Experimental research on load bearing capacity of adhesively jointed beech timber lamellas

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Abstract. The aim of this work was to verify behavior of a beech timber finger-joint in local conditions in the Central Europe. The samples were produced with a glued joint with the finger length of 23 mm according to standard ČSN EN 14 080. Commonly used polyurethane adhesive for production of engineered wood products in the Czech Republic was used. The samples were loaded by destructive four-point bending tests according to standard ČSN EN 408, and the achieved bending strength was statistically evaluated and compared with results of non-glued samples. The results showed that bending strength of lamellas with a finger-joint reached about 65% of the strength of samples without a joint, and the failure of lamellas occurred in most cases at the joint.

Keywords: Beech (*Fagus sylvatica*); glued joints; finger-joints; polyurethane adhesive; bending strength.

Introduction

Apart from gradually disappearing spruce wood, hardwood, particularly beech, oak, hornbeam, and maple, will be among the future local sustainable sources in the Central Europe. Some of the most important criteria for selecting materials include costs, thermal bridging, and load-bearing capacity; the exterior material are selected based on localisation, environment performance, durability and weight. The most important criterion of assessment is the cost of primary structures (Zavadskas, Bausys, Juodagalviene, & Garnyte-Sapranaviciene, 2017). A multi-criteria analysis using the PROMETHEE method was performed and the evaluation revealed that in civil engineering the use of beech wood seems the most suitable from the group (beech, oak, hornbeam, maple) (Šuhajdová et al., 2018).

One of potential uses of beech timber in bearing structures is in the form of glue laminated timber (GLT). By producing elements from more wooden lamellas jointed together, it is possible to eliminate negative properties of solid timber, such as buckling, occurrence of seasoning splits, limited profile length, etc. Joints of individual lamellas, both the longitudinal laminated joint, and the joint of individual lamellas within the cross-section thickness, are crucial for bearing capacity of the whole glue laminated element.

Individual lamellas are longitudinally jointed with the use of the so-called finger-joint. Finger joint is a self-centering longitudinal joint created by a profiling cutter by milling more identical conic symmetrical fingers in the fronts of timber elements, which are subsequently glued (ČSN EN 14 080). In the Czech Republic the finger length of 15 mm is used for connecting lamellas of GLT. This joint length is suitable for spruce sawn timber, however, it is, at least according to conclusions from literature (Tran, Oudjene, & Méausoone, 2014), insufficient for beech sawn timber. In Germany, the most used length is 20 mm (Aicher, Höfflin, & Behrens, 2001), but the length of 30 mm is used as well. Neither requirements for glued laminated timber, nor for finger-joints of hardwood are dealt with by the legislation in greater detail in the Czech Republic.

This paper aims to verify bearing capacity of a finger-joint of beech lamellas in local conditions, i.e. when using polyurethane adhesive commonly used for glued bearing joints in the Czech Republic, in order to find whether this joint can be used for production of principal structural glued beech elements. Based on findings from literature (Tran et al., 2014) and production capabilities, the joint geometry was chosen with the finger length of 23 mm.

Glued samples were loaded, in compliance with ČSN EN 14 080, in bending in horizontal position, when the loading was applied parallel to the joint fingers. The obtained strength of glued lamellas was compared with the strength of reference samples, i.e. samples without a joint.

Finger-joint lamellas are often described in foreign literature. Bourreau studied finger-joints from different types of hardwood (Bourreau, Aimene, Beauchene, & Thibaut, 2013). In his conclusions he claims that strength of these

joints depends on several factors related to gluing, such as application of adhesive, pressing time, and applied pressure. Other factors affecting the strength of joints are density of used timber, course of annual rings and lamella thickness. Tran presented an experimental investigation on full-scale glued solid oak beams for structural purposes (Tran, Oudjene, & Méausoone, 2016). Other works (Ammann et al., 2016; Messmer, Anjos, Guerrini, & Oliveira, 2017 and others) focus on glued joints, effect of adhesive compositions, degree of adhesive penetration into timber structure, and timber moisture on the formation of glued joints and their stability, or the effect of surface roughness on gluing. Lara-Bocanegra investigated the influence of geometric and material parameters, assembly pressure and failure modes on finger-joint bending strength of eucalyptus hardwood (Lara-Bocanegra, Majano-Majano, Crespo & Guaita, 2017). Several numeric and theoretical studies (Tran et al., 2014, 2015 and others) focus on mechanical properties of finger-joints in relation to FE modelling of mechanical behavior of finger-joints.

Aicher describes testing of tension strength of finger-joints on beech samples. He tests joints with the finger length of 20 mm and uses a melamine type adhesive. According to (Aicher et al., 2001), those beech samples with the cross-section of 115×42 mm reach the tension strength of around 70 N/mm². Experimental research and numeric modelling of two-layer and three-layer glued beech timber beams with finger-joints are described in literature (Tran et al., 2014). This work describes behavior of a glued element with the lower lamella longitudinally jointed with a horizontal finger-joint with the finger length of 20 mm, while using melamine-urea-formaldehyde adhesive. In this study the finger joint was found non-functional, and new finger-joint geometry with the finger length of 30 mm was designed by mathematical methods.

Materials and methods

Preparation of samples

Since no supplier was found that would be able to produce samples from hardwood and with a different finger length than 15 mm, the samples were prepared in laboratory conditions. The requirements of standard ČSN EN 14080, listed in Annex I, were met for the preparation of samples, even though the standard is limited just to elements mostly produced from coniferous species. Adhesive manufacturer's requirements were respected accordingly.

Finger-joints in lamellas with the profile of 53 mm × 33 mm were produced by profiling cutter-blades with 25 mm length, 6.2 mm pitch and 1 mm tip gap, see finger geometry in Figure 1a. The vertical joint – fingers are visible from the top/bottom of the lamella, see Figure 1c – was tested. Finger geometry allows self-locking of the joint and meets the requirements of standard ČSN EN 14 080.

Gluing of lamellas was performed immediately after milling. Kestopur 1030, manufactured by Kiilto, one-component, moisture curing PU-adhesive, for jointing of wooden materials, was used for gluing. Based on the technical sheet, this adhesive is suitable for horizontal finger jointing, horizontally jointed laminated timber, preparation of joints with excellent resistance to moisture, and gluing of wet timber. The average moisture of lamellas before gluing *w* was measured by an electric resistance hygrometer and reached 11.3% on average. The adhesive was applied on both glued surfaces with the use of a tooth spatula in the total weight of 250 g/mm².

Pressing of the joint was made with the use of an agent which helped to ensure flatness of the element after gluing. The applied pressure, complying with standard ČSN EN 14080, was 7.5 N/mm², pressing time was 2 s. Extraction of adhesive during pressing on all surfaces indicates correct application of adhesive, see Figure 1b. Hardening took place in standard laboratory conditions for 2 weeks.

Figure 1. (a) Finger-joint geometry; (b) extraction of adhesive during pressing on all surfaces, (c) lamella dimensions and scheme of four-point bending test (source: authors)

Tests of four-point bending strength

According to ČSN EN 14 080, tests of lamellas with finger-joints are performed either by horizontal bending or by tension. For feasibility reasons bearing capacity was verified by bending. Bending tensile strength was experimentally determined in compliance with standard ČSN EN 408, the samples were formed to 50×30×570 mm. In total 20 pcs testing bodies were tested and the tests were performed in compliance with standard ČSN EN 408; for the scheme of four-bending point bending test see Figure 1c. Loading was applied by constant speed until failure. Testing determined the maximum applied force F_{max} .

The obtained maximum applied strength F_{max} was used to determine the bending strength $f_{m,w,j}$ according to standard ČSN EN 408. Since the testing bodies were not air-conditioned in a standard environment with the temperature $(20 \pm 2)^\circ\text{C}$ and relative moisture $(65 \pm 5)\%$, the moisture of samples ranged around 9.8%. In order to make a comparison, the results were calculated so that they corresponded with the strengths of samples with 12% moisture, according to relationship specified in ČSN 49 0115.

Requirements for finger-joints

The joint must meet requirements for effectiveness of a finger-joint, the ratio between the glued finger area and the basic cross-section area should be higher or equal to 6 (Kuklík, 2005):

$$\frac{A_g}{A} \geq 6, \quad (1)$$

where A_g is the area of fingers, $A_g = A_1 + A_2$, and A is the corresponding cross-section area, see Figure 2.

Figure 2. Finger-joint effectiveness (source: authors)

Finger-joint strength must meet the requirements of standard ČSN EN 14 080, which compares characteristic values of bending strength of finger joints and lamellas. In simplified terms, the strength of a lamella with a finger-joint should not be generally lower than the strength of a lamella without a joint.

$$f_{m,j} \geq f_{m,l}, \quad (2)$$

where $f_{m,j}$ is bending strength of finger-joints (in N/mm^2) and $f_{m,l}$ is bending strength of lamellas without a joint (in N/mm^2).

Results and discussion

After analysing the results, the conclusion is that the effectiveness of the finger-joint is satisfactory. The ratio of the glued area of fingers to the basic cross-section area A_g/A for the used geometry equals 7.13, which corresponds with the relationship condition (1).

Based on the results of experimental tests, the reference samples without a glued joint reached on average 110.7 N/mm^2 of bending strength $f_{m,12,l}$. The bending strength of lamellas jointed by a finger-joint $f_{m,12,j}$ reached on average 70.3 N/mm^2 . The results are summarized in Table 1. It is obvious that samples jointed with a finger joint reach approximately 65 % of bending strength of non-glued reference samples.

Table 1. Experimentally determined bending strength of lamellas jointed with finger-joint with PUR adhesive, comparison with reference samples (source: authors)

	Sample moisture w (in %)	Density (in kg/m^3)	Bending strength $f_{m,12}$ (in N/mm^2)		
			average $\bar{x}$	median $\tilde{x}$	standard deviation s
Glued samples	9.8	702	106.8	110.7	13.86
Reference samples	9.8	693	67.7	70.3	6.82

Two different failure modes could be distinguished in the bending tests as shown in Figure 3a, b by way of representative specimens. The failure of glued joints of most samples occurred in the middle, where the fingers on the stretched part of the cross-section parted, alternatively, at the same time, horizontal cracks between the compressed and stretched part occurred in lower extent. The separation occurred either in the adhesive layer or in its close vicinity. Just around one quarter of samples showed a developing large horizontal crack between the compressed and stretched part, as shown in Figure 3a.

Figure 3. Failure of sample under loading: (a) failure in the adhesive layer with horizontal crack between the compressed and stretched part; (b) failure mostly along the bondline surfaces of the joint profile with some failure at the finger roots (source: authors)

After the complete break of samples, a white film made it obvious that the adhesive was applied correctly over the whole area of fingers. The results can also be expressed with the use of a boxchart, see Figure 4.

Figure 4. Results of four-point bending strength tests expressed by boxchart, where | is median, o is average value, boxes represent the 25% and 75% percentiles (source: authors).

Discussion

As obvious from the experiment results, even though the geometry has the required effectiveness, the bearing capacity of the finger-joint fails to meet the condition (2). The experiment results confirmed the conclusions from literature (Tran et al., 2014) even in local conditions, i.e. with the use of local beech sawn timber and adhesive that is commonly used for finger-joints of laminated elements. In contrast to the experiment described in this paper, the experiment described in literature (Tran et al., 2014) tested a horizontal joint (fingers visible from lamella's side) glued with MUF adhesive.

As mentioned above, the reliability of a joint is affected by many factors, finger geometry and adhesive are just some of them.

A significant and important factor includes manufacturing conditions. In this described experiment as well as in the experiment described in literature (Tran et al., 2014) the samples were hand made. It is clear that hand-made production cannot reach the same quality as machine production, but all standard requirements and manufacturer's requirements (geometry and self-locking of joint, timber moisture during gluing, requirements for hand-made adhesive application, time between milling and gluing, applied pressure and pressing time, hardening) were met. The methodology according to standard ČSN EN 14 080 was used for production of samples. The mentioned standard was also respected by authors (Tran et al., 2014). However, this standard is only applicable for softwood. The requirements according to this standard may not be suitable for beech timber, particularly the requirement for applied pressure may not be suitable.

Conclusions

The experiment results show that bending strength of jointed lamellas only reaches 65% of that of non-jointed lamellas. Therefore, the results verified and confirmed conclusions from literature (Tran et al., 2014), which claim that a joint with finger length of 30 mm is insufficient for beech timber.

A finger-joint of the above-mentioned geometry with the finger length of 23 mm, glued with PUR adhesive, is unsatisfactory for beech sawn timber. Based on the experiment results, the given finger joint fails to reach the required bearing capacity and this joint cannot be used for production of supporting structure laminated beech elements.

A potential effect of adhesive and geometry with a higher joint length (probably 30 mm, as the study (Tran et al. 2014) implies) will be verified by further research.

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