

Session IV - Hardwood structure and properties

Session V - Hardwoods in composites and engineered materials

Session VI - Modification & functionalization

Analysing innovative wood joints crafted by laser cut spline curves

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Keywords: spline curves, laser cut, wood joints, wood panel, design, finite element analysis.

ABSTRACT

This study investigates the shape of the longitudinal joints in hardwood panels, inspired from veneer joints commonly used in the industry. The design of these joints is tailored to facilitate creative and flexible compositions. The joints adopt a mathematical description using splines, serving a good technological purpose for the wood processing. Employing laser cutting technology, the shapes are precisely crafted by a laser beam on the hardwood panels. After the process, the joints undergo a visual inspection, the material loss due to the technology is calculated, and other parameters are determined. Additionally, significant characteristics relevant to practical applications, such as joint fit, shape of accuracy, and aesthetics, are assessed. To enhance the understanding of the mechanical interactions, finite element analysis (FEA) is performed to model the mechanical contacts within the joints. A primary motivation for this research is the efficient utilization of residual wood materials. This approach aims to extend the life of the available raw materials within the value chain, contributing to sustainability goals.

INTRODUCTION

Several techniques are available for making curved cuts for decorative purposes. In order to choose the right technique the following parameters should be taken into consideration: final purpose, properties of the raw material, and the expected parameters of the processing. Options include cutting with a blade, which can be used mainly for thin wallboards and veneers. Among saws, scroll saws and bandsaws are suitable for cutting along curved lines. It is also possible to use a special cutting medium for wooden materials, such as water jet cutting. The birth of high-pressure abrasive water-jet (AWJ) cutting can be traced back to the early 1970s, when non-metallic soft materials were first cut (Jiazhong et al., 2008). With the continuously developing process, it is possible to make curved cuts, however, the watery environment and the soaking of the raw material still indicate a problem from the point of view of further processing. Laser processing is another option for curved-line cutting of wood. Certain parameters need to be considered in this procedure, including the cutting performance of the available system and the properties of the end result, such as the burnt surface obtained.

The design and analysis of the shape of joints made with different technologies were in focus of several studies, hence, the connections are vital points of any structure. Liu (2000) analysed the distribution of the stress of serpentine-end matched (SEM) joints from veneer. Sebera and Simek (2010) analysed numerically the mechanical properties of the dovetail joint made by CNC technology. Wielinga (2023) performed finite element analysis (FEA) on interlocking timber connections in order to investigate the influence of the shapes.

The main goal of our research was to determine specific curves, which can be used for joints made by laser cutting technology. This may serve as the basis for new innovative wood-based products. Therefore, our work had the following steps: curve definition for the joints with mathematical equations, laser processing with the defined curves to prepare for the joints, and finite element analysis of the joints for stress analysis.

MATERIALS AND METHODS

Definition of the curves

The base of our curves is the planar cubic Bezier curve. Let $\boldsymbol{p}_0, \boldsymbol{p}_1, \boldsymbol{p}_2$, and $\boldsymbol{p}_3$ be the control points of a Bezier curve, where $\boldsymbol{p}_0$ and $\boldsymbol{p}_3$ are the endpoints according to the left-hand side of Figure 1. Then the vector-scalar equation of the curve is

$$r(t) = p_0 B_0^3(t) + p_1 B_1^3(t) + p_2 B_2^3(t) + p_3 B_3^3(t),\ \ t \in [0,1], \tag{1}$$

where the Bernstein polynomials are $B_i^3(t) = \binom{3}{i} t^i (1-t)^{3-i}$. Its matrix form is

$$r(t) = \begin{bmatrix} t^3 & t^2 & t^1 & t^0 \end{bmatrix} \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{bmatrix},\quad t \in in[0,1] \tag{2}$$

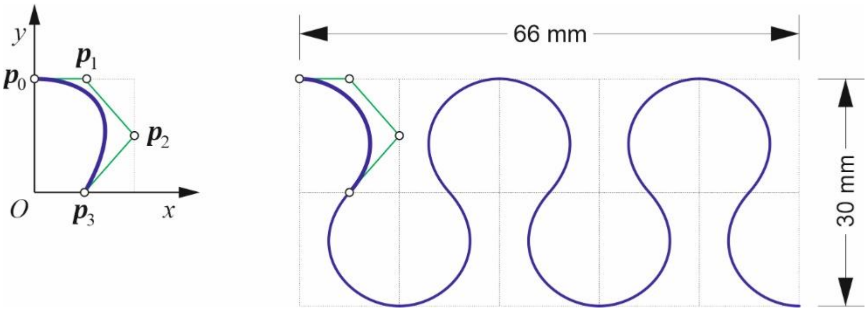


Figure 1: Definition of the joint curve no. 1

Since the width of our panel is 66 mm, we divided it into five parts, and we chose 30 mm for the joint part (see Figure 1). That way, for a symmetric joint curve, we have ten blocs, for which we define cubic Bezier arcs with four control points. Let $a = 66/5 = 13{,}2$ and $b = 30/2 = 15$. We give the coordinates of the control points of the first arc with the functions of a and b, the coordinate system can be seen in Figure 1. In all the cases, we have $\boldsymbol{p}_0 = (0, b)$ and $\boldsymbol{p}_3 = (a/2, 0)$, moreover, except the last case, $\boldsymbol{p}_1$ *and* $\boldsymbol{p}_2$ are on the lines $y = b$ and $x = a$, respectively. Table 1 shows their coordinates in detail.

Table 1: Coordinates of $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$

curves serial number	$\boldsymbol{p}_1$	$\boldsymbol{p}_2$
1	$(a/2, b)$	$(a, b/2)$
2	$(a/2, b)$	(a, b)
3	$(a/2, b)$	$(a, -b/2)$
4	$(a/2, b)$	$(a, 3b/2)$
5	$(3a/2, b)$	$(0, b)$

Let the second arc be the central rotation image of the first arc with 180° around the vertex $\boldsymbol{p}_3$. Then the mirror of the first two arcs around the line $x = a$ provides the second pair of arcs. The following pairs are also obtained by mirrors around the vertical lines $x = 2a$, $x = 3a$, and $x = 4a$. The definitions of the control points yield that not only the tangent lines, but also the curvatures are continuous in the jointing points, which means the curve provides continuous speeded laser catting.
Figure 2 shows the other four curves with their control point.

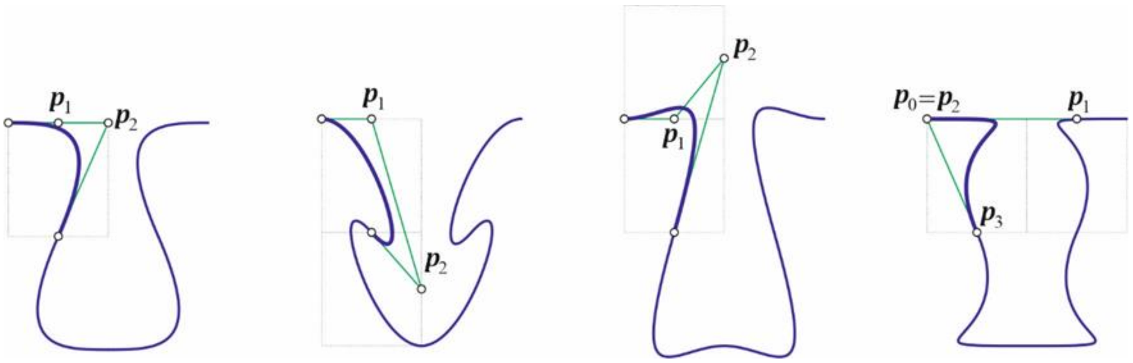


Figure 2: Definition of the joint curve no. 2 – 5

Laser processing

In our experiments involving curved cuts, we utilized European beech (*Fagus sylvatica* L.) material, which was 4 mm thick and 66 mm wide. The prepared sample bodies had a polished quality surface, the samples did not receive surface treatment. Before cutting, the curves were transformed into a form readable by the equipment (CorelDraw, cdr format). To achieve an exact fit, the cutting tool paths were perpendicular to the edge of the material at the exit, so that the cut everywhere resulted in a clean and clear exit from the material. The power of the laser beam (150 W) and the speed of the mirror head (10 mm/s) were set to optimize the cutting result (Universal Laser Systems, ILS 9.150D, Pmax=150 W, 2” focal length lens). The goal was that the beam exiting the material would cut the material, but not look for unnecessary surface burns. With this approach, our aim was to minimize material loss resulting from the cutting gap during the cutting process. Each sample was cut one by one by placing a template in the workspace, which positioned each sample, thus ensuring regular cut images. During the processing, no negative experimental effects or factors were experienced; the parameters of the cutting results coincided with the goals defined at the beginning of the experiment.

Finite Element Analysis

To conduct preliminary stress analysis, computational simulations were performed using Ansys Workbench for linear static analysis under tension (licensed product is Ansys® Academic Research Mechanical, Release 15). Pre-processing of the analysis consisted of importing the geometry definition according to the cutting samples, meshing, and defining the boundary conditions. The European beech (*Fagus sylvatica* L.) material was modelled an orthotropic one, which is described using nine material constants, namely three normal Young’s moduli in longitudinal (E_L), radial (E_R), and tangential (E_T) directions; three Poisson’s ratios in radial-tangential (ν_{RT}), longitudinal-radial (ν_{LR}) and longitudinal-tangential planes (ν_{LT}); and three shear moduli in radial-tangential (G_{RT}), longitudinal-radial (G_{LR}), and tangential-longitudinal planes (G_{TL}). These constants were derived from Szalai (2001) and are presented in the Table 2. The global *X, Y, Z* axes corresponded to the anatomical coordinate system of the wood (*L, R, T*). The orientation of the samples are were in the *LT* plane. The joint was modelled as a bonded contact because the focus was on the shape of the joints. Quadratic order element was applied with the size of 3.0 mm except of the contacts, where the mesh size was 1.00 mm. The future experimental setup is not known. Therefore the grip of the samples was modelled with displacement support ($u_x = 0$) in order to prevent localized high stress from Poisson’s effect. Weak springs were added in order to prevent rigid body motion during simulation. 1 mm displacement was applied to simulate the tension. The main area of interest is the peak stress locations and the stress distributions around the joints.

Table 2: Used material parameters of European beech (Fagus sylvatica L.) from Szalai (2001)

Species	**Density**	E_L	E_R	E_T	G_{RT}	G_{TL}	G_{LR}	ν_{LR}	ν_{LT}	ν_{RT}
European beech	750	14000	2285	1160	467	952	1972	0.45	0.51	0.71

Density – density of the beech wood [kg/m3];EL, ER, ET – normal moduli of elasticity [MPa]; GRT, GTL, GLR – shear moduli of elasticity [MPa]; vLR, vLT, vRT – Poisson's ratios [-]

RESULTS AND DISCUSSION

In the five different cutting samples (Figure 3), it is clear that the shape of the fit is accurate, but the cutting loss arising from the technology leads to a gap between the materials. An almost identical gap can be observed on each sample (input side: 0.7-0.6 mm, output side: 0.3-0.15 mm), so it is possible to minimize them by modifying the trajectory curves.

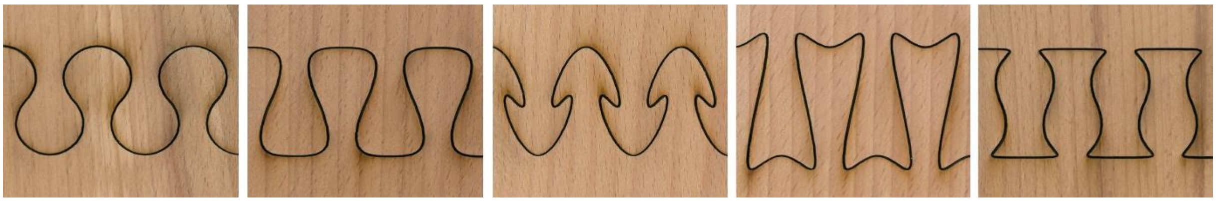


Figure 3: Cut samples 1-5

In addition to being a technical obstacle (incorrect fit during gluing), the visible gap between the elements is also a problem from an aesthetic point of view. An additional aesthetic problem can be the appearance of randomly located surface burns at the cutting gap narrowing towards the output side, as well as the burnt surface in the gap depending on the wood species. The cause-and-effect relationship between the resulting gap and the size of the surface burn is summarized in the Ishikawa diagram below (Figure 4). Surface burning and unevenness resulting from the nature of the technology cannot be eliminated, only the size can be reduced.

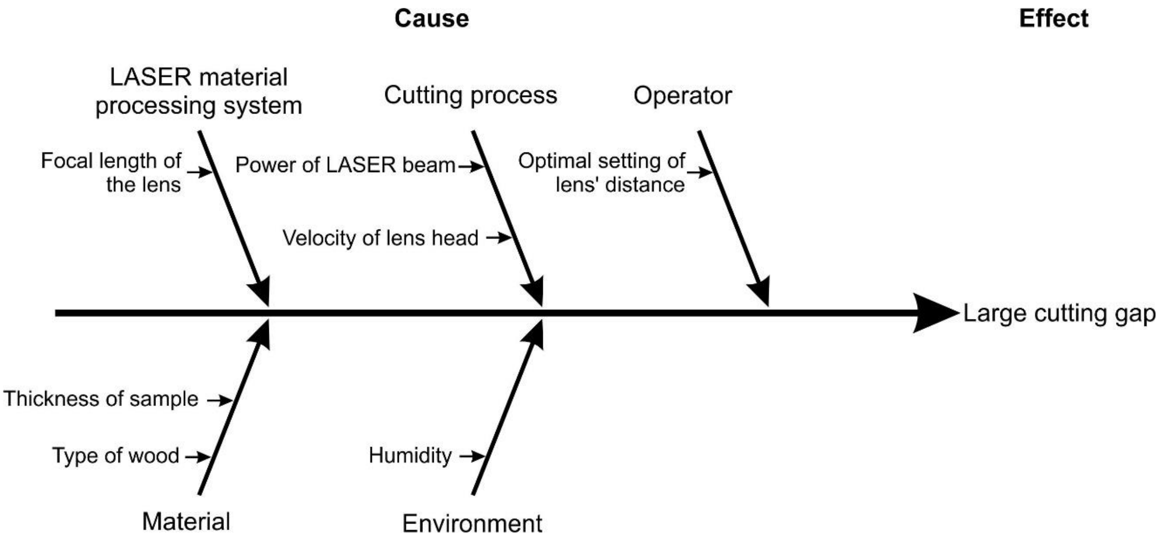


Figure 4: Ishikawa diagram of gap reduction

The curve geometry has a significant influence for the stress distribution around the joints (Figure 5 and Figure 6). Significant normal stresses occur around the wall of the joints. Although the cutting gap and the adhesive is not taken into consideration into this simulation, the differences between the joint geometries are visible. The highest peak stress occurred at joint curve 1 (112.42 MPa) but the peak stresses at the other joints have also similar peak stresses: joint curve 2 (σ_{LL} = 106.81 MPa), joint curve 3 (σ_{LL} =106.60 MPa), joint curve 4 (σ_{LL} = 101.31 MPa) and joint curve 5 (σ_{LL} = 109.84 MPa). Joint curve 1, 2 and 4 are similar to traditional joints, and joint curve 3 and 5 are more design specific. The sharp corners and arches with small radius may be not advisable.

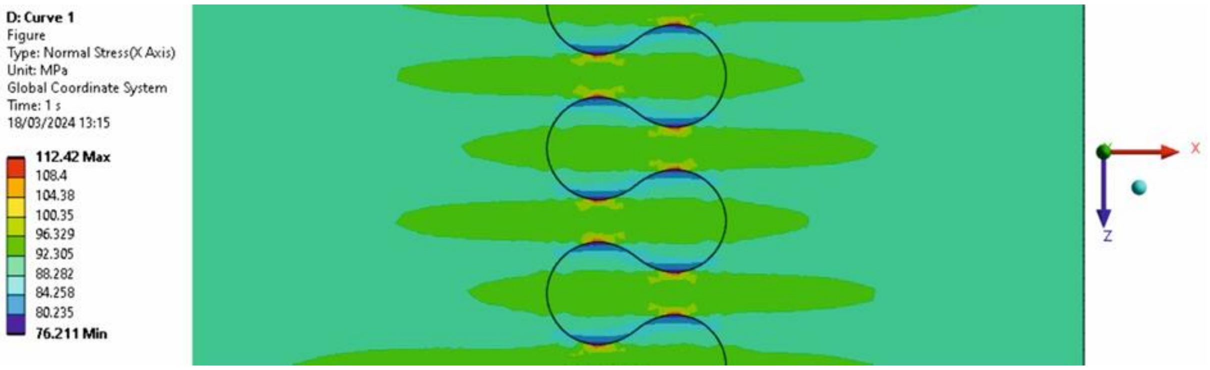
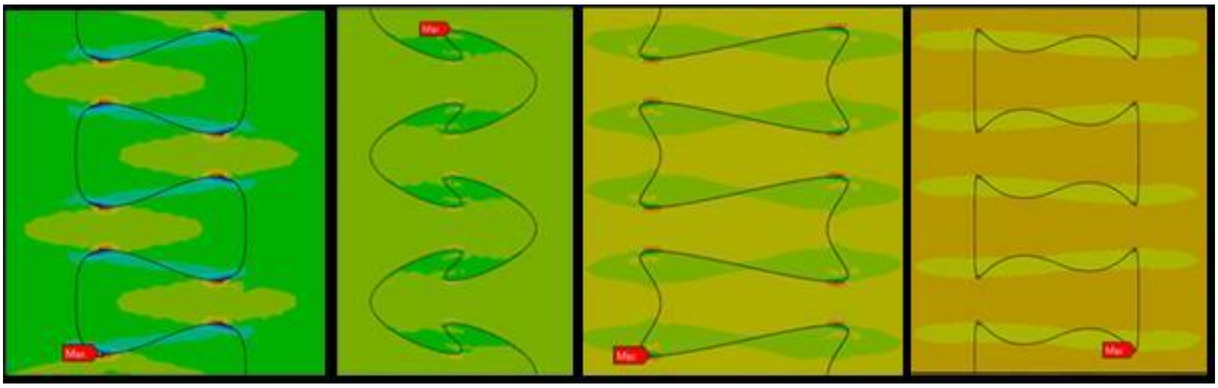


Figure 5: Normal stresses parallel to the longitudinal directions on the joint made by Curve 1



Curve 2 ***Curve 3*** ***Curve 4*** ***Curve 5***

Figure 6: Normal stresses parallel to the longitudinal directions on the joints made by joint curves 2 - 5

CONCLUSIONS

Mathematical relationships can be used to select the cutting image, during which cutting lines for different purposes can be defined by changing the parameters. The formation of gaps in general cutting toolpaths can be observed here as well, and it can also be reduced by changing technological parameters. The finite element analysis was a useful preliminary analysis tool. The stress distributions are different according to the joint curve geometry. However, future investigations are needed to incorporate the adhesives and the laser cutting gap into the model. Furthermore, physical testing should be performed in order to gather experimental results for the joints.

The flexibility of the presented laser cut system is emphasized. There is no need for different cutting tools, only the laser is used. Utilizing even smaller pieces of waste wood further contributes to sustainability goals.

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