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RESEARCH ARTICLE

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Thermal behavior of adhesively bonded timber-concrete composite slabs subjected to standard fire exposure

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Abstract

Fire tests were performed for the first time on adhesively bonded timber-concrete composite slabs. The two medium-scale (1.8 × 1.25 m) slabs were produced by gluing an 80-mm thick three-layer cross-laminated timber (CLT) board to a 50 mm thick prefabricated reinforced concrete (RC) slab with epoxy and polyurethane (PUR) adhesives, respectively. The behavior of the composite slabs under elevated temperature was monitored by (1) observing the burning behavior of the used CLT, for example, charring and delamination and (2) measuring the temperature development at different locations of the CLT slabs, in the adhesive bond between concrete and timber boards, and in RC slabs. It was found that employing a one-dimensional charring model for pure softwood, as prescribed by Eurocode 5-1-2, underestimated the charring depth of CLT due to the delamination effects. Measurements revealed that the average charring rates in the middle layer of CLT panels were approximately 0.65 mm/min, suggesting that the presence of concrete does not significantly affect the thermal behavior of the CLT panel. Delamination within the CLT was observed when its adhesive temperature was around 230°C. It was followed by the free-fall of delaminated wood plies, which progressed slowly and lasted until the end of the test. At 90 min into the test, the temperatures of epoxy at the nine locations ranged between 55°C and 130°, while that of PUR between 60°C and 100°. The adhesive between concrete and CLT could lose stiffness significantly along the rising of temperature after surpassing of glass transition temperature (58°C for epoxy and 23°C for PUR in this study). The results indicated a high risk of weakening the composite action between the concrete slab and timber board. The measured temperatures of steel rebar were lower than 50°C. However, the concrete temperature reached about 120°C and the concrete cracked due to the distinct thermal expansions between concrete and timber and the rigid constraint of adhesive bond.

KEYWORDS
adhesive bond, fire safety, fire tests, timber-concrete composite

Qiuni Fu and Haoze Chen these authors contributed equally to this work.

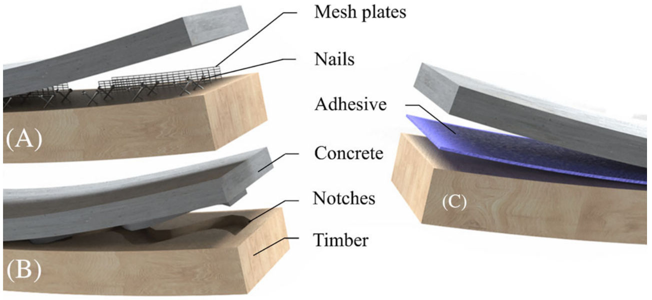


FIGURE 1 The schematic representation of different shear-resistant connection systems for timber-concrete composite (TCC): (A) mechanical fasteners, (B) notches, and (C) adhesively bonding.

1 | INTRODUCTION

Concrete is a widely used building material due to its high compressive strength and stiffness, but the tensile strength of concrete is low. In comparison, timber has a significantly lower density (300–550 kg/m^3 for most species used in construction) and higher tensile strength than concrete. Combining timber and concrete into a composite cross-section results in the effective use of both materials, where timber mainly sustains tension and concrete is under compression. Therefore, timber-concrete composite (TCC) sections are mainly used as slabs. Compared with pure reinforced concrete floor systems with similar dimensions, TCC systems are lighter. Compared with pure timber floors with similar dimensions, TCC floor systems have better performance against vibration, fire loads, and improved sound insulation performance.[1]

Timber and concrete are integrated by a shear-resistant connection system, the stiffness of which governs the degree of effectiveness of the composite action. In engineering practice, the most used connections are notches and mechanical fasteners (e.g., nails, screws, mesh plates, dowels, etc.).[2,3] Mechanical fasteners are considered to be semi-rigid, at best and do not provide strain compatibility at materials (concrete-timber) interfaces. In addition, recent studies showed the potential deterioration of wood subjected to alkaline environments, especially during concrete hydration.[4] Such degradation may be prevented when adhesive is used to separate wood from concrete, providing that no degradation of the adhesive occurs. Adhesively bonded TCC systems (see Figure 1) have been recently studied[5–9] since adhesive bonding provides for strain compatibility at the interfaces and requires less machining (e.g., cutting and drilling) compared to mechanical connections.[1] A rigid connection enables a slender design of TCC floor systems, which can reduce the consumption of materials. Thus, an adhesively bonded TCC floor has great potential to be used in civil engineering practice.

Fire safety is a critical and complex issue for timber structures since wood is considered to be a combustible material, resulting in the reduction of its cross-section under fire. Massive cross-sections, however, can display relatively high fire resistance. Besides, the strength and stiffness of wood will be strongly influenced by elevated temperature. In the annex of Eurocode 5-1-2,[10] it is recommended to assume that, the softwood totally loses strength and stiffness when the temperature reaches 300°C. Engineered timber products, for example, cross-laminated timber (CLT), are produced by laminating several plies of solid timber. Under fire exposure, engineered timber experiences charring, delamination, and falling of charred timber plies, leading to the complexity of a temperature development within the timber, which is difficult to predict. Frangi and Fontata[11] noted an accelerated charring rate in CLT during fires, primarily attributable to its delamination characteristics. A simplified bilinear model for estimating the charring depth of CLT in fire was accordingly proposed. Aguanno's research[12] indicated that, during a fire, the delaminated layers of CLT do not uniformly fall off all at once. Wang et al.[13] developed a heat transfer model for CLT in fire scenarios considering the falling off of the CLT layer. However, it did not effectively capture the localized delamination and falling off of layers, which leads to a rapid temperature increase within the CLT structure. For floor systems, high temperatures result in a decrease in the stiffness of the connection system between timber and concrete. This indicates a reduction of composition action between the two materials, which reduces the load-bearing capacity of the TCC floor systems. Load-bearing structural members require minimal fire resistance evaluated in terms of survival time periods in fire, for example, 90 min (R90). Therefore, the investigation of the fire resistance of TCC and the development of design methods for fire resistance of TCC is essential in practice. Fontana and Frangi[14] reported a series of fire tests on TCC connections. The connection behavior of small-scale (span of 1150 mm) TCC floor systems composed of timber beams and concrete panels with screws or glued dowels connections were tested under tension or shear, respectively. Based on this, a set of simplified formulae for the calculation of the strength and stiffness of screw connections were developed. A simplified design method for the fire resistance design of TCC floors was developed by incorporating connection behavior and was validated by the fire test of a TCC floor (span of 5210 mm).[13] The failure of the full-scale TCC floor in the fire started from the failure of the screw connection and was followed by the successive failure of timber beams. This failure mechanism was predicted by the design method,[15] showing the importance of the connection behavior for the design of TCC in fire. O'Neill et al.[16] presented the fire tests on TCC beam-type floors (span of 5210 mm) connected by screws-reinforced notches or toothed steel plates. The floor with steel plate connections exhibited stiffer performance and lower deflections in the fire when compared with the reinforced notches connected TCC floor. The different behavior of TCC floors connected by the two connection types highlighted the importance of the investigation of the different connection systems for TCC in the fire. In the study[17] performed at Oregon State University, USA, the fire resistance of two slab-type TCC floors (span length of 4800 mm) were tested, the connection systems of which were composed of screws and truss plates, respectively. The results indicated that the connection system and concrete top layer did not affect the thermal response of timber in the fire. Under the protection of a thick timber panel, the concrete remained at nearly ambient temperature. Both two TCC floors showed high fire resistance (R 90 and R 180, respectively).

Adhesives are generally temperature sensitive. The stiffness of adhesives could decrease rapidly with elevated temperature, especially when the corresponding glass transition temperature of adhesive is reached. As a result, the TCC structures have a high risk of losing load-bearing capacity significantly when the Tg of the adhesive layer is reached. Slabs will be suitable for adhesively bonded TCC floors since the timber panel can protect the adhesive layer from reaching the Tg for an extended period of time.

To this point, there have been no studies on adhesively bonded TCC floors in the fire. It has not been known, how the temperature develops in an adhesively bonded TCC floor, especially at the interface. Knowledge of the structural performance of adhesively bonded TCC floors under elevated temperatures is also missing. The lack of knowledge pertaining to the TCC performance under fire and the lack of data to validate the models and develop the design models prevents the application of TCC in practice. In such context, this study aims to identify the thermal response (or temperature development) of the adhesively bonded TCC slabs exposed to fire. Two slab-type TCC floors glued with epoxy and polyurethane (PUR) adhesives were fabricated and subjected to ISO fire.[18] The temperature development in timber, adhesive bonding layer, and reinforced concrete were analyzed and discussed in detail. Notably, when the temperature rises, a rigid adhesive connection restrains the distinct thermal expansions of concrete and wood. Specifically, the thermal expansion coefficient of concrete is around 1.0×10^{-5} (/°C)[19] while that of wood in the right direction about the grain is around 3.0×10^{-5} (/°C).[20] The distinct responses may cause strains at the bonding interface, resulting in cracks of concrete in tension. It was particularly investigated in the present study.

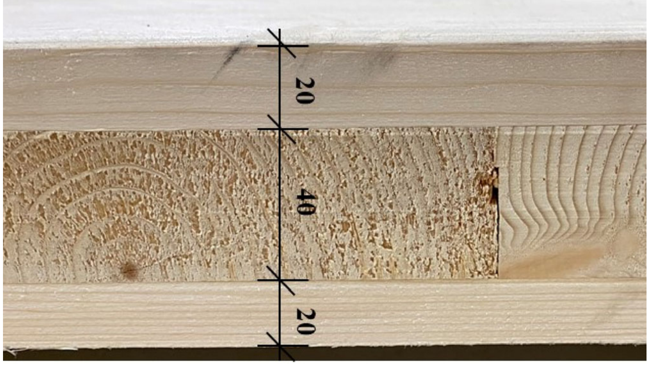


FIGURE 2 The cross-section of the timber board (unit: mm).

TABLE 1 Basic parameters of the cross laminated timber (CLT) boards.[23]

Parameters	
Plies	3 (20 + 40 + 20 mm)
Wood type	Spruce
Adhesive between plies	1-Component-PUR
Density	480 kg/m^3
Thermal conductivity	0.12 W/(mK)
Specific heat capacity	1600 J/(kgK)
Modulus of shear paralleled to grain	690 MPa
Modulus of rolling shear	50 MPa
Rolling shear strength	1 MPa
Pressure in plane	21 MPa
Pressure normal to the plane	2.5 MPa

2 | EXPERIMENTAL STRATEGY

2.1 | Specimen design

The medium-size furnace, constructed according to EN 1363-1[21] (exposed area 1.5 × 1 m), at the Institute of Building Materials, Concrete Construction and Fire Safety (iBMB) of TU Braunschweig was selected for the fire tests. The exposed area of the furnace (i.e., 1.0 × 1.5 m) represents the span of the TCC specimens, which are around one-quarter of the dimensions of real slabs. If ensuring the realistic load-bearing capacity (in kN/m^2), the thickness of the TCC slab should be reduced proportionally. With a preliminary estimation the timber board (herein, CLT) should be thinner than 50 mm. However, such a thin CLT board cannot deliver meaningful thermal information during tests for realistic TCC floors. Specifically, the focus of this study was on the temperature development in TCC slabs, especially at the bonding layer between concrete and timber under ISO fire curve. A timber board at the bottom of a TCC slab is a combustible material and, on the other hand, provides the thermal insulation for the above layer and reinforced concrete slab. Therefore, the thickness of the timber board is critical to the temperature development of the entire TCC slab. Under 90-min of standard fire exposure, the notional design charring depth and the effective charring depth (as per Eurocode 5-1-2[10]) are 58.8 and 65.5 mm, respectively, which has already surpassed the thickness of the CLT board. After the trade-off analysis between scaling concerning load-bearing capacity and realistic thermal behavior, a commercial CLT panel product with 80 mm thickness was selected. The CLT was made of spruce and configured with three layers, that is, 20 + 40 + 20 mm (see Figure 2). Nine wood samples cut from single layers of CLT were tested under bending per standard EN 408.[22] The average flexural E-modulus and density were 10.3 GPa (standard deviation, SD = 1.5 GPa) and 472 kg/m^3 (standard deviation, SD = 43 kg/m^3) at the moisture content of 11.8%, determined with oven-drying method at a temperature range between 100 and 105°C. The other mechanical properties under shear and physical properties including density, thermal conductivity, and specific heat capacity, retrieved from the product datasheet[23] are shown in Table 1.

Being used for building floors, normal strength concrete C30/37[24] was selected, with the composition shown in Table 2. Given a CLT thickness of 80, 50 mm thickness was decided for concrete to ensure that the neutral plane was close to the adhesive layer between timber and concrete when the TCC slab was under bending. This decision was made based on the assumption that both concrete and wood

TABLE 2 The composition of concrete.

Composition					
Water	CEM I 42.5R cement	0–2 mm Sand	2–8 mm medium aggregate	Super-plasticizer (PCE)	Total
0.544	1	2.754	2.315	0.001	6.615

TABLE 3 The parameters of adhesives obtained from datasheets.

Properties	Sikadur®-330	Sikaforce®-7710L100
Type	Epoxy	PUR
Glass transition temperature	58°C	23°C
Initial mixture viscosity [mPa·s]	6000	10 000
Density [kg/L]	1.3	1.5
Tensile modulus of elasticity [GPa]	4.1[a]	0.106[a]
Tensile strength [MPa]	35.1[a]	6.2[a]

[a]Obtained by tests; the others were obtained from the manufacturer.

would fail simultaneously upon reaching the ultimate load. The quality of cast concrete could be influenced by the fluidity and air content, which affect the thermal properties of cured concrete. During the casting of concrete, typical slump tests and compression tests were used following the standard EN 12350-1[25] to check the flowability and air content of fresh concrete. The flow class and the air content of fresh concrete by volume were F3 and 1.8%, respectively, indicating the good workability and quality of the concrete. Five fresh concrete cylinder samples were made and cured following the standard procedure EN 12390-2.[26] After 28-day curing, the hardened concrete cylinders were tested as per EN 12390-3,[27] showing an average compressive strength of 48.3 MPa with a standard deviation (SD) of 1.1 MPa. In addition, steel mesh (Type Q188A as per DIN 488-4[28]) was used to prevent the concrete from cracking caused by shrinking or self-weighting during transportation before bonding to timber boards. The steel mesh consists of 6 mm-diameter rebars with 150 mm spacing in both directions, having a nominal yield/ultimate strength of 500/550 MPa.

The epoxy (Sikadur®-330[29]) and PUR (Sikaforce®-7710L100[29]) were used in this study for bonding timber and concrete, considering their good bonding performance for TCC connection.[8,9] The TCC slabs connected by epoxy and PUR will be referred to as Epoxy-TCC and PUR-TCC. Dumbbell-shaped adhesive samples were made and cured at 20°C for a week to be tested for the tensile properties according to EN ISO 527-1.[30] The average tensile strength and E-modulus of the epoxy were 31.5 MPa (SD = 3.0, the number of samples $n = 6$) and 4.0 GPa (SD = 0.1, $n = 6$), respectively. The average tensile strength and E-modulus of the PUR were 6.2 MPa (SD = 0.2, $n = 10$) and 0.106 GPa (SD = 0.017, $n = 10$), respectively. The physical properties such as density, glass transition temperature, and initial mixture viscosity are shown in Table 3. Notably, despite the high viscosity described in the datasheet from the manufacturer, it was found that the fresh PUR has better fluidity than epoxy during the bonding process. In a study by Nemati Giv et al.,[9] the same fresh epoxy showed a higher loss shear modulus than the PUR by amplitude sweep tests. It indicates that the fresh epoxy has higher viscosity.

2.2 | Production of TCC slabs

The overall production process of two adhesively bonded TCC slabs is shown in Figure 3. Two concrete slabs (1800 × 1250 × 50 mm) were prefabricated and cured in a test hall with an average temperature of about 20°C and relative humidity of 65%RH for 1 month. Then, the bottom side of the concrete slabs was ground and cleaned to be prepared for bonding. Sikadur-330 epoxy and Sikaforce-7710L100 PUR were respectively spread onto a prepared concrete surface uniformly within an area of 1000 × 1500 mm bounded by metal spacers that were used to ensure the average adhesive thickness of approximately 2 mm, which is an optimized thickness according to Nemati Giv et al.[9] Subsequently, the tailored CLT boards (1800× 1250 × 80 mm) were pressed onto the concrete slabs to be TCC slabs, which were clamped for the first 3-day curing of the adhesives. Afterward, the two TCC slabs were transported to a climate room with a temperature of 20°C and RH of 65% for the post-curing of the adhesives.

2.3 | Instrumentation

To monitor the temperature development in TCC slabs, 21 thermocouples were installed in each specimen and grouped by different heights (Figure 4). The specific locations on the plan view can be found in Figure 5. For ease of reference, the four groups were ordered to be first through fourth from the bottom upwards. The first-group thermocouples were labeled as A1, B1, C1, and D1 and embedded at the mid-height of the middle ply of CLT to measure the temperatures in the CLT. The second-group thermocouples were labeled as A2, B2, C2, and D2 and embedded at the boundary between the top and middle plies of CLT to monitor the temperature development at the glue layer between plies and the potential delamination and free-fall of the charred ply. The thermocouples were inserted into the designed depths of timber through predrilled holes with a diameter of 4 mm (Figure 6). The third group, nine thermocouples K1–K9 covered with copper caps were fixed parallelly to the surface of the CLT board. In this way, the error of the results can be greatly avoided.[31] After the bonding process, K1 through K9 were embedded into the adhesive layer between CLT and concrete to measure the surrounding

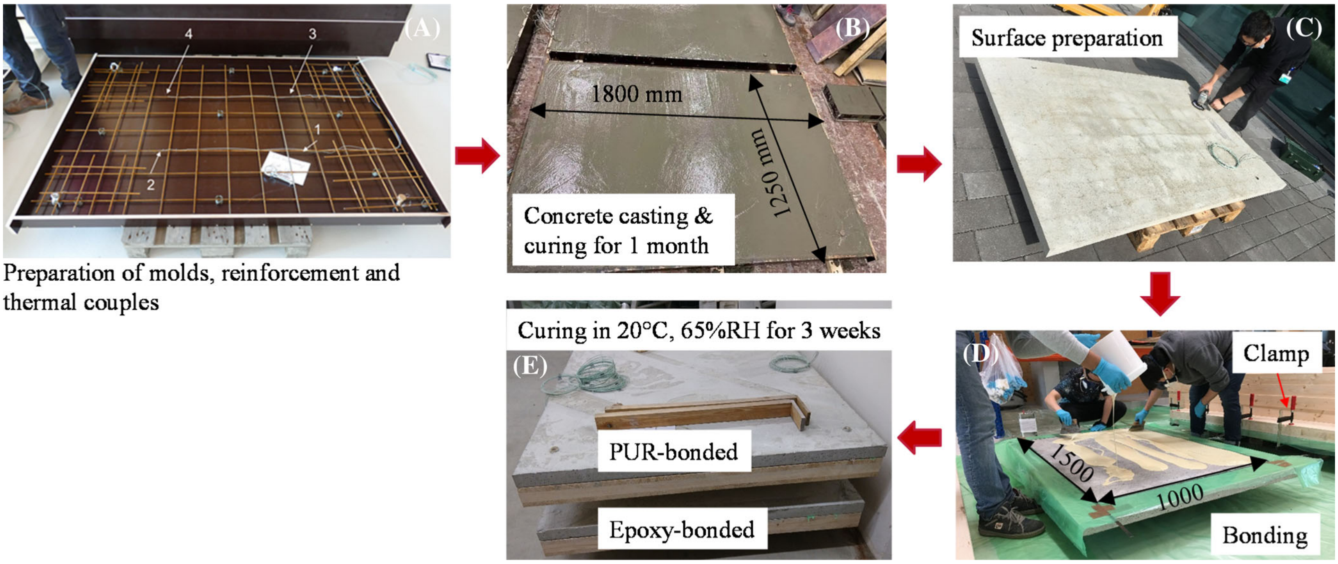


FIGURE 3 Production of the timber-concrete composite (TCC) slabs: (A) preparation of molds, (B) concrete casting, (C) surface preparation, (D) bonding, and (E) post-curing.

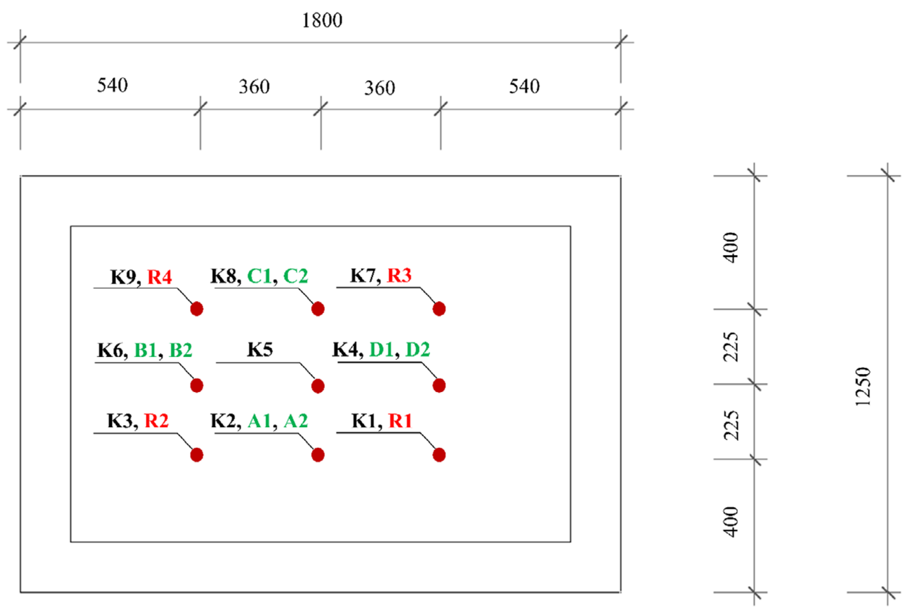


FIGURE 4 The vertical position of the thermocouples (units: mm).

temperatures. Before concrete casting, the fourth-group thermocouples R1–R4 were mounted on the reinforcement (see Figure 3) to monitor the temperature development of the rebar.

2.4 | Test procedure

The medium-sized fuel-based furnace, constructed according to EN 1363-1,[21] at iBMB of TU Braunschweig, Germany, was used for the fire tests. Two oil burners were controlled manually to meet the standard fire curve[18] based on the feedback of temperature from two thermocouples in the furnace (Figure 7A). The TCC slab was simply supported by aerated concrete blocks on four edges, with the timber facing down. The adhesively bonding area was aligned with the exposing area of the furnace. Mineral wool was used to fill the gap between the slab and aerated concrete blocks. The side surfaces of the timber were covered with 12.5 mm thick gypsum board. The bonding lines were covered with a plastic sealing tape (Figure 7B). These two measures were to ensure one-dimensional heat transfer from the bottom upwards through the concrete top surface. Thus, the temperature of the structure could increase with the maximal speed under the standard fire exposure.

The fire-exposing protocols of the two tests were in compliance with ISO-834.[18] After 90-min standard fire exposure, the burners were shut down. Two bricks on the wall in the opposite side were removed to create openings to maintain the pressure balance in the furnace. During this period, the temperature of the TCC slab

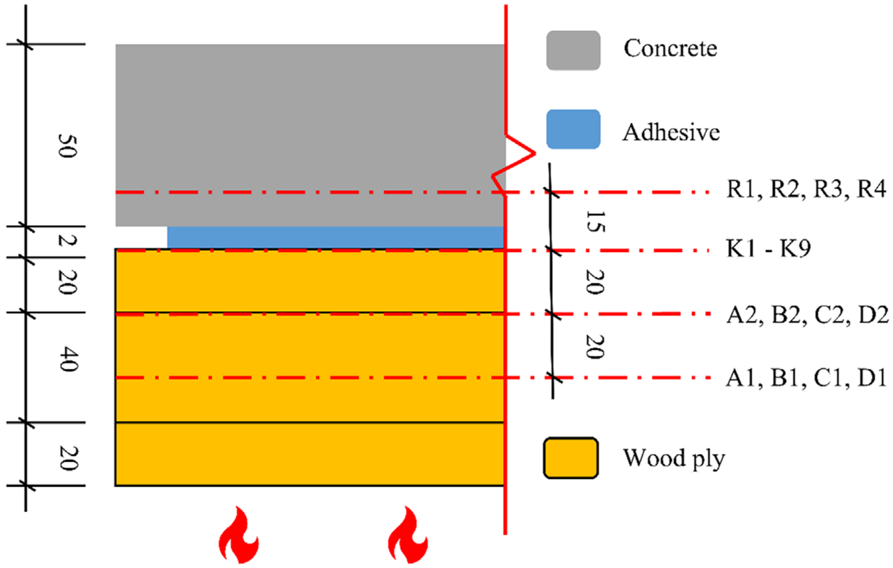
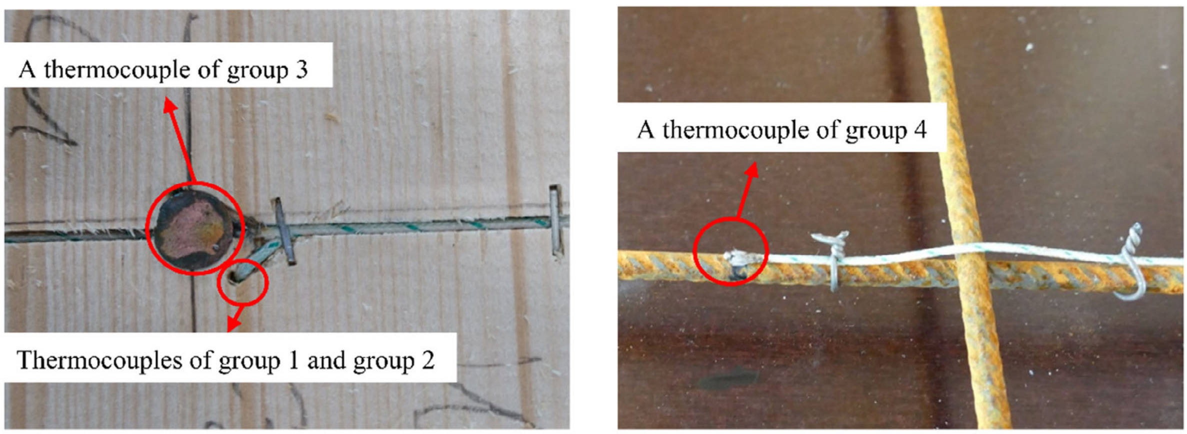
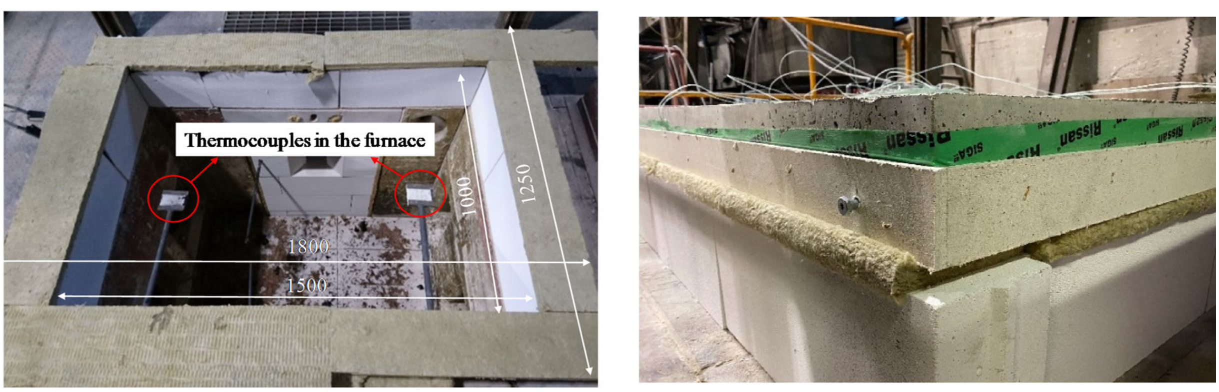


FIGURE 5 Locations of thermocouples in the plan view (units: mm).



(A) Thermocouples in timber and adhesive layer (B) Thermocouples on reinforced concrete

FIGURE 6 Details of thermocouples installation.



(A) Top view of the furnace **(B)** Overview of the testing side

FIGURE 7 Details of the test setup (unit: mm).

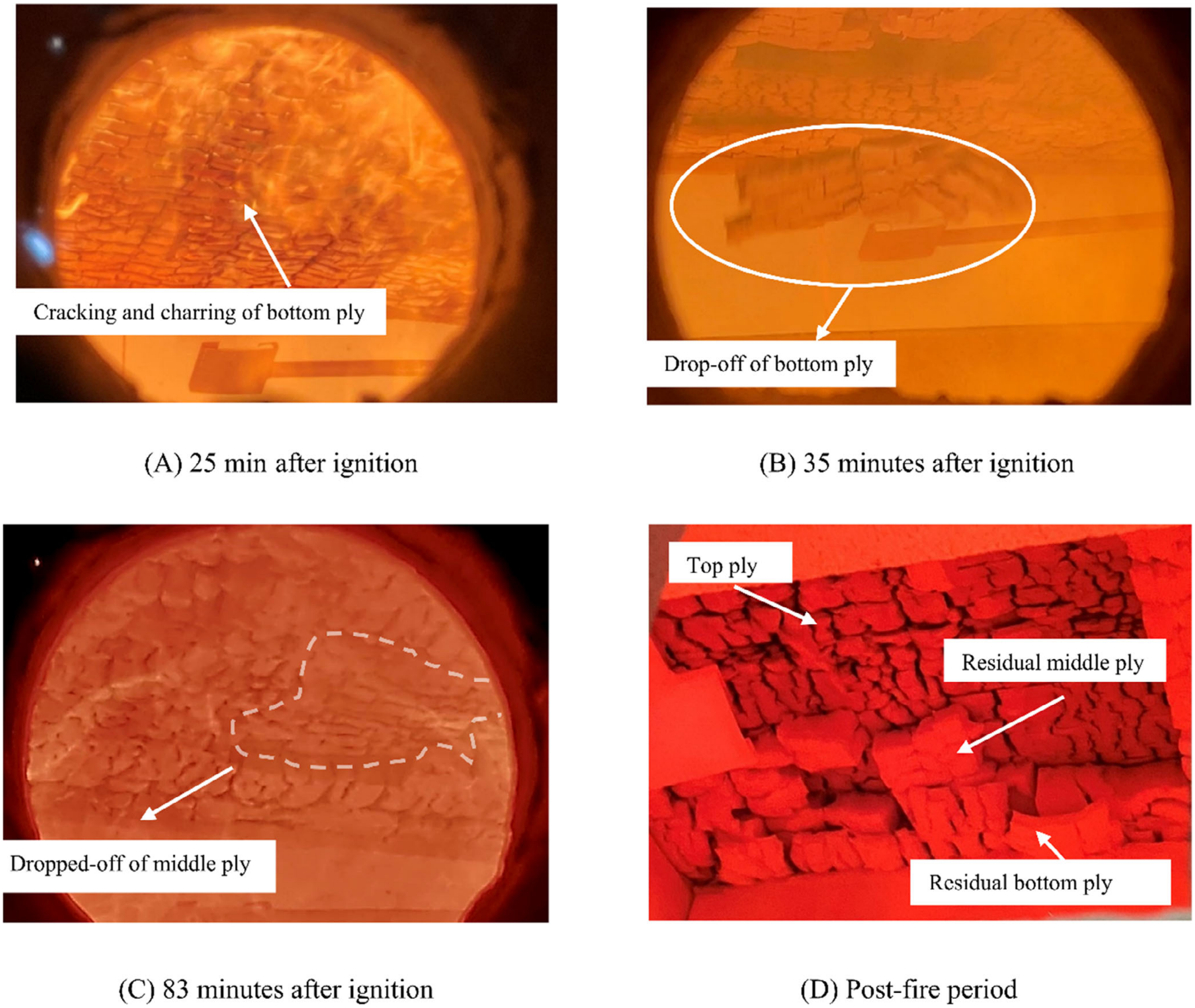


FIGURE 8 Burning behavior of the cross laminated timber (CLT) of Epoxy-TCC.

continued to rise for about 10 mins and then decreased due to convection, smoldering, and extinguishment of the fire. The changes in temperature were strongly influenced by external factors, so the data in this stage was not interpreted. After the cooling of the furnace and sample for about 24 h, the TCC slab was lifted up from the furnace by crane and shifted away.

3 | RESULTS AND DISCUSSIONS

3.1 | Behavior of timber

3.1.1 | Visual observations

During the tests, the bottoms of the TCC slabs were visually observed through three round-shaped transparent windows (with a diameter of around 10 cm) on the walls of the furnace. Both epoxy- and PUR-bonded TCC slabs showed similar behavior. It was visible, that the exposed timber surfaces of the specimens ignited shortly after the fire exposure was started. Until the 30th minute of fire exposure, a charred layer was observed and the non-glued lateral joints between the lamellas of the CLT ply showed cracks. Within 30th minutes after the ignition, shrinkage cracks started from the center of the CLT and developed toward the peripherals (Figure 8A). After 30 min of the test, we observed the gradual delamination and char fall-off of the bottom ply of CLT, starting from the center (Figure 8B). Till 60th minute, most of the bottom ply fell off. At around 80 min of the test, a central part of the middle ply dropped off (Figure 8C). After shutting down the burners, the CLT of the TCC slabs was photographed through the openings on the walls of the furnace (see Figure 8D), showing the burning residual plies of the CLT.

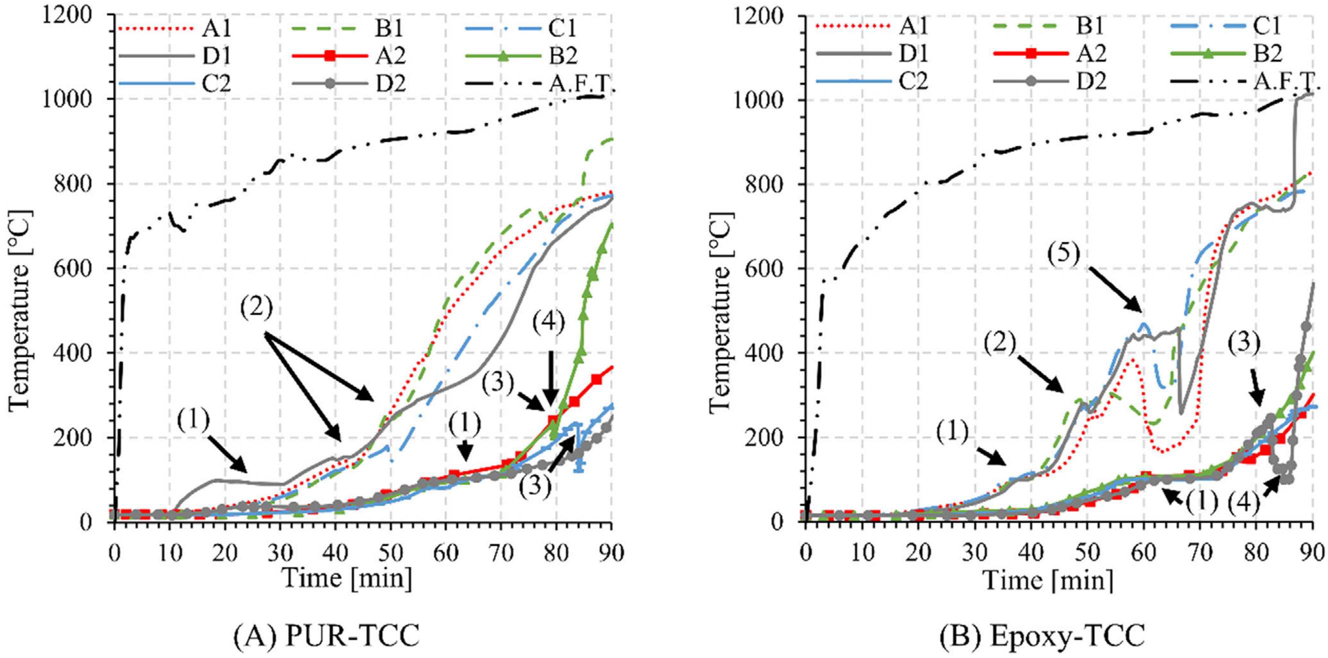


FIGURE 9 Time–temperature curve recorded by thermocouples in timber. A.F.T. represents average furnace temperature; (1): Evaporation (2): Pyrolysis of wood (3): Peak (4): Delamination (5): The fluctuation.

3.1.2 | Temperature development

Figure 9 shows the temperature–time (T–T) curves measured by the Group-1 and -2 thermocouples in the CLT, where the numbers on the horizontal coordinate indicate the time period after the ignition. There are moderate variations among the T–T curves in one group at the same height (Figure 9A). The effects mainly are moisture movement (evaporation and condensation), char fall-off, cracking of lateral joints of ply lamellas as well as the natural distribution of the thermophysical properties of timber.

After an initial slow heating process, most of the T–T curves measured by all the thermocouples in wood showed a plateau or a gentle slope when the temperature reached 100°C (Figure 9). The evaporation of water inside timber is considered as the reason, due to the high amount of required heat of evaporation (approx. 2257 kJ/kg), the temperature rise of the CLT will be delayed. For the epoxy-bonded TCC slab, the plateau of T–T curves of A1–D1 in the mid-height of the CLT middle ply appeared during the period between 35 and 40 min, while that of A2–D2 between 56 and 72 min (Figure 9B). For the PUR-bonded TCC slab, the T–T curves of A2–D2 in Group 1 showed a gentle slope at a temperature range of between 95 and 105°C during the period between 60 and 70 min (Figure 9B). However, the T–T curves of A1–D1 did not show such a clear tendency. It may be due to low moisture content in wood around A1–D1. Another reason could be that A1–D1 were partially located in gaps in CLT where water concentration was low, and the temperature continued to increase in the hot air.

Wood starts to decompose at a temperature range of 160–180°C. The intensive pyrolysis occurs at around 300°C.[32] That should be the reason that, when close to those temperatures, the curve may have a small fluctuation. On the other hand, the fluctuation of T–T curves in timber especially between 55 and 70 min for epoxy-TCC is mainly caused by the moisture of CLT (evaporation shown by the plateau of group 2 thermocouples) in combination with falling off the lamellas. The test specimen is moisture-sealed at the top by the adhesive layer and at the sides by airtight masking and gypsum boards. The water vapor can therefore only escape in the direction of the flamed surface (see Figure 9B; marked as the fluctuation) and a vapor pressure occurs which can lead to an uncertainty of the temperature measurements in this range. After falling off the lamellas the vapor is set free. The strong rise in temperature from the 70th minute onward may result from the temperatures in the fire room and the combustion of the wood. The water vapor could also cause a kind of "spalling," as the water vapor can lead to greater stresses in the glue joints of the CLT lamellae.

From T–T curves of thermocouples A2–D2, which were installed in the interface between the top and middle plies, the first peaks were found at a temperature of between 200 and 300°C. These points should be the starting points of the delamination process of CLT plies. After the first peaks, the curves suddenly dropped due to the delamination of plies, which absorbed heat for decomposition or degradation of the adhesive and wood. Afterward, the bottom ply fell off, the middle layer was directly exposed to the flame, where the temperature of A2–D2 rose rapidly and approached the furnace temperature.

For instance, the first peaks of T–T curves of A2–D2 between 200 and 300°C were identified at around 230°C and 80 min, as shown in Table 4. After reaching 230°C, fall-off of ply at some locations did not occur. The possible reason was that the charred timber

TABLE 4 The turning points of T–T curves that are assumed to be the delamination points.

Thermocouple	Specimen	Temperature [°C]	Time [min]
B2	PUR-TCC	230	79.5
C2	PUR-TCC	230	83.8
D2	Epoxy-TCC	238	82.0

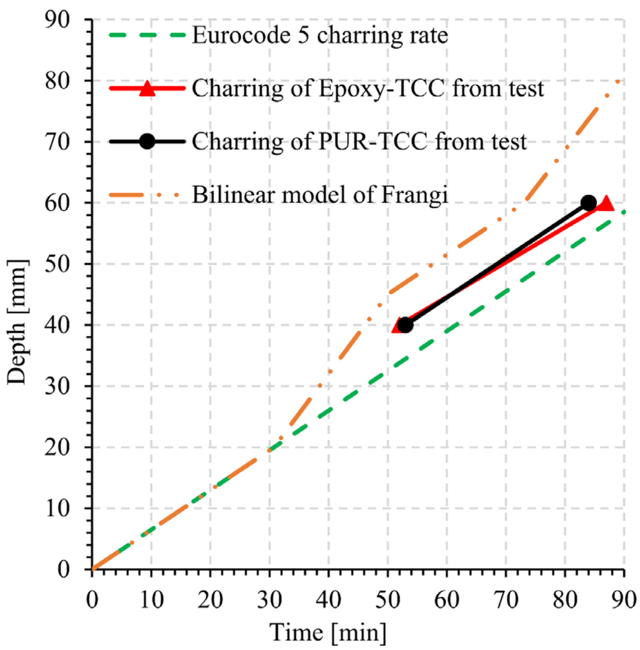


FIGURE 10 The charring of timber from measurement and calculation.

became light and could be remain in position due to the residual adhesive force and simple support from the peripherals.

3.1.3 | Charring of the timber

The isotherm at 300°C is considered as the position of the char-line in Eurocode 5-1-2.[10] By picking the points at 300°C from the T–T curves, the average time required for the charring of timber to the depth of 40 and 60 mm in the test was calculated to be about 52 and 85 min (Figure 10), respectively. At the same time, the notional design charring depths were calculated based on a one-dimensional charring rate for solid softwood (0.65 mm/min) according to Eurocode 5[10] (Figure 10), which is smaller than the given depths of 40 and 60 mm, respectively. It indicates the one-dimensional charring model for solid softwood in Eurocode 5-1-2[10] may be unsafe for estimating the charring depth of CLT. The glue lines in CLT can cause delamination of charred timber at high temperatures, exposing new layers of CLT to fire without the protection of charred wood. However, the charring rate of two slabs in the time range of 52 to 85 min is close to the one-dimensional charring rate (0.65 mm/min) in Eurocode 5-1-2.[10] It showed that the concrete topping and adhesively bonding layer had no impact on the thermal behavior of the timber panel, which was expected since the fire exposure was from the bottom of the slab. Considering the delamination of CLT layers during a fire, Frangi and Fontana[11] proposed a bilinear model to estimate the charring depth of CLT. The charring rate for the initial layer of CLT panels is presumed to be 0.65 mm/min. Once the first layer is fully charred, it falls off. Subsequent layers of the CLT panels begin to char, with a rate assumed to be double that of the first layer, that is, 1.3 mm/min, until the charring layer reaches a thickness of 25 mm. Subsequently, the charring rate reduces to 0.65 mm/min. Kleinhenz et al.,[33] conducted a fire test on a large-scale CLT rib panel. The bilinear model was used for comparison with the measured charring depth. The result revealed that the fall-off of charred layers was less significant than assumed in the simplified bilinear model. This discrepancy was attributed to a less severe detachment of charred CLT layers, but rather, the dropping of parts from these layers. In the present study, the charring depth of the CLT calculated by the bilinear model (see Figure 10) overestimates the measured values with differences ranging from +6.95 to +18.1 mm. In the experiment of this study, the thermocouples at the same height were placed relatively far apart in plane, where the delamination of the CLT occurred unevenly and resulted in a slower temperature increase. Conversely, in the experiment by Frangi and Fontana[11] used for deriving the bilinear model, thermocouples were positioned along the longitudinal central axis of the CLT board, where CLT cracking, and delamination happened more rapidly. This difference in sensor placement could account for the variation in charring depth observations between the studies.

3.2 | Behavior of adhesive bond between concrete and timber

The T–T curves recorded by thermocouples K1–K9 in the glue layer between concrete and timber boards are shown in Figure 11. The temperature development of K1–K9 in the PUR-bonded slab was more stable and that in the epoxy-bonded slab which was more fluctuating. This could be due to the different compactness of the PUR and epoxy layers resulting from the bonding process. Specifically, the authors used a tooth-shaped spatula (Figure 12) to spread the adhesives, leaving grooves in the adhesive layers. The PUR layer became smoothed after the flattening due to the high fluidity, forming a compact glue layer (Figure 13A). In contrast, the grooves remained in the epoxy layer (Figure 13B) and were not filled under the limited pressure applied by clamps (Figure 3). In the burning process, hot water vapor traveled through these grooves and disturbed the temperature development. The unfilled epoxy grooves can be seen (Figure 14) by cutting through the slab depth.

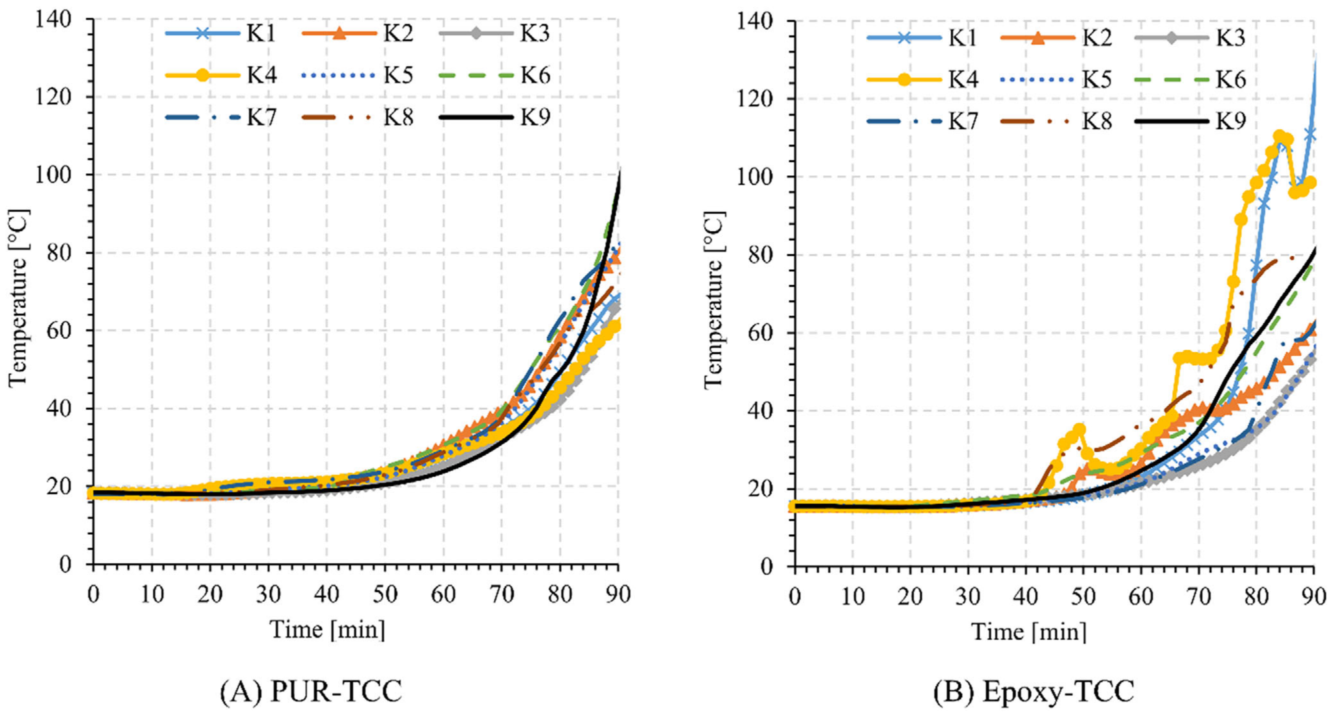


FIGURE 11 Time–temperature curve recorded by thermocouples in the adhesive bond between concrete and timber.

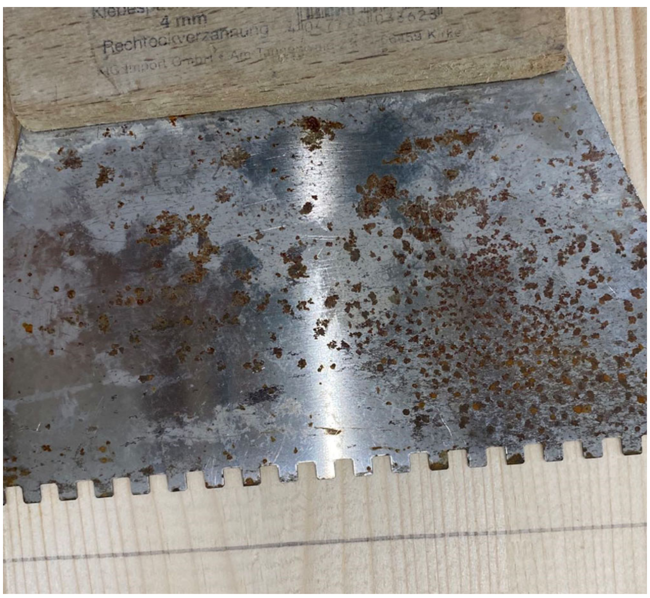


FIGURE 12 Tooth-shaped spatula is used to spread the adhesive.

Within 75 min into the tests, the temperatures measured by K1–K9 in Epoxy-TCC were lower than the glass transition temperature of epoxy (58°C), indicating uncompromised mechanical performance (e.g., shear modulus and strength) of the epoxy.

At 90th minutes into the tests, the maximum temperature of thermocouples K1–K9 in PUR-TCC and Epoxy-TCC were 96.8 and 121.4°C, respectively. The debonding between concrete and timber was not observed, since there was no additional mechanical loading except for the self-weight of the specimen and the remained load-bearing capacity of the reinforced concrete slab (refer to Section 3.3) was far more than sufficient to carry the self-weight. Frangi and Fontana et al.[34] tested the shear strength of different PUR adhesives bonded timber blocks at elevated temperatures. The result showed that the shear behavior of PUR-bonded timber at elevated temperatures highly depends on the composition of the PUR adhesives itself. At 96.8°C, the shear strength of PUR-bonded timber blocks could remain at around 25% to 75%, meanwhile the shear strength of timber itself remains only at around 70%. Clauss et al.[35] conducted the lap-shear test on the adhesively bonded beech specimens at elevated temperatures. The specimens using three different PUR adhesives showed good performance at elevated temperatures, with above 78% remained shear strength at 110°C. On the other hand, a similar test on epoxy-bonded spruce overlapped specimens was conducted by Fecht et al.[36] The specimens at 120°C remained at more than 54% of shear strength at room temperature. However, the numerical investigation performed by Klippel et al.[37] showed that the performance of adhesive at elevated temperatures minimally affects the shear resistance of glued laminated timber beams, where failure primarily stems from exceeding bending moment resistance. Therefore, further studies are needed to clarify whether adhesively bond will control the failure of adhesively bonded timber-based structural elements, for example, CLT and TCC, under standard fire conditions, especially when subjected to mechanical loading simultaneously.

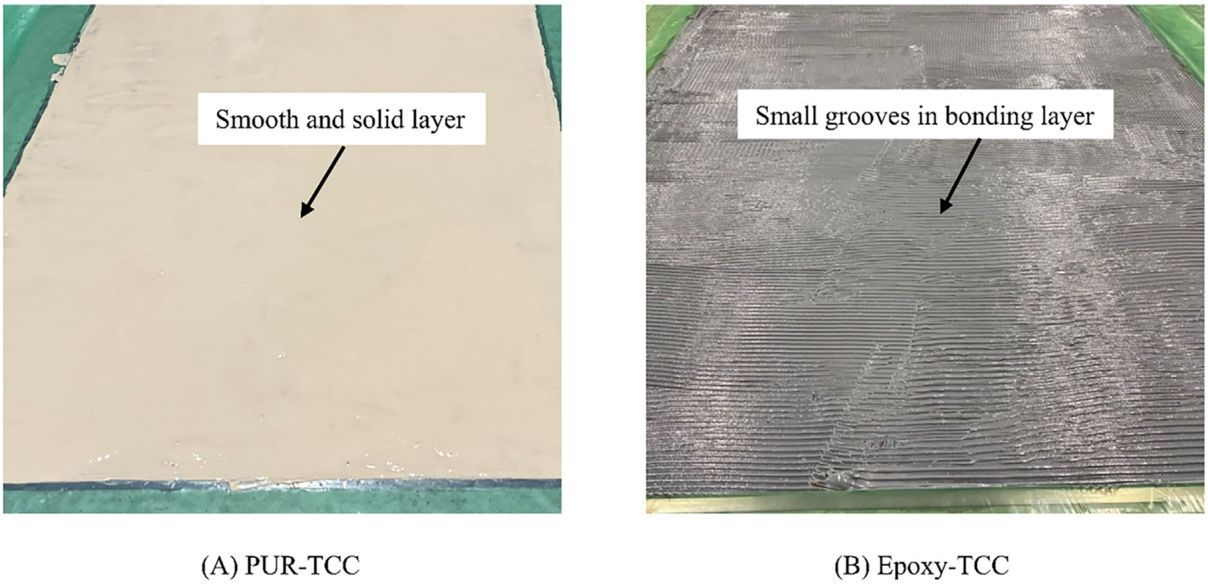


FIGURE 13 Flattening of the adhesive layers.

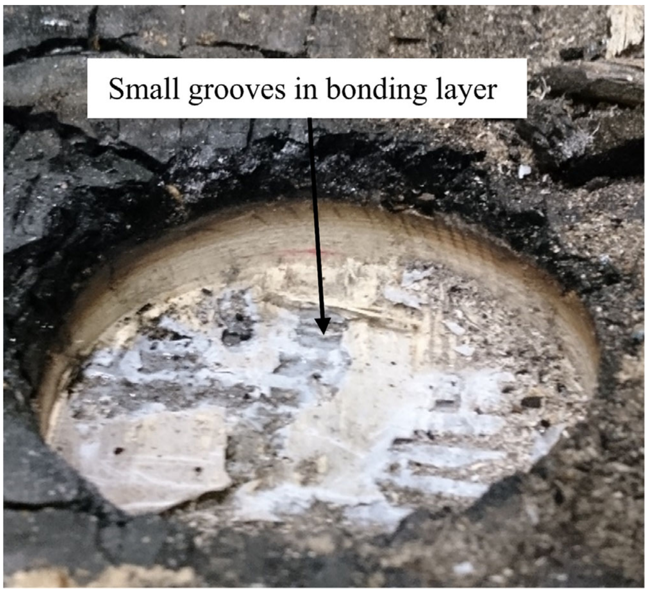


FIGURE 14 Cutting through the cross laminated timber (CLT) depth.

3.3 | Behavior of reinforced concrete slab

The T–T curves of Group 4 thermal couples (R1–R4) on the steel reinforcement are shown in Figure 15. Based on Eurocode 2-1-2,[38] no changes in the stress–strain relationship of hot rolled steel at 100°C need to be considered. During the tests up to 90 min, the maximum temperature of R1–R4 in both slabs was limited to 50°C, which hardly influenced the mechanical performance (e.g., tensile modulus and strength) of the steel.[38] The temperature of the concrete at the bonding interface can be approximated by the temperatures of K1–K9 that were lower than 120°C. According to Eurocode 2-1-2,[38] the design compression strength of concrete at 100 and 200°C can be considered as 1 and 0.95 times, respectively, of its original strength at room temperature. Such a degree of temperature (i.e., 120°C) had a minimum influence on the mechanical performance of concrete. However, during the fire tests, cracks gradually developed in concrete from the bonding interface, due to the distinct thermal expansions of concrete and timber, as shown in Figure 16. At the end of the fire tests, the cracks developed through the depths of the reinforced concrete slabs and were perpendicular to the slab edges and located at about one-third of the spans in both directions. It was reasonable because the tensile strain in concrete caused by different expansions accumulated from the free edges toward the mid-span. When the tensile strain surpassed the ultimate tensile strain of concrete, a crack occurred, and the strain was released. Then new strain accumulation began until sufficient cracks were developed. It indicated that adhesively bonded TCC slabs with larger continuous bonding areas will have the same issue under ISO fire exposure. In future studies, special measures should be taken to avoid the occurrence of concrete cracks. Alternatively, the consequence of the presence of cracks should be investigated. For instance, cracks would result in the reduction of flexural stiffness of the remained TCC slab and increase the environmental exposure such as to carbon dioxide and chloride.

4 | CONCLUSIONS AND OUTLOOK

The ISO-standard fire tests were conducted on two timber-concrete-composite slabs with the respective epoxy- and PUR-bonding for the first time. The dimensions of the TCC slabs were

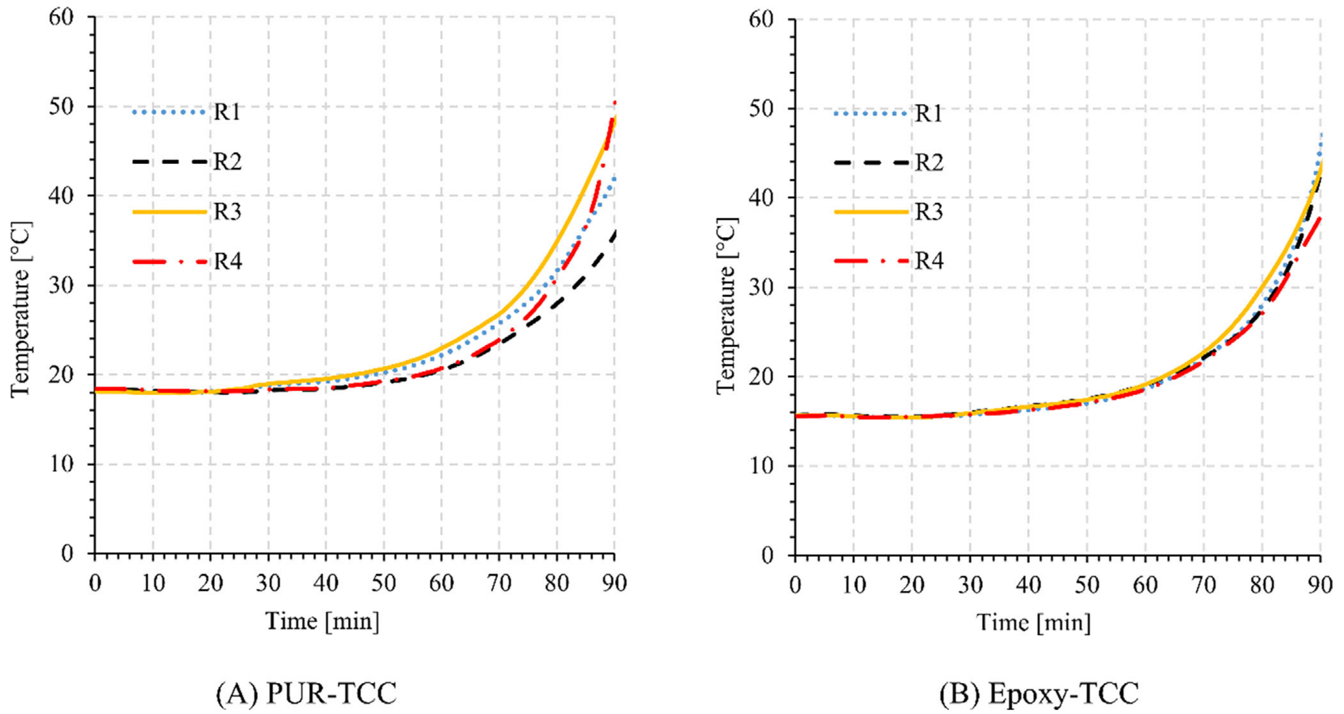


FIGURE 15 Time–temperature curve recorded by thermocouples in reinforced concrete slabs.

1800 mm long, 1250 mm wide, and 130 mm thick. The cross-section was configured with an 80 mm thick CLT at the bottom and a 50 mm reinforced concrete topping. With the only difference of the thin (2 mm) adhesive-type layers, two TCC slabs showed similar temperature developments, demonstrating the reproducibility of the tests. Based on the limited observations and measurements, the following conclusions can be drawn, which might be applied to the adhesively bonded TCC slabs with similar dimensions and boundary conditions.

- The charring depth calculated per the one-dimensional charring rate according to Eurocode 5-1-2[10] is smaller than the measured charring depth in the experiment. The bilinear model[11] overestimates the charring depth when compared to the measured values.
- The average charring rate observed in the middle layer of CLT in two TCC specimens aligns closely with the one-dimensional charring rate of solid softwood specified in Eurocode 5-1-2.[10] This similarity suggests that the concrete panel did not affect the thermal behavior of the CLT panel in TCC structures.
- Timber plies of CLT glued by one-component-PUR delaminated at around 230°C. At the 90th minute after the ignition, the middle ply of the CLT board was partially delaminated. At the 90th minute since the ignition, the average temperatures of the epoxy and PUR layer between concrete and CLT were around 76 and 78°C, respectively, which surpassed their respective glass transition temperatures.
- After 90 min into the fire test, the temperature of the concrete increased to 120°C approximately and the temperature of steel rebar was limited to 50°C under the protection of 80 mm thick timber material, which had negligible influence on the mechanical properties of concrete and steel.
- During the fire tests, cracks were initiated from at the bonding interface and developed within the concrete, due to the distinct thermal expansion properties of concrete and timber.

The results of this fire test showed the thermal behavior of adhesively bonded TCC under ISO-standard fire exposure. However, the thermal-mechanical behavior of the adhesive layer between the concrete and timber board at elevated temperatures has not been investigated. The load-bearing behavior of adhesively bonded TCC slabs with concrete cracks and reduced cross-sections under ISO fire has not quantified yet. Therefore, it is necessary to conduct tests on adhesively bonded TCC slabs under both mechanical and fire loading in the follow-up work.

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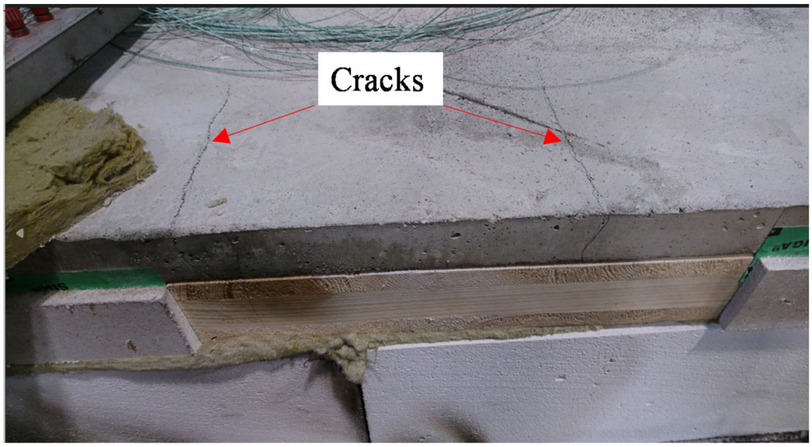
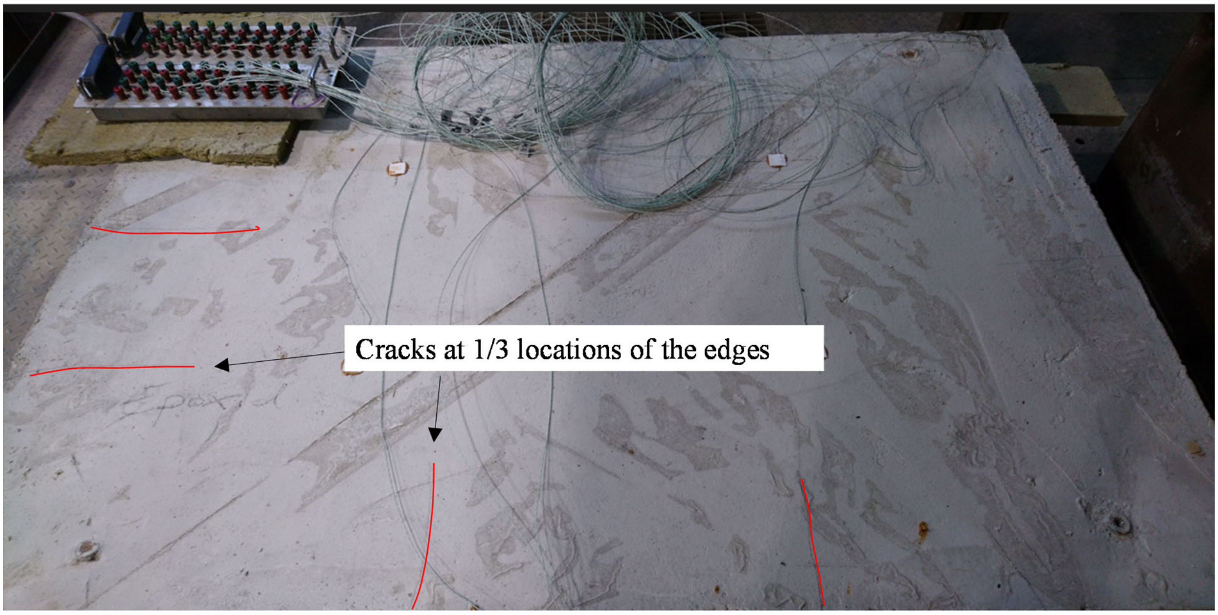


(A) Cracks in PUR-TCC specimen



(B) Cracks in Epoxy-TCC specimen

FIGURE 16 Cracks developed in concrete due to the different thermal expansions between concrete and timber.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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