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Hybrid cross-laminated timber plates with beech wood cross-layers

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HIGHLIGHTS

- Industrial manufacture of 3-layered, beech-spruce hybrid CLT.
- Rolling shear properties were tested with compression shear and bending tests.
- Rolling shear modulus and strength exceed classic softwood CLT by 7 and 3 times.
- Sufficiently accurate calculation as a rigid composite ignoring shear-lag.
- Greatly enhanced load capacity and deflection behavior as compared to softwood CLTs.

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ABSTRACT

A hybrid, three-layered, softwood-hardwood cross-laminated timber build-up with outer layers of European spruce (*Picea abies*) and a center cross-layer of European beech (*Fagus sylvatica*) has been investigated with regard to out-of-plane bending. The determination of the rolling shear properties of the beech cross-layer performed by different test and measurement methods comprising bending and compression shear tests was of primary interest. The shear capacity of the composite is significantly influenced by the spruce longitudinal shear strength at the beech-spruce interface. The characteristic values of rolling shear modulus and strength of the beech cross-layer from the bending tests were $G_{r,mean}$ = 350 N/mm^2 and $f_{v,r,05}$ = 2.6 N/mm^2, respectively. Direct strain gauge measurements and compression shear tests resulted in 10–20% higher values. The high rolling shear properties render the shear lag implications of the softwood CLTs to a negligible quantity. The hybrid build-up can be designed as a rigid composite with small error versus a more exact analysis. The novel investigations reveal the great potential of mixed softwood-hardwood CLT build-ups for structural elements in the building sector.

1. Introduction

Cross-laminated timber (CLT) is undoubtedly today's most outstanding timber construction product, which is steadily gaining reputation in the building industry worldwide. The composite member CLT is built-up in the slab thickness direction by several (3–9) orthogonally crossed and adhesively bonded layers of boards, hereby resembling a solid-wood version of the classical plywood build-up of thin, cross-wise layered veneers. The dimensions of the panel type elements, which are produced up to edge lengths of 4 m × 30 m and thicknesses of about 0.1–0.3 m, far exceed those of plywood. The dimensional possibilities, the dimensional stability, the sufficiently high mechanical properties and the easy machinability enabling spacious, largely prefabricated constructions, make CLT ideal for commercially competitive, rapidly erected, sustainable and CO_2-storing buildings. All timber high rise buildings, which now reach up to 14 stories, and many medium timber buildings are based on CLT products [1,2]. Of further importance is the product's suitability for tall buildings subject to earthquake impacts [3,4].

Currently, CLT is world-wide almost exclusively manufactured from softwood boards, mainly spruce and fir. Despite the indisputable assets of softwood CLT's, the product shows some material/build-up inherent deficiencies which result from the very low stiffness and strength properties of softwoods in rolling shear. This feature leads to a significant shear lag between the layers oriented parallel to the main span direction and the cross-layers, manifesting itself in a considerable shear deformation contribution and significantly reduced load capacity as compared to glued laminated timber (glulam) which is composed of laminations bonded exclusively along the fiber/grain direction.

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In recent years, the issue of an increased use of hardwoods in wooden construction products has become a very important topic in Central Europe due to two main reasons. First, large, and so far little used hardwood forest stands of mainly beech (*Fagus sylvatica*) and oak (*Quercus robur*, *Quercus petraea*) exist in Central Europe. Second, the forestry policy has changed in several European countries towards an increased plantation of hardwoods instead of softwoods, as hardwoods are more soil and climate apt and less prone to large, strong wind falls. An evaluation of the appropriate uses of beech boards, especially lower grades used currently almost entirely for thermal/energy purposes, reveals immediately that the material should be very apt for CLT cross-layers. This hypothesis is based on recently proven, significantly higher rolling shear properties of beech as compared to spruce/fir [5].

This paper reports on the materials and production of the first industrially produced, hybrid beech-spruce, prototype CLT elements. Further, extensive experimental and theoretical investigations on the mechanical behavior of the specific CLT build-up are discussed, primarily addressing the rolling shear properties relevant for out-of-plane bending. Finally, it is revealed in a generalized analysis to what extent the new hybrid build-up exceeds the homogeneous softwood CLT build-up and how it enables a significantly reduced calculation effort.

2. Materials

The raw material for the beech wood cross-layers of the manufactured three-layered plates consisted of a batch of 200 beech boards (width $b = 140$ mm, thickness $t = 40$ mm, length $l = 2.5$–3.5 m) with different sawing patterns and qualities. The beech wood (*Fagus sylvatica*) originated from a forest in south-west Germany. The boards were kiln-dried to a moisture content of $u = 12\%$ after a sheltered outdoor drying period of 12 months ($u \sim 14$–16%). The boards were cut to length at the Materials Testing Institute (MPA), University of Stuttgart, in sections of 1.0 and 1.2 m in order to reduce their sometimes substantial longitudinal curvature of up to 30 mm. Sections containing large cracks with gaps $\geqslant 5$ mm were sorted out; nevertheless 50% of all sections showed shrinkage cracks. The visual grading according to the German hardwood grading standard DIN 4074-5 [6] performed at the MPA, University of Stuttgart, disregarding the longitudinal curvature, resulted in a yield of 75% for combined grades LS10 and LS13 and 5% were classified as LS7 representing the lowest grade. The remaining 20% did not fulfill the requirements of any grading class because of either inboard pith or excessively large knot diameters. The classification of the sawing pattern, which was shown to moderately influence the rolling shear properties [5], led to 12% quarter-sawn boards, 39% semi-quarter-sawn boards and 35% flat-sawn boards; 14% of the boards included pith. Density ρ_{12} of the boards ranged from 593 to 791 kg/m^3 with a mean density of (694 ± 39) kg/m^3. The density values corresponded well to those specified by [7] for the respective species, with $\rho_{12} = 530\ldots700\ldots890$ kg/m^3. Before gluing, the sections were planed to a thickness of 30 mm.

For the outer layers of the three-layered plates, finger jointed spruce (*Picea abies*) laminations ($b = 140$ mm, $t = 40$ mm, $l = 6.5$ m) were used. The softwood, originating from Scandinavia, was graded visually at the cooperating CLT manufacturer to S10 according to DIN 4074-1 [8], corresponding to strength class T14/C24 [9]. The finger joints were glued by use of a certified, one-component Polyurethane adhesive (Loctite® HB S139 Purbond) with the European-wide, prevailing finger joint profile with a finger length and pitch of 15 and 3.8 mm, respectively. For mechanical characterization of the unjointed spruce laminations, tensile strength $f_{t,0,l}$, bending strength $f_{m,l}$ and modulus of elasticity (MOE) $E_{t,0}$ were determined by tests according to EN 408 [10] with 25 specimens each, sampled representatively over the entire source. Furthermore, the tensile strength $f_{t,0,j}$ and bending strength $f_{m,j}$ of the finger joints were tested according to [10] with 25 specimens, respectively, though it should noted that the bending test specimens were not tested randomly, but rather with regard to the "worst section." Table 1 presents the statistical evaluation of the spruce material tests. The characteristic (5% quantile) lamination tensile strength and density ($f_{t,0,l,05} = 21.4$ N/mm^2, $\rho_{12,05} = 390$ kg/m^3) corresponded to the characteristic values of strength class T21/C35 [11]. The MOE $E_{t,0,mean} = 11{,}700$ N/mm^2 conformed to strength class T16/C27.

3. CLT Plate manufacture

3.1. Prototypes

Prior to manufacture of the hybrid CLT elements on an industrial scale, principle feasibility and tentative mechanical results were investigated with laboratory made specimens. The prototypes manufactured at the laboratories of MPA, University of Stuttgart, comprised two, three-layered hybrid CLT specimens with finger jointed spruce outer layers and a beech cross-layer. The thickness of the laminations was throughout 30 mm and hence cross-sectional depth of all elements was 90 mm. The length and width of the plates, and hereby resulting specimens, were 1200 mm × 300 mm, respectively. The face bonding for one hybrid build-up (specimen Lab 1) was performed with a phenolic-resorcinol adhesive (PRF) (Dynea Prefere 4040 with hardener Prefere 5839), which had previously proven to be well suited for hardwood gluing. As currently no European CLT producer can employ PRF in an industrial CLT manufacturing process, the second specimen, termed Lab 2, was glued with a one-component Polyurethane (1C PUR) adhesive, predominantly used for CLT elements. Hereby, the constraint had to be overcome that at present no 1C PUR is approved for beech wood face bonding without the application of a primer. Considering the demands of the producer of the industrially manufactured elements, the specific 1C PUR adhesive Loctite® HB S139 Purbond was used in combination with an aqueous primer (Loctite® PR 3105 Purbond). The specific primer is certified according to German National Technical approval Z-9.1-679 [13] for bonding of beech or beech and spruce laminations in combination with the 1C PUR Loctite® HB S309 Purbond, being chemically very similar to the actually employed brand Loctite® HB S139 Purbond, as it belongs to the same adhesive "family" line. The layering of the boards and the application of the primer and the adhesives were performed manually. The narrow board edges were not bonded. The employed adhesive amounts were 450 g/m^2 and 180 g/m^2 for the PRF and 1C PUR bonded specimens, respectively. The total assembly times were 50–60 min for PRF and 10–12 min for 1C PUR. The specimens were manufactured with a cramping pressure of 1.0 and 1.2 N/mm^2 and maintained for 6 and 2.5 h for specimens Lab 1 (PUR) and Lab 2 (1C PUR), respectively. No bonding or manufacturing problems were encountered for either of the specimens Lab 1 or Lab 2.

3.2. Industrial

The industrial manufacture of the three-layered, hybrid, full-scale CLT plates with finger jointed spruce outer layers and a cross-layer from short, unglued, butt jointed beech laminations was performed in the plant of an experienced softwood CLT producer (Eugen Decker Holzindustrie KG, Morbach, Germany). The plates were 6.5 m long (parallel to the outer layers) and 2.2 m wide (parallel to the cross-layer); the total thickness of the plates was $h = 2 \cdot 40$ mm + 30 mm = 110 mm. The face bonding of the boards