Review of Connections for Timber-Concrete Composite Structures Under Fire

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A timber-concrete composite structure has the advantages of energy saving, environmental protection, and low carbon, and has wide application prospects. However, the effects of fire on timber-concrete composite structures are complicated. It is important to study the fire performance of connections and their influencing factors for the promotion and application of timber-concrete composite structures. This paper summarizes the research progress of connections for timber-concrete composite structures under fire. Firstly, research on the performance of connections in timber-concrete composite structures under fire is introduced, including screwed connections, notched, and grooved connections, and steel truss plate connections. Secondly, the calculation methods focused on connections of timber-concrete composite structures under fire are introduced. Finally, the main points of modeling timber-concrete composite structures under fire are also briefly introduced.

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INTRODUCTION

The timber-concrete composite (TCC) structure utilizes the advantages of the materials, namely the good tensile property of parallel grain wood and the strong compression ability of concrete. Compared with traditional wood structures, TCC structures have higher stiffness and strength, improved sound insulation (Martins *et al.* 2015; Zhang *et al.* 2020), better vibration behaviour (Mertens *et al.* 2007; Xie *et al.* 2020), and more effective fire resistance (Frangi 2001; Du *et al.* 2021; Shi *et al.* 2021). Compared with modern reinforced concrete structures, replacing the easily cracked concrete beams with wood beams not only can effectively utilize the advantages of materials, but it also can reduce the weight of the structure. In some countries, TCC structures are commonly used in multi-story buildings, renovation of old timber structures and short-span bridges (Ceccotti 2002). Since the beginning of the 21st century, TCC structures have developed rapidly in Europe and North America, and mid-highrise TCC structures have emerged one after another in Norway, Austria, Canada, and other countries. In TCC structures, the commonly used connectors are steel fasteners, such as self-tapping screws (Kavaliauskas *et al.* 2007), lag screws (Yeoh *et al.* 2008), steel dowels (Dias *et al.* 2007), steel truss plates (Yeoh *et al.* 2011), *etc*. There are also notched connectors (Yeoh *et al.* 2011). Notched and steel truss plate connections are generally stronger than dowel type fasteners such as screws (Ceccotti 2002).

Notched connectors are made by cutting notches into wood beams and filling them with concrete. Yeoh *et al.* (2008, 2011) and Jiang *et al.* (2019, 2020) carried out shear tests of notched connectors in TCC beams at room temperature, which showed that notched connectors were one of the best shear connectors, and also one of the most effective and cost-saving connectors. If the notch is used as the main connector, most of the shear force is transmitted through the compression surface of concrete and wood, which can effectively improve the stiffness of the connector. As the auxiliary connector, steel fasteners can reduce the generation and expansion of cracks in wood and concrete, as well as avoid shear failure of wood and concrete notches, and improve ductility. The reinforced notched connector effectively combines the advantages of the two types of connectors in mechanical properties. In addition, by filling the notch with concrete, the temperature rise of the steel fasteners can be effectively slowed down, and the steel fasteners can be protected from fire.

In the development of TCC structures, wood is also evolving, from logs to glue laminated timber (GLT), oriented strand board (OSB), laminated veneer lumber (LVL), cross-laminated timber (CLT), *etc.* The wood used for TCC structures has long ceased to be dominated by logs, but rather it is now engineered wood processed through industrial methods and advanced technology. Engineered wood has the advantages of stable mechanical properties, reliable fire resistance, and easy reprocessing. It is an ideal material for modern wood construction. Fire is one of the most unfavorable environments for wood constructions, and it is also one of the most frequent and universal disasters that threaten public safety and social development. Many countries have strict regulations regarding the use of wood in construction. The *National Building Code of Canada* (2020) allows heavy timber structures to be built up to 12 stories (42 meters high), and the *International Building Code* (2021) of United States allows timber structures to be built up to 18 stories.

In recent years, in the context of pursuing low-carbon initiatives and development of a circular economy, the application and development of TCC structures have attracted extensive attention. Compared with wood structures, the use of TCC systems can achieve better overall structural performance, noticeably broaden the application of wood in construction and break through the restrictions on the use of wood in constructions. The *Design of Timber-Concrete Composite Structures* (Dias *et al.* 2018) and the *Design Guide for Timber-Concrete Floors in Canada* (Auclair 2020) provided technical support for the development of composite structures in multi-story buildings. Simultaneously, it also means that the fire design of TCC structures faces new challenges.

In the case of a fire, the strength and stiffness of the material decrease due to the increase in temperature, and the cross section of the wood decreases due to charring. The impact of high temperatures can cause a rapid loss of connector stiffness (Frangi *et al.* 2010). At present, there are few studies on the fire performance of connectors in TCC structures. The aim of this paper is to provide a literature review of shear connections for TCC structures under fire. Fire tests, calculation methods and modeling on shear connections, and TCC floors and beams are reviewed in the following subsections.

PERFORMANCE OF CONNECTIONS IN TCC STRUCTURES UNDER FIRE

Steel Screwed Connections

According to some experimental results at room temperature (Djoubissie *et al.* 2018; Du *et al.* 2020), the shear performance of inclined steel screws in TCC structure is better than that of vertical steel screws. Therefore, the performance of inclined steel screws in TCC structures under fire has also attracted the interest of some scholars. There are extensive experimental studies on the fire performance of TCC structures with steel screws (Fontana and Frangi 1999; Frangi and Fontana 2000; Frangi 2001; Frangi *et al.* 2010; Caldová *et al.* 2013, 2015; Osborne 2015; Dagenais *et al.* 2016; Du *et al.* 2021; Shephard *et al.* 2021).

Steel Screw Oriented at 45°

Caldová *et al.* (2013, 2015) conducted a fire test on a TCC floor with a length of 4.5 m and a width of 3 m. The floor was composed of a wood frame, two secondary beams, a steel fiber-reinforced concrete (SFRC) layer with 60-mm thickness, and a glue-laminated floor. Fire precautions were taken for the wood frame, but not for the secondary beams. The concrete layer and the glulam floor were connected by inclined 45° screws with a diameter of 7.3 mm, a length of 150 mm, and a spacing of 100 mm. A uniform load was applied to the top surface of the specimen. The specimen was exposed to the standard fire for 150 min and then naturally cooled. It was observed in the experiment that when the specimen was exposed to fire for 45 min, the secondary beams were damaged and dropped. The deflection of the specimen was 220 mm after 150 min of fire, and the specimen was completely damaged after 154 min of fire. At temperatures below 400 °C, the deflection of the beam was mainly due to thermal bowing. At higher temperatures, the deflection of the beam was dominated by mainly mechanical deflection, and the deflection increased at a faster rate. As the deflection of the concrete slab increased, the membrane action became larger, and finally most of the vertical load on the concrete slab was borne by the membrane action. That is, the reinforcement was anchored by the peripheral concrete in compression and acted as a net in tension, absorbing forces perpendicular to its surface through tension.

Osborne (2015) and Dagenais *et al.* (2016) studied the fire performance of TCC floors using different connectors. The first TCC floor was 4.8 m long and 1.83 m wide, and it consisted of CLT panels with a total depth of 175 mm (5 layers) and a concrete slab with a thickness of 89 mm. The wood and concrete layer were connected with self-tapping screws with a total length of 180 mm and arranged at an inclination of 45°. The threaded part of the screw was inserted into the wood to a depth of 100 mm. The second TCC floor was 4.8 m long and 3.25 m wide, and consisted of LVL beams with a depth of 133 mm and a concrete layer with a thickness of 89 mm. The LVL beams and the concrete layer were connected by lag screws with a diameter of 13 mm and a length of 152 mm. The depth of the screw into the wood was 89 mm, and into the concrete layer was 64 mm. A uniform load of 2.4 kPa was applied to all specimens, which included a residential live load of 1.9 kPa. The specimens were exposed to fire based on CAN/ULC-S101 (2019), which is similar to the ASTM E119 (2018) standard.

The wood of the first TCC floor started to fall off when it was burned for 60 min, and the wood fell off obviously when it was burned for 80 to 110 min. After the TCC floor was exposed to fire for 200 min, the deflection of the floor rapidly increased, and the floor was damaged after being exposed to fire for 214 min. After the test, it was observed that the first three laminations of the CLT had fallen off. The tip of self-tapping screw was exposed to fire due to the detachment of the third lamination. The screw temperature rose rapidly, but the heat transferred into the concrete was negligible. The maximum deflection of the first TCC floor before failure was 75 mm. Because of heat delamination of the adhesive, thermocouple readings showed charring rates of 0.50, 0.91, and 0.73 mm/min for the first, second, and third laminations of the CLT, respectively. The deflection of the second TCC floor slowly increased by 10 mm after being exposed to fire for 120 min, and no detachment of veneers in LVL were observed. After the floor was exposed to fire for 170 min, the rate of deflection began to rapidly increase. When the floor was exposed to fire for 191 min, because of the sharp increase in the deflection rate of the TCC floor, it can be considered that the floor was damaged, and the maximum deflection at this time was 137 mm. The temperature of the lag screw was 96 °C at the LVL interface and 47 °C at the mid-depth of the concrete, which had no remarkable effect on the mechanical properties of the surrounding wood and concrete.

Shephard *et al.* (2021) conducted fire tests on a CLT-concrete floor with a length of 4.8 m and a width of 1.219 m. The floor consisted of 5 layers of plywood with a total thickness of 175 mm and a concrete layer with a thickness of 57.2 mm. The CLT with a width of 1.219 m was composed of two CLT slabs with a width of approximately 0.61 m connected by timber screws and a spline with a length of 152 mm. Fully threaded timber screws with a diameter of 9.53 mm and a length of 200 mm were used as connections between the CLT and the concrete layer. The timber screws were embedded at a depth of 150 mm in the CLT at a 45° angle, and 50 mm in the concrete layer. The specimen was exposed to ASTM E119 (2018) standard fire and subjected to a uniform live load of 3.83 kPa applied to the specimen using hydraulic rams. Test results showed that when the floor was exposed to fire for 52 min, the wood began to separate and fall. When the floor was subjected to fire for 92 min, large pieces of wood began to fall off, which manifested a delamination phenomenon. The deflection rate of the floor began to rapidly increase at 105 min of exposure time, at which point the load applied to the floor was removed. After 187 min of fire, the CLT-concrete floor was damaged by bending. The wood delaminated throughout the test, resulting in an increase in the charring depth. The remaining depth of the wood was measured to be 25 mm.

The fire tests described above showed that TCC floors using CLT tend to suffer from delamination under fire, which could lead to direct exposure of screw tips to fire. The screw temperature rose rapidly, but the heat transferred into the concrete was negligible.

Steel Screw Oriented at ± 45°

Frangi and Fontana (2000) conducted shear tests of TCC specimens under fire and a fire resistance test of a TCC slab. There were two types of loading systems for fire tests. Type I: the specimen was applied a constant permissible load and exposed to the fire as per ISO 834-1:1999/Amd1:2012 (2012) standard requirements for 20, 30, or 40 min, and if the specimen did not fail within the specified fire time, then the load was increased until failure. Type II: the specimen was also applied a constant permissible load and exposed to fire as per ISO-834-1:1999/Amd1:2012 (2012) requirements until failure.

Frangi and Fontana (2000) designed a connection in which screws with a diameter of 6 mm were arranged at an inclination of ± 45° to form a virtual truss structure with wooden beams and a concrete layer with a thickness of 80 mm. They carried out shear tests under ISO 834-1:1999/Amd1:2012 (2012) fire with Type I loading system on this connection to study the effects of beam size (width and height), wood thickness around the connection (lateral and bottom), wood type (glulam and solid wood), and fire time (30 and 40 min) on the connection deformation and shear strength. Tests showed that the residual shear strength of glulam beam joints was greater than that of solid wood joints with the same beam size. The shear strength of the connection decreased linearly, and the reduction of shear strength was almost independent of the wood bottom thickness of the connection but depended on the lateral thickness of the surrounding wood.

Frangi and Fontana (2000) also conducted a fire resistance test on a TCC beam-type slab with a span of 5.21 m and a width of 2.8 m under four-point bending. The TCC slab consisted of glulam beams with a width of 180 mm and a height of 240 mm, a concrete layer with a thickness of 80 mm, and a thin wood board with a thickness of 20 mm. The concrete layer and wood beams were connected by screws with a diameter of 6 mm and arranged at an inclination of ± 45°. Unlike the shear tests, screws in TCC slab were arranged in four rows instead of two. The experiment investigated the temperature, deflection, curvature, and relative deformation of wood and concrete slab at specific locations. A hydraulic jack was installed at one-third of the span of the TCC slab, and the load remained unchanged during the fire test. The research showed that the TCC slab was damaged after 67 min of fire, the average charring rate was about 0.7 mm/min. The failure of the TCC slab was due to the damage of the screw connection and the glue line of the beam.

Table 1. Summary of Latest Research on Steel screws in TCC Structures under Fire Conditions

Timber Type	Connection	Type of Test	Calculation Method for Connection	Fire Numerical Modeling	References
Solid, sawn and glulam timber	Screw (*Φ*6 × 150/100) oriented at ± 45°	Shear tests of TCC specimens; Bending tests of TCC slab	Modification factor	-	Frangi and Fontana 1999, 2000
GLT	Screw (*Φ*7.3 × 150) oriented at 45°	Fire resistance tests of TCC floor	-	3-D FE-model	Caldová *et al.* 2013, 2015
CLT, LVL	Self-tapping screw (*Φ*8 × 180/100) oriented at 45° and lag screw (*Φ*13 × 152)	Fire resistance tests of TCC floor	-	1-D FE-model	Osborne 2015; Dagenais *et al.* 2016
GLT	Screw (*Φ*12) oriented at ± 45°	Bending tests of TCC beam	Modification factor	3-D FE-model	Du *et al.* 2021
CLT	Fully threaded screw (*Φ*9.35 × 200) oriented at 45°	Fire resistance tests of TCC floor	-	-	Shephard *et al.* 2021

Du *et al.* (2021) conducted fire tests of TCC beams under four-point bending to investigate the effect of load ratio, and the presence of wood and gypsum boards on the fire resistance of TCC beams. The TCC beam had a span of 3.6 m and a width of 0.8 m. It consisted of 150-mm-wide and 300-mm-high glulam beams, a concrete slab with 80 mm thickness and a thin wood board with 15 mm thickness. The wood and concrete layer were connected using 19 pairs of screws inclined ± 45°. The screws had diameters of 12 mm, a transverse spacing of 50 mm, a penetration length of 100 mm into the wood, and a length of 70 mm embedded in the concrete slab. In the fire test, the specimen was loaded to a specific load level at a loading speed of 0.2 kN/s, and the load remained stable during the test until the specimen failed. Test results showed that TCC beams were damaged by the failure of the screw connections and glulam beams. The specimen under 10% load ratio had a fire resistance of 69 min, which was 25 min longer than the specimen under 30% load ratio. The fire resistance time of the specimen (including the wood board) under 20%

load ratio was 61 min, which was 15 min longer than that of the specimen (excluding the wood board) under the same load ratio. The TCC beam with the best fire resistance was the gypsum board protected specimen for a duration of 85 min.

The fire tests described above showed that the shear strength of the screw connection under fire was almost independent of the wood bottom thickness of the connection, it depended on the wood lateral thickness.

Notched and Grooved Connections

The unreinforced notched connector is an effective system if only stiffness is considered. The disadvantage of this connector is that the shear failure of wood and concrete in the notch is often sudden and brittle, due in part to the hardness and brittleness of the cured resins in the glue-line, and the low tensile strength of the concrete. In order to reduce the expansion of wood and concrete cracks and to avoid shear failure of wood and concrete notches, steel fasteners are often used as additional reinforcement at the notches. The pull-out failure of steel fasteners is sometimes gradual, and more ductile failure may occur in reinforced notched connectors. The notched connections discussed in this article are rectangular or trapezoidal wood notches that are filled with concrete and reinforced or unreinforced with steel fasteners in the center of the notch. There have been only a few studies on notched and grooved connections of TCC structures under fire in the existing literatures (Frangi and Fontana 2000; O’Neill *et al.* 2009, 2011; Klingsch *et al.* 2015; Shi *et al.* 2021).

Reinforced Notched and Grooved Connections

Frangi and Fontana (2000) performed shear tests on TCC specimens. The specimen consisted of wood beams and a concrete layer with a thickness of 80 mm, connected by grooves and vertical dowels. Trapezoidal grooves were cut in the wood beams with a transverse spacing of 350 mm. The dowels were inserted into the center of the groove to a depth of 80 mm and glue was added to the dowel holes. Finally, concrete was poured in the groove. The trapezoidal groove had an angle of 100° in the bottom, a depth of 20 mm, and a length of 150 mm. Shear tests were performed on this connection using the Type I loading system discussed earlier to study the effects of beam size (width and height), wood thickness around the dowel connection (lateral and bottom), wood type (glulam and solid wood), and fire time (20 min and 30 min) on the deformation and shear strength of the connection were studied. Test results showed that the residual shear strength of glulam beam joints was greater than that of solid wood joints with the same beam size. The shear capacity of the grooved connection with glue dowel depended on the width of the wood beam. No loss of shear stiffness of the connection was observed in the test.

Frangi and Fontana (2000) conducted fire tests on a TCC beam-type slab with a span of 5.21 m and a width of 2.8 m under four-point bending. The TCC beam slab consisted of glulam beams 180 mm wide and 240 mm high, an 80-mm-thick concrete slab and a 20-mm-thick wood board. Unlike the shear tests above, the rectangular grooves were cut in the wood boards instead of the wooden beams. The grooves had a length of 150 mm and a width of 140 mm, with a transverse spacing of 0.3 m and a longitudinal spacing of 0.56 m. The dowel was inserted vertically in the center of the groove with a penetration length of 80 mm, and glue was added in the dowel hole. Again, concrete finally was poured in the groove. The temperature, deflection, curvature, and relative deformation at specific locations of the TCC slab were studied. A hydraulic jack was installed at one-third of the span of the TCC slab, and the load remained unchanged during the fire. Test results showed that the glue lines of the glulam beam were damaged after the TCC slab was exposed to fire for 63 min. Due to the good transverse protection of the wood board, the groove remained largely intact.

O'Neill *et al.* (2009, 2011) investigated the fire performance of two different sizes of TCC beam-type floors. The difference between the two TCC floors was the span length (5 m and 7 m) and the LVL beam height (300 mm and 400 mm). The floor was composed of a 65-mm-thick concrete layer, two LVL beams with a length of 4.6 m and a spacing of 1.2 m, and a plywood of 17 mm. The LVL beam was composed of two pieces of wood with a width of 63 mm through self-tapping screws. The connection between the concrete slab and the LVL beams was a cut rectangular notch with a length of 300 mm and a depth of 50 mm on the wood beams, a coach screw with a diameter of 16 mm inserted vertically in the center of the notch and filled the notch with concrete. The depth of the screws into the wood was 100 mm. The wood beams were connected to the concrete slab by 4 notches combined with screws. During the fire tests, a uniform live load of 2.5 kPa (excluding self-weight) was applied to the TCC floor until the specimen failed. Test results showed that when the floor with a span of 5 m was exposed to fire for 75 min, the notch connection failed, and the floor was damaged. The average charring rate of the beam side was 0.58 mm/min, and the charring rate of the beam bottom was 4 times that of the beam side. The separation phenomenon occurred in the wood beam during the tests, which accelerated the charring inside the beam.

Shi *et al.* (2021) conducted push-out tests under fire on 10 glulam-concrete composite specimens. The specimen consisted of glulam beams with a width of 150 mm and a height of 300 mm, a concrete layer with a thickness of 80 mm, and a wood board with a thickness of 15 mm. A rectangular notch cut from glulam beam with a depth of 40 mm, a lag screw with a diameter of 16 mm and a length of 195 mm was vertically inserted in the center of the notch and filled the notch with concrete were used for the connection of wood and concrete. The effects of fire time (30, 45, and 60 min) and notch lengths (150, 200, and 250 mm) on the shear behavior of notch connections were investigated. Before fire tests, an axial shear force was applied to the end of the specimen and the load was kept stable for 15 min. After that, the furnace was turned on and the wood beams were completely exposed to the fire. The furnace was heated according to ISO-834-1:1999/Amd1:2012 (2012) standard fire requirements. If the specimen did not reach failure within the fire time, the furnace was turned off, and the axial load was increased until failure. Test results showed that the charring rate of the beam side was 0.67 mm/min, and the charring rate of the beam bottom was 0.71 mm/min. The failure mode of the specimen changed from shear failure of notched concrete to compression failure of notched wood with the increase of notch length.

The fire tests described above showed that the shear performance of the notched connections with screw reinforcement and concrete infill was primarily related to the effective cross-sectional area of the notch and the temperature of the notched wood.

Unreinforced Notched Connections

Klingsch *et al.* (2015) investigated the fire resistance of two TCC slabs with a span of 5.21 m under four-point bending and ISO-834-1:1999/Amd1:2012 (2012) fire. The two TCC slabs consisted of LVL with a thickness of 40 or 80 mm and a concrete layer with a thickness of 160 or 120 mm. The total thickness of both TCC slabs was 200 mm. The connection between the concrete layer and the LVL was rectangular wood notches with a length of 200 mm, a depth of 15 mm, and a transverse spacing of 200 mm filled the notch with concrete. The temperature, deflection, and inclination of the TCC slabs at different locations were measured in the fire tests. Before fire tests, the TCC slabs were loaded according to EN 1363-1 (2020), and the load was kept constant for 30 min. The combustors were then started, and the load remained unchanged until the end of the tests. Test results showed that no remarkable deflection was measured in the midspan of the Type 1 slab (with a thicker concrete layer) when exposed to fire for 45 min. When the Type 1 slab was exposed to fire for between 45 and 60 min, parts of the wood and concrete fell off in the notched area and the deflection increased rapidly. When the fire time of the Type 1 slab was 96 min, the fire test was stopped because a large area of concrete fell off and holes appeared on the top surface. At this time, the deflection of the slab was 55 mm, and the average charring rate of the LVL was measured as 0.65 mm/min. When the Type 2 slab (with thicker LVL) was exposed to fire for 50 to 60 min, it was observed that the charring layer fell off, resulting in a sharp increase in the charring rate of the LVL, and parts of the wood and concrete fell off in the notched area. When the Type 2 slab was exposed to fire for 68 min, the midspan deflection was 86 mm, and the fire test was stopped. The average charring rate of the LVL was 0.9 mm/min. Test results of both fire tests showed that the TCC slabs achieved sufficient fire resistance and integrity within 60 and 90 min of being exposed to the fire.

The fire tests described above showed that the wood and concrete in the notched area were the most likely to be damaged first. The deflection of the TCC slab under four-point bending and ISO-834-1:1999/Amd1:2012 (2012) fire increased rapidly when the wood and concrete in the unreinforced notches began to fall off.

Table 2. Summary of Latest Research on Notched and Grooved Connections in TCC Structures under Fire Conditions

Timber Type	Connection	Type of Test	Calculation Method for Connection	Fire Numerical Modeling	Ref.
Solid and glulam timber	Groove (20 × 150) with glued dowel (*Φ*12)	Shear tests of TCC specimens; Bending tests of TCC slab	Modification factor	-	Frangi and Fontana 1999, 2000
LVL	Notch (50 × 300) with coach screw (*Φ*16)	Fire resistance tests of TCC floor	-	3-D FE-model	O'Neill *et al.* 2009, 2011
LVL	Notch (15 × 200)	Fire resistance tests of TCC slab	-	-	Klingsch *et al.* 2015
GLT	Notch (40 × 150/200/250) with lag screw (*Φ*16)	Shear tests of TCC specimens	Reduced properties method	3-D FE-model	Shi *et al.* 2021

Steel Truss Plate Connections

A steel truss plate is a highly rigid and reliable connection, but there are only a few studies on the connection of TCC structures under fire in the existing literatures (O'Neill *et al.* 2009, 2011; Dagenais *et al.* 2016; Shephard *et al.* 2021).

O’Neill *et al.* (2009, 2011) investigated the fire performance of two different sizes of TCC beam-type floors. The difference between the two TCC floors was the span length (5 m and 7 m) and the LVL beam height (300 mm and 400 mm). The floor was composed of a 65-mm-thick concrete layer, two LVL beams with a length of 4.6 m and a spacing of 1.2 m, and a plywood with thickness of 17 mm. The LVL beam was composed of two pieces of wood with a width of 63 mm through self-tapping screws. The connection between the concrete slab and the LVL beam was steel truss plates with a length of 333 mm and a height of 136 mm. The depth of the truss plate into the wood was 86 mm. The wood beam was connected to the concrete slab through 8 truss plates. During the fire tests, a uniform live load of 2.5 kPa (excluding self-weight) was applied to the TCC floor. After the floor exposed to fire for 60 min, the wood protected the truss plate connections from fire, the steel truss plate did not suffer from pull-out failure, and the wood did not suffer from compression failure.

Dagenais *et al.* (2016) studied the fire performance of a TCC floor with a length of 4.8 m and a width of 1.83 m. The floor was made of 5 spruce boards connected by 180-mm self-tapping screws to form a screw-laminated wood, and an 89-mm-thick concrete layer was poured on the wood floor. The wood and concrete were connected by steel truss plates with a length of 254 mm and a height of 127 mm, and the depth of the truss plate into the wood was 76 mm. A uniform load of 2.4 kPa was applied to all specimens, which included a residential live load of 1.9 kPa. The specimens were exposed to fire based on the standard CAN/ULC-S101 (2019), which is similar to ASTM E119 (2018). The test was stopped due to the failure of another specimen in the furnace at 214 min of the fire test. The floor was undamaged and had a maximum deflection of 30 mm. Thermocouple readings showed a steady rate of charring for this floor, approximately 0.56 to 0.58 mm/min. The temperature of the truss plate increased 64 °C; however, it had no effect on the temperature of its surrounding concrete.

Shephard *et al.* (2021) conducted fire tests on an NLT-concrete floor with a length of 4.8 m and a width of 1.257 m. The floor was composed of NLT with a height of 140 mm and a concrete layer of 76.2 mm thick. The NLT with a width of 1.257 mm was composed of 33 pieces of solid sawn timber with a width of approximately 38 mm connected by smooth shank nails with a length of 76.2 mm and a diameter of 3.05 mm. The steel truss plates were used in the floor as the connection between the NLT and the concrete layer. One truss plate connection was installed for every three NLT boards. The truss plates penetrated the wood to a depth of 76 mm and the concrete layer to a depth of 51 mm. Due to the expansion and contraction of solid sawn timber along with temperature and humidity, expansion gaps were set in the floor to prevent unintended stress. The specimens were exposed to ASTM E119 (2018) standard fire, and a uniform live load of 3.83 kPa was applied to the specimens using hydraulic rams. Test results showed that the wood did not have delamination. The NLT-concrete floor was stopped after 187 min of fire and the load was removed. The remaining depth of the wood was measured as 38 mm after the test.

The above fire tests showed that the wood and concrete around the truss plate connector could protect the connector from fire, and the connectors were less likely to be pulled out and damaged.

Table 3. Summary of Latest Research on Steel Truss Plate Connections in TCC Structures under Fire Conditions

Timber Type	Connection	Type of Test	Calculation Method for Connection	Fire Numerical Modeling	Ref.
LVL	Steel truss plate (333 × 163)	Fire resistance tests of TCC floor	-	3-D FE-model	O'Neill *et al.* 2009, 2011
Screw-laminated wood	Steel truss plate (254 × 127)	Fire resistance tests of TCC floor	-	-	Dagenais *et al.* 2016
NLT	MiTek MT20 steel truss plate	Fire resistance tests of TCC floor	-	-	Shephard *et al.* 2021

CALCULATION METHOD OF CONNECTIONS IN TCC STRUCTURES UNDER FIRE

Evaluating the shear behavior of connections under fire conditions is important for estimating the fire resistance of TCC structures. At present, the methods for evaluating the shear performance of connections for TCC structures under fire can be roughly divided into two types. The first type is to determine the effective cross-section of timber and concrete. The other is to consider the effects of temperature on the material or mechanical properties of timber, concrete, and connection. In fire tests, the temperature measurement at different locations of wood, concrete and connector sections is a key parameter for calculating the fire resistance of TCC structures. Type K thermocouples were often used to measure the development of the charring depth and temperature. Development of charring depth with time of fire exposure can be calculated on the basis of thermocouples. The furnace temperature was controlled with plate thermometers. Detailed temperature measurement methods can be seen in the ISO-834-1:1999/Amd1:2012 (2012).

Steel Screwed Connections

According to the strength and stiffness properties of screwed connections, based on the fire test results (Fontana and Frangi 1999), simplified calculation formulas of the modification factor $k_{\text{mod, fi}}$ were established by Frangi *et al.* (2010). The modification factor $k_{\text{mod, fi}}$ was expressed as a function of the thickness of the wood on the connector side. In this way, the temperature of the wood beams did not need to be determined, making it easier for designers to calculate the strength and stiffness of screw connections under fire. The modification factor $k_{\text{mod, fi}}$ of the shear strength for the inclined screw connection in the TCC beam under fire was calculated as shown in Eq. 1:

$$k_{\text{mod,fi}}=\begin{cases}0 & (x\leq 0.6t)\\ \dfrac{0.44x-0.264t}{0.2t+5} & (0.6t\leq x\leq 0.8t+5)\\ \dfrac{0.56x-0.36t+7.32}{0.2t+23} & (0.8t+5\leq x\leq t+28)\\ 1.0 & (x\geq t+28)\end{cases} \tag{1}$$

The modification factor $k_{\text{mod, fi}}$ of the shear stiffness for the inclined screw connection in the TCC beam under fire, is shown as Eq. 2,

$$k_{\text{mod,fi}}=\begin{cases}0 & (x\leq 0.6t)\\ \dfrac{0.2x-0.12t}{0.2t+3} & (0.6t\leq x\leq 0.8t+3)\\ \dfrac{0.8x-0.6t+1.8}{0.2t+21} & (0.8t+3\leq x\leq t+24)\\ 1.0 & (x\geq t+24)\end{cases} \tag{2}$$

where t is fire time on three sides of the wood beam (min), and x is lateral thickness of wood around screws.

Considering the influence of temperature on the connection strength, Eq. 3 can be used to verify the ultimate limit state of the longitudinal shear stress design between concrete and wood in the connector during fire.

$$T_{\text{d,fi}}\leq T_{\text{R,d,fi}}=k_{\text{mod,fi}}\cdot k_{fi}\cdot T_{\text{R,k}} \tag{3}$$

In Eq. 3, $T_{\text{d,fi}}$ is the ultimate limit state in fire for the design load, $T_{\text{R,d,fi}}$ is the design strength of the connection in fire, $T_{\text{R,k}}$ is the 5% fractile characteristic strength of the connection at normal temperature, and k_{fi} is the modification factor for fire taking into account the 20% factiles of strength of the connection.

Notched and Grooved Connections

Based on the fire test results (Shi *et al.* 2021), calculation formulas of the shear capacity for notched connection with screw reinforcement and concrete infill were established by Shi *et al.* (2021). The temperature fields of timber near the notch were divided into finite rectangular elements i of parallel and constant width, which had different compressive strength (Fig. 1). It was assumed that the wood was charred at a temperature above 300 °C. The effective notch width b_{ef} was the transverse distance where the wood temperature of the notch was less than 300 ℃. The shear capacity of notched connection under fire was expressed as a function of the compressive strength of wood elements dependent on temperature. The compressive strength of notched wood under fire was obtained by adding up the compressive strength of wood elements. When the failure mode is compression failure of the notched wood, the shear capacity of notched connections with screw reinforcement and concrete infill could be estimated by Eq. 4,

$$F_{\text{c,0,fi}}=2t_{\text{n}}\sum_{\text{i=1}}^{\text{n}}\left[f_{\text{c,0,i}}\left(\theta_{\text{mean,i}}\right)\Delta b_{\text{ni}}\right] \tag{4}$$

where $F_{c,0,\,fi}$ is the compressive capacity of timber near the notch (N/mm^2), $f_{c,0,\,i}(\theta_{mean,\,i})$ is the compressive strength for element *i* of timber parallel to the grain according to the average temperature $\theta_{mean,\,i}$ (N/mm^2), t_n is the notch depth (mm), and Δb_{ni} is the width of the timber element *i* near the notch (mm).

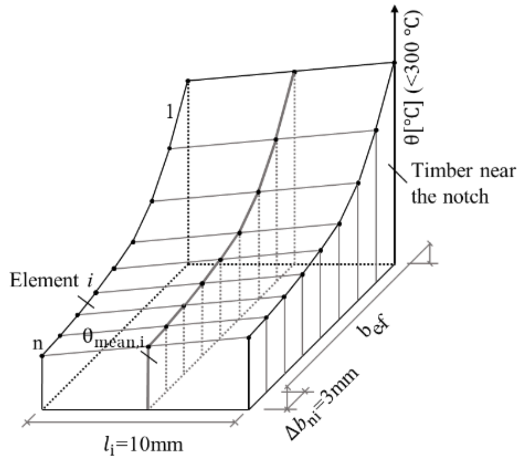

Fig. 1. Element i of a 3D temperature field of timber near the notched connection

Concrete in the notch was also divided into finite rectangular elements *i* of parallel and constant width, which have different compressive strength. The shear capacity of notched connection under fire was expressed as a function of the compressive strength of concrete elements dependent on temperature. The compressive strength of notched concrete under fire was obtained by adding up the compressive strength of concrete elements. When the failure mode is shear failure of the notched concrete, the shear capacity of notched connections with screw reinforcement and concrete infill could be estimated by Eqs. 5 and 6:

$$F_{s,fi} = \beta^* l_n v \sum_{i=1}^{n} \left[f_{c,i}\left(\theta'_{mean,i}\right) \Delta b'_{ni} \right] \tag{5}$$

$$\beta^* = \frac{l_n - 2\phi_{cs}}{2 l_n} \tag{6}$$

In these equations, $F_{s,\,fi}$ is the concrete shear capacity in the shear resistance plane (N/mm^2), $f_{c,\,i}(\theta'_{mean,\,i})$ is the compressive strength for concrete element *i* according to the average temperature $\theta'_{mean,\,i}$ (N/mm^2), $\Delta b'_{ni}$ is the width of the concrete element *i* in the notch (mm), β^* is a reduction factor based on loading distance and notch length, l_n is the notch length (mm), ϕ_{cs} is embedded screw diameter (mm), and v is a strength decrement factor for concrete fractured under shear, which is estimated as 0.516 (Yeoh *et al.* 2011).

MODELING OF TCC STRUCTURES UNDER FIRE

1-D Finite Element Model

In addition to the fire tests, finite element (FE) models were developed to simulate the fire behavior of the TCC structures (O'Neill *et al.* 2014; Caldová *et al.* 2015; Dagenais *et al.* 2016; Shi *et al.* 2022). Dagenais *et al.* (2016) established 1-D finite element models of three TCC floors based on experimental studies discussed earlier to predict the time-varying TCC floor deflection. The model assumed a constant charring rate of 0.55 mm/min, considered the elastic modulus of wood and concrete, the bending and tensile strength of wood, and ignored the tensile strength of concrete. Dagenais *et al.* believed that with the increase of fire time, the decrease of the wood penetration depth of the lag screw and the increase of the heat transfer of the screw were the reasons for the decrease of the stiffness of the screw connection. To test this theory, the connection strength was multiplied by a coefficient (on a scale of 0 to 1) in the model. It was assumed that the coefficient was linear with the wood penetration depth, 0 for a penetration depth of 0 and 1 for a penetration depth of 102 mm. The simulation results showed that the deflection of the TCC floor could be reasonably predicted before the fire time was approximately 180 min, but because the model did not fully consider the composite actions between the screw-laminated wood, the deflection of the floor was overestimated.

3-D ANSYS Finite Element Model

Caldová *et al.* (2015) used ANSYS software to build a 3D thermo-mechanical coupled model of wood-steel fiber reinforced concrete floors based on experimental studies discussed earlier. The boundary conditions of the thermal analysis model were radiation and convection. The convective heat transfer coefficient of the fire exposed surface was 30 W/m^2K, the air convection coefficient was 30 W/m^2K, and the emissivity coefficient was 0.9. The mechanical analysis of the TCC floor under fire could be regarded as a geometric nonlinear static analysis. The failure load was applied to the structure at the beginning of the model calculation, and then the temperature load was applied through the thermal model. During the solution process, the Newton-Raphson method was used to determine the solution of the nonlinear static analysis. Comparing the simulation results with the horizontal displacement of the TCC floor obtained by the fire tests, the trend of the curve was the same, and the model could simulate the complicated phenomenon in the test.

3-D ABAQUS Finite Element Model

O'Neill *et al.* (2014) used ABAQUS software to conduct a 3-D finite element sequential thermo-mechanical coupling analysis on the fire resistance of TCC floors under fire. Thermal conductivity, specific heat, density, and latent heat of wood in thermal model were taken from Annex B of EN 1995-1-2 (2003) to calculate the moisture movement, charring, and shrinkage of wood. An 8-node linear solid element (DC3D8) was used in the thermal analysis. The convection coefficient of 25 W/m^2K and emissivity of 0.8 were taken from EN 1995-1-2 (2003) and EN 1991-1-2 (2002). The cross-section of the model was divided into 5-mm meshes, and the model was roughly divided into 300-mm meshes along the length of the floor. The thermal model calculated the temperature distribution of the TCC floor under ISO-834-1:1999/Amd1:2012 (2012) fire. Then, a mechanical model was established with the same mesh size and the results of the thermal analysis imported into it. An 8-node linear solid element (C3D8R) was used in coupled thermo-mechanical analysis. The strength and elastic modulus of wood as a function of temperature were taken from Annex B of EN 1995-1-2 (2003). Because both wood and concrete exhibit brittleness in tension and elastic-plastic in compression, the concrete damage model can also define the stress-strain curve for wood. Thermal analysis results showed that the latent heat method overestimated the temperature in regions with the largest rate of temperature change and reliably predicted temperature in regions with a smaller rate of temperature change. The coupled thermo-mechanical analysis results showed that although the model could not capture the variation of displacement caused by the thermal expansion of the concrete slab or the charring of the wood during the tests, it could accurately predict the final displacement and fire resistance time of the floor.

Shi *et al.* (2022) established a 3-D finite element thermo-mechanical coupling analysis using ABAQUS software, reproduced shear tests of TCC specimens under fire, and carried out parametric analysis. The material properties of wood, concrete, and screws are taken from EN 1995-1-2 (2003), EN 1992-1-2 (2004), and EN 1993-1-2 (2005), respectively. An 8-node linear solid element (DC3D8) was used in the thermal analysis. The convection coefficient of 25 W/m^{2}K and emissivity of 0.8 were taken from EN 1995-1-2 (2003) and EN 1991-1-2 (2002), respectively. The notched wood and notched concrete were divided into meshes of 12.5 mm and 10 mm, respectively. Other parts were divided into 15 to 25 mm meshes. The FE model was simplified using a variable section steel rod instead of a lag screw. The thermal model calculated the temperature distribution of the TCC floor under ISO-834-1:1999/Amd1:2012 (2012) fire. The predefined field for thermo-mechanical model was the result of the temperature field of thermal model and kept the meshes of the two models consistent. An 8-node linear solid element (C3D8R) was used in coupled thermo-mechanical analysis. The interaction of screws, wood, and concrete was modeled using friction-dependent contact elements. The friction coefficient for wood and steel was 0.5, for wood and concrete was 0.57, and for concrete and steel was 0.9. The simulation results and parametric analysis showed that the beam width, the notch depth, and the notch length had a positive effect on the shear performance of the connection, while the screw diameter and the screw penetration depth had no remarkable effect on the shear performance of the connection.

CONCLUDING STATEMENTS

In this paper, the current research of connections for timber-concrete composite structures under fire was introduced. The experiments, calculation methods, and numerical studies of timber-concrete composite structures and connections under fire were discussed. As a sustainable and cost-effective connection system, the timber-concrete composite structure is not recognized by the current fire-safety building codes for the contribution of composite actions to its composite strength and fire resistance, and detailed research on this topic is still insufficient, hindering the structure development. Mechanical properties of connections in timber-concrete composite structures under fire are complicated. For screwed connections, scholars have considered factors such as the withdrawal strength of screws, the wood thickness around screws, the type and size of wood beams, and the fire time of specimens. For notched connections, scholars have considered factors such as notch length, the type and size of wood beams, the fire time of specimens, and wood thickness around steel screws. More impactful factors need to be considered, such as the embedment strength and moisture content of the wood. The research on the steel truss plate connection is still insufficient. Although calculation methods for screwed and notched connections under fire have been presented, their general applicability has not been demonstrated and more data are still needed. There is no calculation method for the steel truss plate connection under fire, which still needs to be investigated.

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