Acta Polytechnica CTU Proceedings **33**:175–180, 2022
https://doi.org/10.14311/APP.2022.33.0175

BENDING BEHAVIOR OF ADHESIVELY-BONDED ENGINEERED WOOD-CONCRETE COMPOSITE DECKS

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Abstract.
Four-point bending tests were conducted on five medium-sized (i.e., 2300 mm in length and 215 mm in width) engineered timber (laminated veneer lumber (LVL) and cross-laminated timber (CLT)) - concrete (wood chip concrete and plain concrete) composite decks. The concrete was glued to the wood substrate with epoxy and polyurethane adhesives. The observed failure modes of the composite decks were concrete crushing or wood failure in tension or shear. No failure of the adhesive interface was observed and the decks behaved linearly until failure. In the subsequent analysis, the authors quantified the shear flexibility of transverse layers (stressed perpendicular to the fiber direction) in CLT and LVL boards and its effect on the bending stiffness on the composite decks using γ-method described in EN 1995-1-1 (EC5). The analytical predictions of the effective bending stiffness were verified via experiments, showing consistently good agreement.

Keywords: γ-method, adhesive bond, bending behaviour, timber-concrete composite, wood chip concrete.

1. Introduction

Timber-concrete composite (TCC) structural elements have advantages of higher stiffness, fire resistance and better acoustic performance compared with massive timber. Connection between concrete and wood is usually achieved by conventional mechanical dowel-type fasteners (shear studs) or notches. Mechanical fasteners are not rigid and there is always a slip between the wood and concrete. Thus, full composite action of TCC connected by mechanical fasteners is hardly achievable. Adhesive bonding is often considered as rigid. The application of glued wood-concrete connections is not fully explored and the knowledge in this area is limited [1–7], let alone the relevant specifications in standards.

Studies [1–7] demonstrated that glued TCC systems had higher stiffness (e.g. slip modulus of connections and bending stiffness of TCC beams) compared to mechanically connected ones, and sufficient adhesion strength for structural applications under short-term loading and ambient-temperature. The wood products involved in these studies [1–7] were solid timber, glulam or vertically used laminated veneer lumber (LVL) Assuming the rigid characteristics of the used adhesives, the behavior of these kinds of TCC beams was characterized by assuming continuous strain at the wood-concrete interface and using the known transformed cross-section procedure [5, 8–10].The low shear modulus of transverse layers in the CLT and LVL boards subjected to bending can cause significant shear deformation (or slip) and hence increase the deflection. In the present work, the authors studied the shear behavior of glued CLT- and LVL-concrete connections [11]. They further experimentally investigated the bending behavior of CLT- and LVL-concrete composite decks. Specifically, CLT and LVL boards were bonded wood chip concrete (WCC) and with plain concrete (PC) using epoxy and polyurethane (PUR) and adhesives. The addition of WCC [12] resulted in reduced concrete density and increased thermal insulation properties of plain concrete. The polyurethane (PUR) used in the present study was stiff, its modulus of elasticity was as high as that of the used epoxy (around 3.5 GPa), showing nearly no deformability in the adhesive layer. The PUR in this study was different from the PUR in Ref. [13] (modulus of elasticity: 0.008 GPa) that resulted in visible slip at bond line (over 1 mm).

To describe the slip in transverse layers and its effect on the bending stiffness of composite decks, the authors used the shear analogy method [14] for quantifying shear deformation of the transverse layers in combination with γ-method of EC 5 [15]. The predictions of the effective bending stiffness were compared with the experimental results, showing a good match.

	CLT	Flatwise LVL
Thickness (mm)	80 (20 + 40 + 20)	69 (Thickness of each veneer: 3 mm)
Shear modulus (MPa)	50 (Rolling shear, G_r)	22 (Perpendicular to grain, G_{90})
Elastic modulus in grain direction (E_0) (GPa)	12	11.4

Table 1. Mechanical properties of the engineered wood products [16].

2. Experimental studies

2.1. Overview of test plan

Engineered timber, CLT and LVL, and concrete, WCC and PC used in this study were identical to those in the previous study [11]. Epoxy and PUR were selected due to their bonding performance [11]. The authors constructed five medium-sized specimens, WCC-Epoxy-LVL, WCC-PUR-LVL, WCC-Epoxy-CLT, WCC-PUR-CLT and PC-Epoxy-LVL, and tested them under bending. Figure 1 (e) shows the configurations of the specimens.

2.2. Materials

The mechanical data and configurations of CLT and LVL are shown in Table1. Moisture content of the used wood was about 10%. The beech wood chips used in WCC were in a relatively flat shape, having around 20 mm side length and 2.4 mm thickness. The density of the wood chip was 0.68g/cm^3. The mass ratio of the constituents of WCC was CEM II/B-S 42.5 R cement: water: 0-2 mm sand: 2-8 mm gravel: 8-16 mm gravel: wood chip = 1: 0.60: 2.00: 1.27: 2.32: 0.11. The mass ratio of the constituents of PC was CEM II/B-S 42.5 R cement: water: 0-2mm sand: 2-8 mm gravel: 8-16 mm gravel = 1: 0.60: 2.00: 1.27: 2.72. The compressive strength of the WCC and PC cylinders were 25.8 MPa (SD = 3.79 MPa) and 27.9 MPa (SD = 1.73 MPa) based on five samples, respectively. The respective elastic modulus of PC and WCC were 29.9 GPa and 12.3 GPa. According to the product of PRIME$^{\text{TM}}$ 20LV from [17] datasheet, the elastic modulus of epoxy is 3.5 GPa. The pull-off tests in authors previous study [11] showed that the load-displacement curves of the used epoxy and PUR almost overlapped at the initial loading stage, so the elastic modulus of the used PUR is similar to that of the epoxy.

2.3. Specimen preparation

When the concrete was cured for 28 days, the concrete surfaces were cleaned and glued to shaped wood decks with wood decks on the top for the first 3 days. The specimens were turned upside down since the fourth day and tested after the seventh day. The detailed processes can be found in Ref. [16].

2.4. Experimental setup

A load (F) was quasi-statically applied on the TCC decks with a rate of 0.35 mm/s through a two-point spreader, as shown in Figure 2. It also shows the locations of the support and loading points. A deflection at the mid span was measured by two LVDTs (linear variable differential transducers).

3. Results and discussion

3.1. Load-carrying capacities

The load versus mid-span deflection curves of all the TCC decks showed linear behaviour until the ultimate failure. Figure 3 shows the response of WCC-PUR-CLT as an example, and the ultimate loads, the ultimate mid-span deflections and bending stiffness (EI)test of all the specimens are summarized in Table 3. The calculation of (EI)test was based on the ascending slope of a load versus mid-span deflection curve as follows [16]:

$$(EI)_{\text{ef}} = \frac{F}{w} \frac{a\left(3l^2 - 4a^2\right)}{48} \tag{1}$$

where w is the average reading value of the two LVTDs; a is the shear span; and l indicates the span of the deck.

From Table 3, it follows that the bending stiffness of a beam was not affected by adhesive type. The reason was that a rigid connection was achieved by using either epoxy or PUR, which was also demonstrated by the absence of slippage between concrete and wood decks (see Section 3.2 and Table 3). The specimens comprising CLT boards were stiffer than the counterparts made of LVL (Table 3). The inherent reasons are discussed in Section 4. On the contrary, the ultimate load-bearing capacities of the LVL-specimens were higher than that of CLT-specimens., due to different failure modes (Table 3). As the PC had higher elastic modulus and strength compared with WCC, PC-Epoxy-LVL had the largest flexural stiffness (4.12×10^{11}N.mm^2) and ultimate load-carrying capacity (63.2 kN) [16].

The average bending stiffness and load-bearing capacity of WCC-Epoxy-LVL and WCC-PUR-LVL was around 78.9% and 70.0% of those of PC-Epoxy-LVL, respectively. Meanwhile, the thermal conductivity of WCC could be only 68.9% of that of PC. [18]. Besides, wide application of WCC can reuse wood waste, and reduce the demand for natural aggregates. The load-bearing capacity of the weakest specimen, WCC-Epoxy-CLT, was 39.1 kN, equivalent to a uniformly-distributed load of 85.4 kN/m^2. Considering serviceability limit design, EC 5 [15] allows the maximum deflection of a slab to be l/300 (i.e. 7.1 mm). This deflection corresponds to an equivalent slab load of 34.7 kN/m^2 in the case of WCC-Epoxy-CLT.

3.2. Failure modes

The failure modes of all the specimens are summarized in Table 3. Neither of the specimens was failed by adhesive bonding interface, indicating that the used adhesives can provide satisfactory bonding performance. The different mechanical properties of CLT and LVL caused different failure modes of the corresponding TCC decks. -see [16] for details. One can also have a deeper appreciation of the structural behaviour of LVL and CLT in TCC decks in Section 4.

4. Prediction of bending stiffness

In building slab design, deflection is one of the important serviceability considerations. Structural engineers usually calculate deflections with Euler-Bernoulli beam theory that does not take shear deformation into account. However, when engineered wood (e.g. CLT) is under bending, transversely stressed layers have significant shear deformation, because of low rolling shear modulus (G_r) and low shear modulus in the perpendicular direction (G_{90}) (Table 1). To consider the shear flexibility of transverse layers, the authors regarded it as sources of partial composite action and calculated the effective bending stiffness (EI)ef for all the specimens based on γ-method in EC 5 [15].

The γ-method [15] allows a composite cross-section to be comprised of three parts with two connecting interfaces featured with the respective degree of composite action (γ_i) relative to the middle layer (referred as "Part 2" in Figure 4 (a)). A term γ_i ranges between 0 (no interaction) and 1 (rigid connection). Then $(EI)_{\mathrm{ef}}$ of a composite deck is calculated with Equation (2) [15].

$$(EI)_{\mathrm{ef}} = \sum_{i=1}^{3} \left(E_i\, I_i + \gamma_i\, E_i\, A_i\, a_i^2\right) \qquad (2)$$

where E_i is the modulus of elasticity of Part i in the longitudinal direction; the term I_i means moment of inertia of Part i; the term A_i denotes the cross-section area of Part i; the term a_i indicates the distance between the neutral axis (i.e. N.A. in Figure 4 (a)) and the centroid of Part i. According to EC5 [15]:

$$\gamma_i = \left[1 + \pi^2\, E_i\, A_i\, s_i / (K_i\, l^2)\right]^{-1} \quad (i = 1 \text{ and } 3) \qquad (3)$$

where K_i is the slope of a shear force - slip curve (i.e. slip modulus) of a connection, and s_i denotes the equidistance between shear fasteners connecting Part 2 and Part i. For a continuous adhesive connection, K_i can be defined based on a given length, e.g. 1 mm. Then, si is equal to 1 mm. As explained in Ref. [16], the CLT board (Part 2) and concrete (Part 1) were rigidly bonded based on the experimental observations (i.e. $K_1 = \infty$ $\gamma_1 = 1$). Part 2 is the reference layer, so γ_2 is equal to 1. In this paper, the slip modulus K_3 relates to the shear connection between the top (Part 2) and bottom (Part 3) longitudinal layers of CLT. Therefore [16],

$$K_3 = G_r \cdot b \cdot (1000\,\mathrm{mm}) \,/\, h_{tr} \qquad (4)$$

where G_r denotes the rolling shear modulus of the CLT (refer to Table 1), h_{tr} denotes thickness of the transversal layer, and b is the width of the decks. According to EC [15]:

$$a_2 = \frac{\gamma_1\, E_1\, A_1 (h_1 + h_2) \,-\, \gamma_3\, E_3\, A_3 (h_2 + h_3)}{2 \sum_{i=1}^{3} \gamma_i\, E_i\, A_i} \qquad (5)$$

The terms a_1 and a_3 can be obtained based on the geometric relationship in Figure 4 (a).

To model the shear flexibility of dispersed transversal veneers in LVL, the longitudinal and transversal veneers were gathered into the respective two layers for simplification. The full concept is illustrated in Figure 4 (b). For details regarding the modelling and analysis, please refer to the authors' previous work in Ref. [16]. In simple terms, Equations (2) through (5) are applicable for TCC decks using LVL, with $h_1 = 0$ and G_{90} replacing G_r. All the detailed derivations can be found in Ref. [16]. For comparison, γ_i and $(EI)_{\mathrm{ef}}$ of TCC decks comprising the respective CLT and LVL boards are presented in Table 2. The degree of composite action in the TCC decks comprising LVL (0.52) was lower compared with that of the TCC decks comprising CLT (0.70). The reason was that the transversely stressed veneers have a very low shear modulus (22 MPa). The $(EI)_{\mathrm{ef}}$ of CLT-involved TCC decks was slightly higher than that of LVL-involved TCC decks, which agrees with the test results (Table 3).

The higher $(EI)_{\mathrm{ef}}$ of CLT-involved TCC decks stemmed from a larger γ_3 and a larger a_3 (see Figure 4). The specimen made of PC had the largest stiffness due to the larger elastic modulus of the plain concrete. The larger elastic modulus of PC led to the largest stiffness of PC-Epoxy-LVL.

As shown in Table 2, the $(EI)_{\mathrm{ef}}$ calculated in this study conservatively predicted the corresponding test results with an error of around 10% [16]. Ignoring the shear deformation (i.e. $\gamma_3 = 1$), EI was overestimated by around 34% on average. With the latter kind of calculation, another undesired situation is that the errors of predictions of EI varied significantly (CoV = 14.1%), depending on different types of engineered wood products having different degrees of shear flexibility. This problem was solved by this study through quantifying the shear flexibility of transversal wood layers [16]. The errors of predicted $(EI)_{\mathrm{ef}}$ of CLT- and LVL-involved TCC decks had small variations

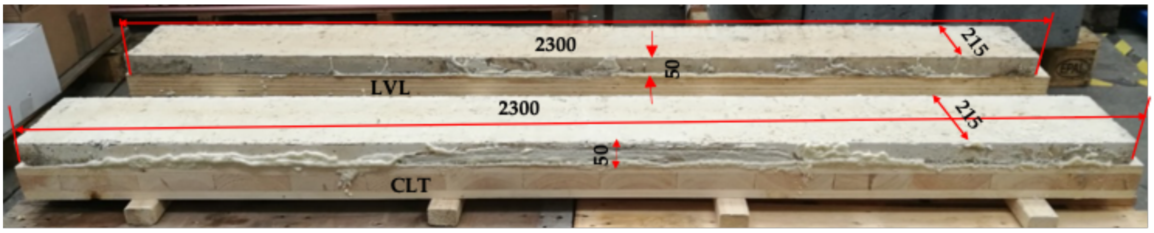


FIGURE 1. Dimensions of fabricated TCC decks.

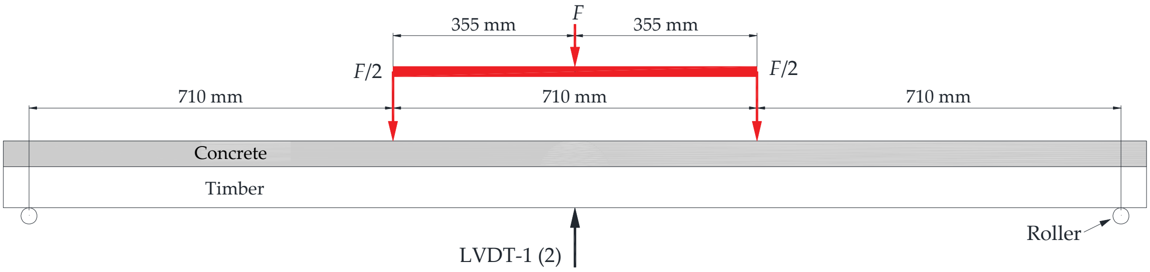


FIGURE 2. Setup of 4-point bending test.

Specimen ID	γ_1	γ_3	EI^a (N.mm^2)	$EI/(EI)_{\text{test}}$	$(EI)_{\text{ef}}$ (N.mm^2)	$(EI)_{\text{ef}}/(EI)_{\text{test}}$
WC-Epoxy-CLT	1	0.70	4.13×10^{11}	1.14	3.21×10^{11}	0.89
WC-PUR-CLT	1	0.70	4.24×10^{11}	1.13	3.33×10^{11}	0.89
WC-Epoxy-LVL	\	0.52	4.62×10^{11}	1.42	2.90×10^{11}	0.89
WC-PUR-LVL	\	0.52	4.90×10^{11}	1.50	3.05×10^{11}	0.93
PC-Epoxy-LVL	\	0.52	6.15×10^{11}	1.49	3.82×10^{11}	0.93
Average				1.34		0.91
Coefficient of variance				14.0 %		2.6 %

[a] The term EI denotes the flexural stiffness of TCC decks, ignoring the shear flexibility of transvers layers.

TABLE 2. Predictions of flexural stiffness.

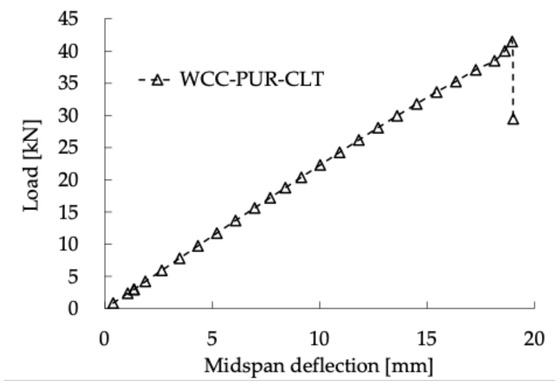


FIGURE 3. Load vs. displacement responses of WCC-PUR-CLT at mid-span.

(CoV = 2.6%) (Table 2). Thus, this study provides an effective solution for the calculation of $(EI)_{\text{ef}}$ (or deflection) of TCC decks using engineered wood.

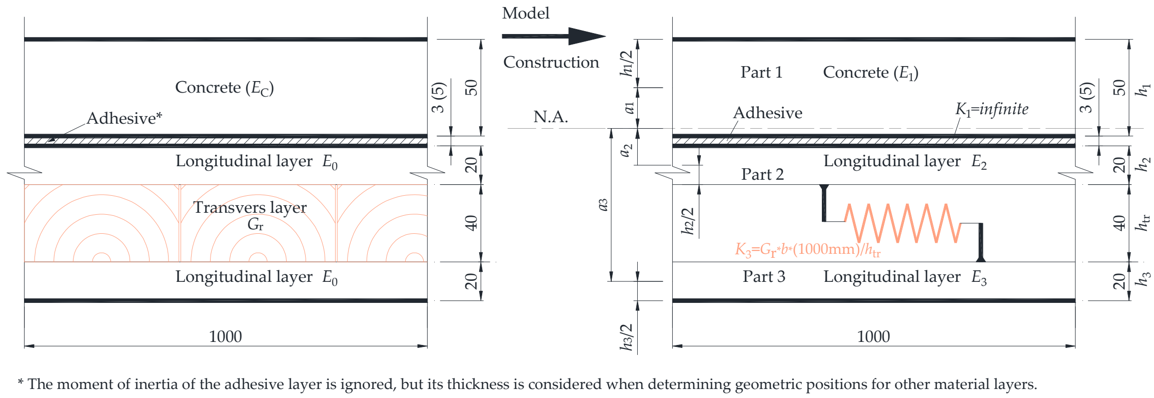
5. CONCLUSIONS

From this study, some conclusions can be drawn, as follows:

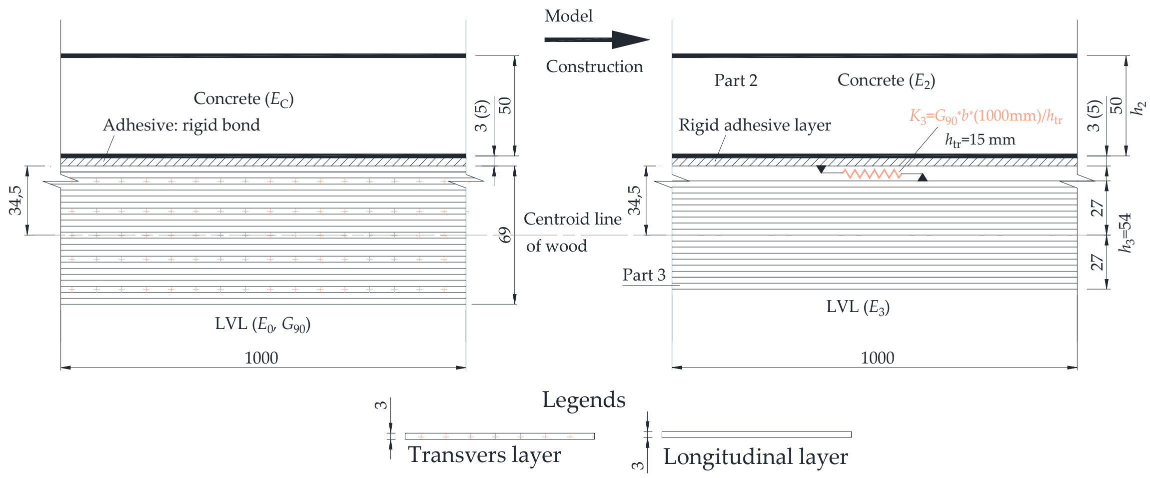
1. The PUR- and epoxy-bonded wood and concrete could form a strong and rigid interfaces to transfer the shear in TCC decks subjected to quasi-static bending, without failure and visible slip.
2. The failures of TCC decks in this study were brittle, which were governed by wood fracture and concrete crushing.
3. Wood chip concrete is feasible to be used with the engineered wood as composite structural slabs. Engineered wood could be used together with WCC to realize a sustainable solution, with satisfactory structural performance.
4. The method in this study provides an effective solution for the calculation of $(EI)_{\text{ef}}$ (or deflection) of TCC decks under bending.

ACKNOWLEDGEMENTS

The research was financially supported by Fachagentur Nachwachsende Rohstoffe e. V. (FNR, Agency for Renewable Resources) founded by Bundesministerium für Ernährung und Landwirtschaft (BMEL), under the Grant Award No.: 22011617, and by Bundesministerium für Bildung und Forschung (BMBF) (Grant No.: 031B0914A).



(a) Concrete-CLT composite decks



(b) Concrete-LVL composite decks

Figure 4. Analytical model of composite decks (unit: mm) - quoted from Ref. [16].

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