

## INTERFACIAL BOND BEHAVIOR OF ADHESIVELY-BONDED TIMBER/CAST IN SITU CONCRETE (WET BOND PROCESS)

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### ABSTRACT.

The goal of this research was to study the strength of the interfacial bond between cast-in-situ concrete and engineered timber (cross-laminated timber (CLT)). Double lap specimens were manufactured using fresh concrete that was cast between two CLT blocks. Polyurethane and epoxy adhesives were used to bond the wet concrete with the CLT blocks. The shear strength of wet-bond specimens was compared with the specimens prepared under dry conditions (prefabricated concrete cube glued to CLT blocks). The statistical analysis (T-test) of bond strength showed that the shear strengths of wet- and dry-bond specimens using epoxy and polyurethane adhesives were no significantly different for the tested C25 plain concrete and the CLT. The failure mode of dry-bond specimens were concrete failure near the interface, however, debonding at interface was the dominant failure for the wet-bond specimens.

KEYWORDS: Cast-in-situ concrete, dry bond, shear strength, timber-concrete composite structures, wet bond.

## 1. INTRODUCTION

Timber-concrete composite system is a construction technique to strengthen and stiffen the existing timber floors and new construction parts such as decks in short-span bridges and multi-story buildings. This technique requires the connection system to transfer shear stress between timber and the concrete composite system. Rigid and strong connection system maximize the composite action. Rigidity of connection system will increase when notches or holes [1] are cut/drilled in the timber or a continuous connector like adhesive is used [2]. Application of adhesive has recently been studied in bonding timber and concrete due to its significant advantages including: a) uniform stress distribution over the bond area, b) removal of cutting and drilling in the wood substrate and c) reduction of workmanship and cost [3]. Satisfactory stiffness and strength is of importance for timber-concrete structures. Besides the stiffness and strength, other aspects should be considered such as quality, simplicity and speed of manufacturing and erection. Two approaches can be taken to manufacture adhesively bonded timber-concrete elements:

- Adhesively bonded timber-prefabricated concrete composite (dry bond).
- Adhesively bonded timber-cast-in-situ concrete composite (wet bond).

In a dry bond, adhesively bonded timber-concrete beam/slab is fabricated in a workshop under the con-

trolled environment, transported to construction site, lifted up and placed on a desired location. In case of wet bond, the wet concrete is directly pumped to wood surface covered with glue. The wet bonding has its own merits such as:

- Easy transport of wet concrete to desired location making time and cost savings especially for multi-story buildings (removal of crane application).
- Elimination of gap and discontinuities in the adhesive interface area.

There is a concern regarding the insufficient bond strength between timber and cast-in-situ concrete when it is compared with dry bond. When the fresh concrete is poured on the wet adhesive, it can cause the adhesive movement, incomplete adhesive curing and consequently bond strength reduction [8, 9]. Few researchers studied the bond behaviour of timber-cast-in-situ concrete connected with glue. Brunner et al [9] investigated the wet bond behaviour of glue laminated timber (GL24h) and cast-in-situ concrete (C25/30) glued with epoxy adhesive. They concluded that the production of wet bond in timber-concrete composite structure is delicate due to danger of adhesive movement during pouring fresh concrete. Clouston et al [10] experimentally studied the influence of epoxy adhesive on strength and stiffness improvement of full-scale wood plank-cast-in-situ concrete composite floor decks. The strength and stiffness were increased by about 4 and 2.2 times compared to wood-cast-in-situ concrete composite with no connection

CLT	
Bending strength (MPa)	18
Modulus of elasticity in fiber direction (GPa)	12
Shear modulus (MPa)	690
Density (kg/m <sup>3</sup> )	527

TABLE 1. Mechanical and physical properties of CLT [4, 5].

Mass percentage	Cement	Water	Fine aggregates (sand)	Medium aggregates	Coarse aggregates
Normal concrete	1	0.6	2	1.27	2.73
Aggregates size (mm)	–	–	0 – 2	2 – 8	8 – 16

TABLE 2. Designed mixing ratio for concrete.

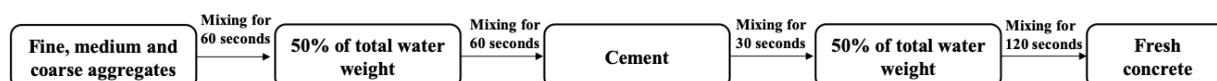


FIGURE 1. Concrete mixing process.

	Epoxy [6]	Polyurethane [7]
Commercial name	Sikadur 300	Semparoc 12 NV
Density	1.16 g/cm <sup>3</sup>	1.25 g/cm <sup>3</sup>
Viscosity	700 mPa.s	8000 – 12000 mPa.s
Pot life (at 23° C)	4 hours	15 minutes
Curing time	7 days	7 days

TABLE 3. Basic information of epoxy and polyurethane adhesives used in this study.

in the interfacial area. Additionally, glue as a continuous connector in the interface area changed the composite failure mode from concrete cracking and debonding between wood and concrete components to interfacial shear failure by sliding concrete over the wood planks.

This paper compares the shear bond strength of two possible manufacturing techniques of adhesively-bonded timber-concrete composite namely wet and dry bonds. Two wood blocks were glued with the prefabricated and cast-in-situ concrete cubes using epoxy and polyurethane adhesives. After adhesive and concrete curing, static shear tests up to failure were carried out up to failure. Fracture surfaces of failed specimens were analysed to investigate possible correlation with shear bond strength.

## 2. EXPERIMENTAL WORK

### 2.1. MATERIAL

To fabricate timber-concrete glued joints, cross laminated timber (see Table 1) with a commercial product name of BBS 125 3-S was used. The CLT wood was made of Norway spruce and was composed of three layers with thicknesses of 20,40 and 20 mm, respectively (totally 80 mm).

Prefabricated and cast-in-situ concrete have the same mixing ratios (see Table 2) and were fabricated

using the same mixer. Portland cement CEM I 42.5 N was used for the concrete mixing. In production of normal concrete, the water was added into two steps (see Figure 1) to ensure aggregates were wet enough causing stronger interfacial transition zone between concrete aggregates and mortar matrix.

One-component polyurethane and two component epoxy adhesives applicable to wood and concrete substrates were used in this study. Some parameters of these products are shown in the Table 3.

### 2.2. DOUBLE LAP JOINT GEOMETRY

Double lap joint is symmetrical about the mid plane of a specimen, therefore, bond rotation and the amount of peel stress is considerably reduced compared to equivalent single lap joint [11]. Figure 2 shows the designed double lap joint with dimensions and material location.

### 2.3. DOUBLE LAP JOINT PREPARATION

#### 2.3.1. DRY BOND PREPARATION

For the dry bond fabrication (see Figure 3), fresh concrete was poured into mold, vibrated and cured for 24 hours. Afterwards, the concrete blocks were immersed in the water for 6 days at temperature of 23° C. Finally, they were taken away from water tank and placed in the climate chamber (65%

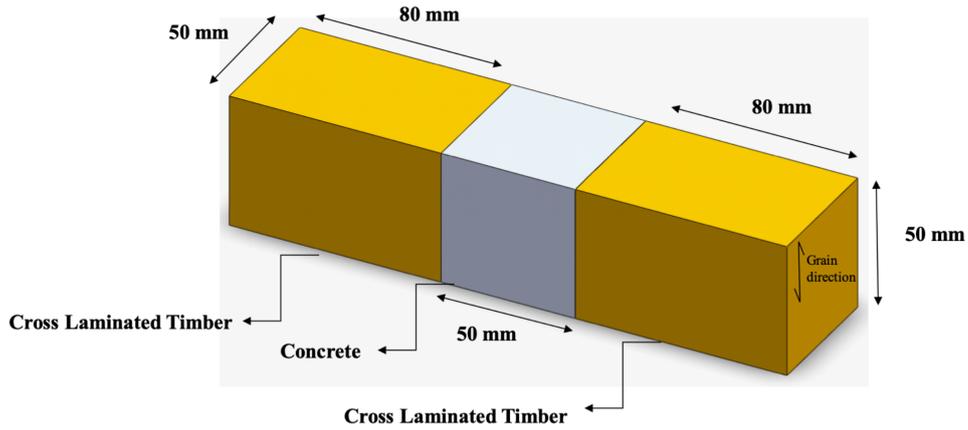


FIGURE 2. Double lap joint geometry.

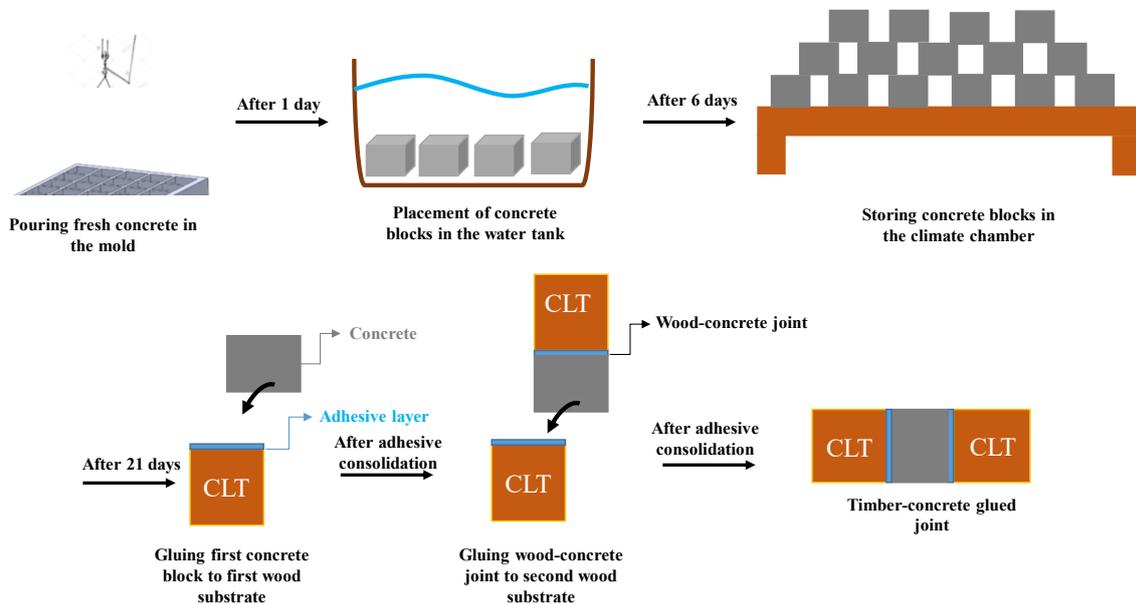


FIGURE 3. Procedure of dry bond preparation.

RH and 23° C) for completion of concrete curing (for the rest of 21 days) based on the German concrete standard (DIN EN 12390-2 [12]). Then, the concrete and CLT wood blocks were bonded together and cured for seven days according to adhesives technical datasheets [6, 7].

**2.3.2. WET BOND PREPARATION**

In the wet bond fabrication, the wood blocks were placed next to each other separated by plywood plates. The surfaces of wood blocks were covered by epoxy and polyurethane adhesives (see Figure 4-a), turned around, fixed by horizontal and vertical C-clamps on their positions and fresh concrete was poured in the middle of the wood blocks (see. Figure 4-b). Timber-concrete double lap joints were released from mold after 24 hours and then the concrete

cubes were wrapped up by damp fabrics to avoid incomplete concrete curing process. Finally, the specimens were stored in the climate chamber (65% RH and 23° C) for the rest of 27 days.

**2.4. SHEAR TEST SETUP**

The shear test of wet bond and dry bond specimens were carried out using DIN-EN 392 standard [13] proposed for timber glued joints. Wood blocks were placed onto the steel plates and constrained from rotation and horizontal movement using two steel plates and C-clamps (see. Figure 5). The load was force-controlled with a loading rate of 30 kN/min through the steel plate positioned on the concrete. The double lap joint specimens were tested up to failure and shear strength of wet and dry bonds was calculated according to Eq. 1:

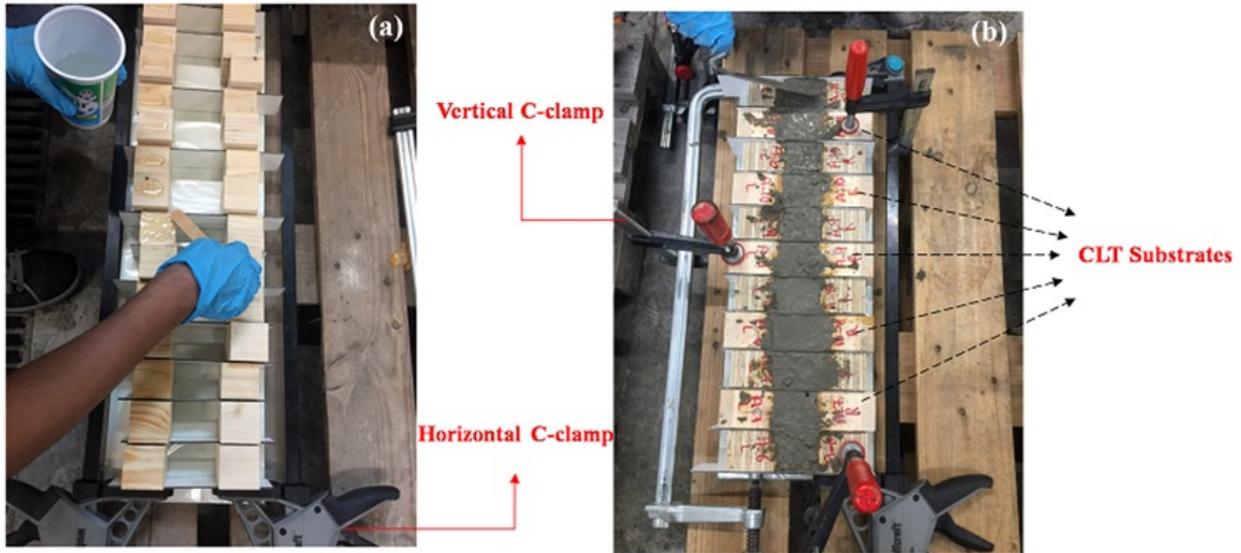


FIGURE 4. Manufacturing process of wet bond a) pouring and spreading glue on the wood surface b) pouring fresh concrete between wood blocks covered with glue.

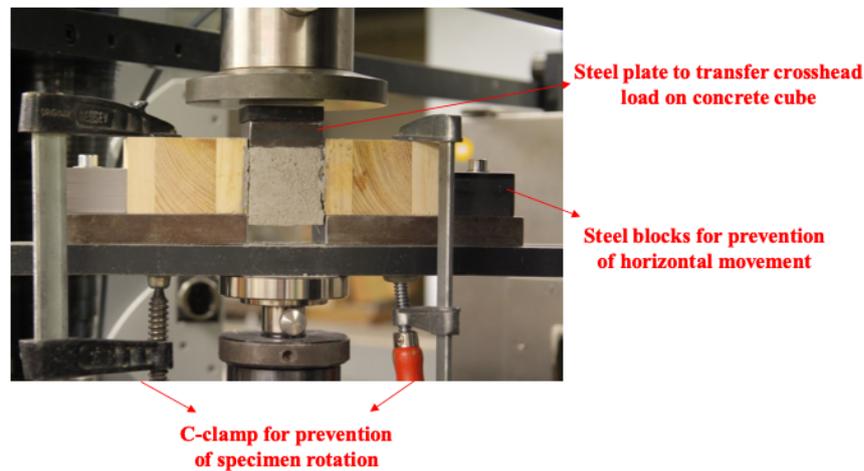


FIGURE 5. Shear test setup for measurement of shear strength of wet and dry bonds.

$$\tau_u = \frac{F_u}{2A} \quad (1)$$

in which,  $\tau_u$ ,  $F$  and  $A$  are shear strength, ultimate shear load and adhesive bond area, respectively.  $\tau_u$  thus represents the average shear strength for both faces of the concrete block.

### 3. SHEAR TEST RESULTS

The average values and standard deviations of wet and dry bond specimens are shown in Table 4. The shear strengths of each adhesive type in wet and dry bond were compared using t-test (Two Sample Assuming Unequal Variances) to reveal whether their expected mean values ( $\mu$ ) were equal ( $H_0 = \mu_{\text{wet bond}} = \mu_{\text{dry bond}}$ ). The two-tail p-values of wet and dry bonds for epoxy and polyurethane adhesives are shown in Table 5. This value indicates the probability of rejecting or accepting the zero hypothesis

(equal mean value for wet and dry bonds). According to Table 5, the two tail p-values of epoxy ( $p = 0.88$ ) and polyurethane ( $p = 0.071$ ) adhesives are higher than the level of significance ( $\alpha = 0.05$ ) indicating no significant difference between mean values of wet and dry bonds by acceptance of zero hypothesis. It should be pointed out that the significance level,  $\alpha$ , is set somewhat arbitrarily but the value of 0.05 represents a reasonable probability of the error in conclusions. As it is evident from the Table 4 that the epoxy adhesive had higher shear strength compared to polyurethane adhesive in wet and dry bonds so that the shear strength increased about 98.2% and 58% in wet and dry bonds, respectively. It is worth mentioning that the increase of shear strength achieved by epoxy adhesive does not diminish the application of polyurethane adhesive. In real application when timber-concrete composite beam/or deck is subjected to flexural loading,

Type of joint	Epoxy	Polyurethane	
Dry bond	$\tau_u$ (MPa)	2.26	1.43
	SD (MPa)	0.72	0.43
	Number of specimens	8	11
Wet bond	$\tau_u$ (MPa)	2.22	1.12
	SD (MPa)	0.49	0.27
	Number of specimens	8	8

TABLE 4. Shear strength ( $\tau_u$ ) and standard deviation (SD) of timber-prefabricated and timber-cast-in-situ glued joints.

Type of joint	Epoxy	Polyurethane
Two tail p-value	0.88	0.071
Level of significance ( $\alpha$ )	0.05	0.05
Reject or accept the zero hypothesis ( $H_0$ )	Accept	Accept

TABLE 5. Two-tail p-value results from wet bond versus dry bond.



FIGURE 6. Fracture surfaces of timber-prefabricated concrete and timber-cast-in-situ concrete glued with polyurethane and epoxy adhesives.

polyurethane adhesive as a ductile adhesive (i.e. adhesive can undergo plastic deformation before failure) can well perform against adhesive peel stress, which may cause premature failure in the adhesive bond-line. Furthermore, polyurethane is cost saving and compatible with wood substrates [14–16], therefore, there is a motivation for further investigation on the polyurethane adhesive in wet and dry fabrications.

### 3.1. FRACTURE SURFACE OF WET AND DRY BOND SPECIMENS

The fracture surfaces of failed specimens of wet and dry bonds are illustrated in Figure 6. As it is evident from Figure 6 that both polyurethane and epoxy adhesives, the amount of concrete failure remained on the wood blocks was significant in dry bond specimens. However, debonding at interface was the dominant failure mode in the wet bond specimens. The failure mode change from concrete failure to debonding at interface is a clear indication of weaker shear strength in wet bond application [17–19].

## 4. CONCLUSION

In this paper, the influence of two main types of concrete fabrication including cast-on and -off sites on shear strength of timber-concrete glued joints was studied. Two types of adhesive polyurethane and epoxy were used in this work. In timber-prefabricated concrete glued joint as a dry bond, the concrete was precast and adhered to wood blocks by its own weight while for timber-cast-in-concrete glued joint (as a wet bond), fresh concrete was added between two wood blocks covered with wet adhesive. The results showed that the shear strength of CLT-prefabricated concrete and CLT-cast-in-situ concrete bonded with epoxy adhesives had no significant difference whereas for case of polyurethane adhesive, the wet bond shear strength reduced by about 21.6% compared to dry bond. In addition, fracture surfaces of wet and dry bond specimens for epoxy and polyurethane adhesives were investigated. The change of failure mode was observed from concrete failure in dry bond to debonding at interface in wet bond which was an evidence in reduction of wet bond shear strength.

In manufacturing wet bond (especially timber-concrete composite deck/beam), it is recommended that the fresh concrete is poured at several locations of timber beam. This is due to distribute adhesive amount along the timber beam/deck. Brunner et al [8] suggested that the height of pumping fresh concrete would be low enough to avoid the adhesive movement. Increasing the height of pumping/or pouring fresh concrete may cause to adhesive splashing and movement in the location of pumping/or pouring fresh concrete. Therefore, no adhesive remains for gluing timber and concrete. Moreover, gentle use of vibrator is approved for debubbling fresh concrete, however, vibrator should not have any contact with adhesive layer.

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