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FIRE RESISTANCE TESTING OF CLT-CONCRETE COMPOSITE FLOOR SLABS WITH STRIP NOTCH SHEAR CONNECTIONS

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ABSTRACT: The latest edition of the National Building Code of Canada (NBCC 2020) permits wood products to be used as the primary material in constructing up to twelve-story buildings. This results in an enduring increase in the application of mass timber sections, such as glued-laminated timber (glulam) and cross-laminated timber (CLT). Timber floors in such tall mass timber buildings can be even more robust and span longer by adding a top concrete layer to allow the formation of timber-concrete composite (TCC) floor systems when adequate shear connectors are utilized. In TCC systems, notch connections can allow a gap between the timber and the concrete top layer to have a better floor system in terms of cost saving and acoustic characteristics.

This paper presents the experimental results of two full-size TCC floor slabs that have been examined under service load and standard fire exposure. Each test assembly had a 5300 mm total length with a 5000 mm clear span and 900 mm width. The composite sections were formed of a 5-ply CLT panel of 143 mm thickness and a 65-mm thick concrete layer on a 25-mm thick insulation layer. In those two fire tests, the performance of CLT-concrete composite slabs was achieved due to the nearly full composite action between the CLT panel and the concrete top layer, resulting from the utilization of 150-mm wide rectangular strip notch shear connections. Test results show that the failure of the composite slabs under standard fire exposure depends mainly on the reduction of the CLT section due to charring. However, due to the activation of the composite action, both composite floor slabs sustained the applied service loads for the 90 min duration of standard fire exposure. However, a whole-wide strip notch connection needs to be designed carefully to achieve acceptable fire resistance based on available design equations. In addition, having a whole-wide notch connection would influence the initial deflections of the supporting CLT panels while poured concrete is still wet if no shoring is provided in the middle of the slabs. Thus, to avoid excessive initial mid-span deflections and to meet the design serviceability requirements, intermediate support needs to be provided until concrete is hardened.

KEYWORDS: Timber-concrete composite sections, CLT panels, Strip notch shear connections, Fire performance

1 INTRODUCTION

Advantageously, engineered wood products, such as glued-laminated timber (glulam) sections and cross-laminated timber (CLT), have been utilized in tall wood building construction since they have less carbon footprint and construction costs than concrete and steel materials. Moreover, since mass timber panels, such as CLT panels, have high tensile strength and sufficient fire resistance, to be utilized in TCC floor systems, it is more likely that they provide flexural strength and stiffness comparable to concrete floor slabs. The current edition of the National Building Code of Canada (NBCC 2020) [1] permits wood products to be used as the primary material in constructing up to twelve-story buildings. This results in an enduring increase in the application of mass timber sections, such as glulam for beams and columns and CLT for walls and floors. Over the past few years, mass timber construction has been assembling momentum in North America since wood is an environmentally friendly and sustainable material with lower construction costs.

The CLT panels with structural polyurethane (PUR) adhesive conforming to ANSI/APA PRG 320 (up to its 2012 edition) were tested in several furnace experimental studies with the FPInnovations research programs [1-4]. Based on the outcomes of those studies, there has been one common observation, which is the falling of localized piece of the charred layers when the CLT lamination interface temperature reached 115 to 250 ºC. This phenomenon led the second and subsequent delamination to start earlier, which also was more pronounced for

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thinner lamination. It is claimed that if it was desirable for greater fire resistance for CLT slabs, there should be no adhesive melting up to 300 ºC [5]. However, it was not a compulsory requirement for CLT manufacturers, that CLT products under fire conditions should be able to reach this temperature at the glue line without excessive delamination until the 2017 edition of ANSI/APA-PRG-320 [6] has been published.

TTC systems includes timber components which can be made of solid, glulam, laminated-veneer lumber (LVL), or CLT sections that are supporting and connected to a topping concrete layer (usually around 70 mm in thickness) utilizing a wide range of shear connectors. TCC floor systems own the advantageous characteristics of both materials (i.e., timber and concrete) if their shear connections are robust enough under service and ultimate design limits. In TCC sections, timber is used as the primary tensile load-carrying material due to its high strength-to-weight ratio. In contrast, concrete is used for its high compressive strength and advantages in terms of stiffness and acoustic characteristics.

The primary technique to provide a sufficient shear connection between the timber section and concrete layer in TCC sections is to use shear connections that come in various metal connectors, grooved connections, or adhesive connections. They include mechanical fasteners such as nails, screws, toothed metal plates, glued-in steel plates embedded into the timber, and notches cut from the timber or a combination of them. In order to estimate the composite strength of a TCC system with a well-recognized shear connection (stiffness and strength), Annex B of Eurocode 5 [7] provides the mechanically jointed beam theory (gamma method). In this method, a uniform distribution of shear connectors along the span of the floor is considered. Moreover, the flexural stiffness of both materials and the shear stiffness of the connection provides the composite flexural stiffness as well as the amount of axial and moment demands imposed on each material in such composite action.

The mechanical characteristics of various fasteners and connectors used for timber-to-timber joints are provided in Eurocode 5 [7]. Also, as far as the connection stiffness is concerned, for steel-to-timber or concrete-to-timber connections, the timber-to-timber joint stiffness might be multiplied by a magnifying factor. Salem and Virdi [8] experimented inclined self-tapping screw (STS) connections of CLT-concrete composite section through push-out direct shear tests. Tests results show that the stiffness of their STS shear connections was almost the same as that provided by Eurocode 5 [7].

As for determining the stiffness of notch connections, there has been no available analytical method so far and thus, only experimental evidences are used to predict its stiffness, otherwise the γ method strength predictions would not be accurate enough.

While the design of TCC sections with various mechanical shear connectors is well addressed in different design codes in the EU, there are no provisions in the current Canadian *Engineering design in wood* standard [9]. The only design guide that recently became available in Canada is the Design Guide for Timber-Concrete Composite Floors in Canada [10], which guides the design of TCC systems in ambient and fire conditions. Although several research studies were conducted to investigate the mechanical characteristics and structural behaviour of TCC floor systems under service and ultimate limit state conditions, there are still several uncertainties related to the influence of elevated temperatures on their structural fire performance. In general, TCC sections possess considerable fire resistance due to the large size of the timber cross-sections utilized in them; however, the type and design of the shear connectors in use significantly impact the actual behaviour of those composite systems when subjected to fire.

Van der Linden [11] introduced a relationship based on differential equations to define the more efficient composite action in which designers could avoid too thin concrete topping layer attached to mass timber beams and vice versa. In other words, an efficient composite action would be achieved with a concrete layer thickness that is more than 70 mm, which is common in construction. That ends up using a thicker concrete layer, which makes a TCC floor uneconomical. However, if there is a gap between the concrete top layer and the timber supporting component underneath, this would allow not only stiffer TCC sections but also economical floor systems. However, the fastener stiffness should be decreased by 25, 44 and 50% for gap/d ratio of 2, 3, and 4, respectively [12], where d is the diameter of the fastener based on Table 7.1 of Eurocode 5 CEN [7]. Therefore, it is significantly likely that a notch connection could accommodate this gap if the shear area of concrete at the notch is able to sufficiently transfer the shear forces at the interface between the concrete top layer and the supporting timber component with the existing constructional gap.

This paper presents the experimental results of two full-size, one-way TCC floor slabs that have been examined under service load and standard fire exposure. In the two fire resistance tests conducted as part of this current study, the performance of CLT-concrete composite floor slabs was achieved due to the nearly full composite action between the CLT panel and the concrete top layer resulting from the utilization of 150-mm wide rectangular strip notch shear connections with 25-mm thick gap in between the two materials to provide a more economical TCC floor system yet having considerable strength and stiffness.

2 EXPERIMENTAL PROGRAM

The main objective of the full-size testing of flexural TCC floor slab presented in this paper was to assess the performance of strip notch connections as they could accommodate the gap between the concrete top layer and the supporting CLT panel. Moreover, most tests done on

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CLT-concrete composite systems experienced excessive ply fall off due to adhesive melting under fire conditions, while it is now an obligation requirement for CLT manufacturers to produce CLT panels that should be able to reach charring temperature without excessive delamination [6].

Therefore, designers might be able to have a low charring rate of 0.65 mm/min throughout the entire fire exposure time instead of the current design procedure assumption of 0.8 mm/min charring rate after the first major ply has burnt out. This assumption was based on ply fall-off phenomena which used to happen for CLT with polyurethane (PUR) adhesive in the past. The CLT panels utilized in the test specimens of this study were produced by Nordic Structures with the industrial name of Nordic X-Lam. This product is certified by APA (Product Report PR-L306C) per ANSI/APA PRG 320 standard [6].

2.1 TEST SPECIMENS DETAILS AND FABRICATION PROCESS

The fabrication of the two full-size TCC floor assemblies and their fire endurance testing were carried out at Lakehead University Fire Testing and Research Laboratory (LUFTRL). Each test assembly had a 5300 mm total length with a 5000 mm clear span and 900 mm width. The composite sections were formed of a 5-ply CLT panel of 143 mm thickness and a 65-mm thick concrete layer on a 25-mm thick insulation layer. The CLT panel in each test specimen was prepared with six rectangular strip notches each aligned in the transverse direction along the entire width of the panel, Figure 1. The insulation layer was deliberately added to enhance the flexural stiffness and the acoustic characteristics of the TCC floor assemblies and to maintain a reasonable cross-sectional moment of inertia with less weight, Figure 1.

The CLT panels utilized in fabricating the TCC floor assemblies tested in this study were Nordic X-lam cross-laminated timber that is certified E1 CLT stress grade, using 1950 Fb-1.7E Spruce-Pine-fir (S-P-F) MSR lumber in the longitudinal layers and No. 3/Stud S-P-F lumber in the transverse layers. This product is certified by APA (Product Report PR-L306C) per ANSI/APA PRG 320 standard [6] and shall be used in dry service conditions. As per the data published by Nordic Structures, the carbon balance is approximately -590.97 CO_2 of one cubic meter of Nordic X-Lam [13]. The concrete poured for the topping layer had a 28-day strength of 43 MPa and its strength on the fire test day was 46 MPa. Four 12-mm diameter lag screws were installed along each strip notch to allow more ductile performance for the TCC floor slabs in the ambient ultimate state.

The strip notch connections are normally strong enough connections to be implemented just at the far ends of a TCC element. However, such approach might not offer sufficient strength nor stiffness required for the fire resistance design based on the reduction of the structural integrity because of the cross-section loss due to charring. Therefore, with 800 mm spacing between the strip notches prepared in the CLT panels, there were six strip notches along the longitudinal direction of the floor slab to provide sufficient structural integrity during fire exposure, Figure 1. As far as the concrete depth along the span is concerned, in the three middle panels, a 65-mm thick concrete layer on top of a 25-mm thick insulation layer was considered to have sufficient composite action behaviour. However, in the two end panels from each end of the slab specimens, a full thickness (90 mm) of the concrete layer was cast to avoid any shear failure that could happened near the ends of the floor test specimens not during the fire tests but when the burned specimens are removed out of the furnace after fire testing, Figure 1.

2.2 TEST SETUP

Test specimens were loaded under four-point flexure bending using a steel spreader beam connected to the piston of a hydraulic cylinder that is attached above the furnace to the steel loading framed structure that is also supporting the fire testing furnace, as shown in Figure 1.

The load applied on each test specimen throughout the fire test consisted of 2.4 kPa dead load including self-weight and additional 2.4 kPa accounting for service live load. These loads were applied to the floor specimen at least 30 mins before the fire test started in conform to CAN/ULC-S101 [14]. Afterwards, the applied load was maintained constant throughout the entire duration of the fire test.

The vertical deflections of the test specimens were measured using draw-wire displacement transducers installed at three different locations along the length of the floor slabs: the midspan and under each point load (1667 mm apart and cantered along the specimen span).

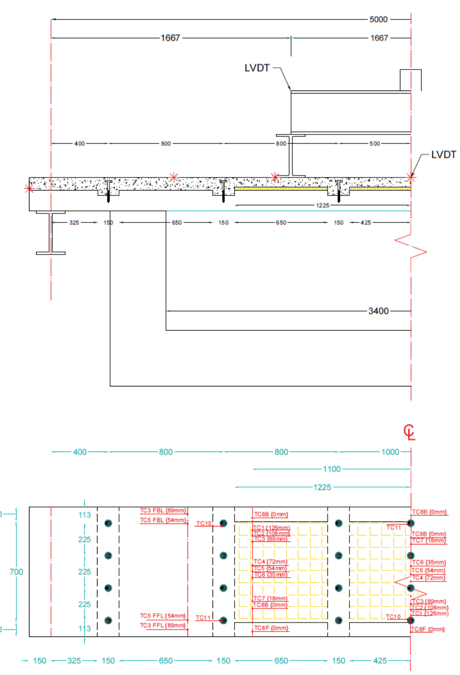

Figure 1: *A general test setup with a typical TCC floor test assembly with strip notch connections and thermocouples layout*

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Each floor assembly was instrumented with 45 Type-K thermocouples that were inserted from the top inside pre-drilled tight holes with various depths into the CLT panels. A few thermocouples were placed at the interface between the CLT plys and at the mid-thickness of each ply. Other thermocouples were located at the interface between the concrete top layer and the CLT panel and at the coach screws. Figure 2 illustrates the distribution of thermocouples around one of the strip notches.

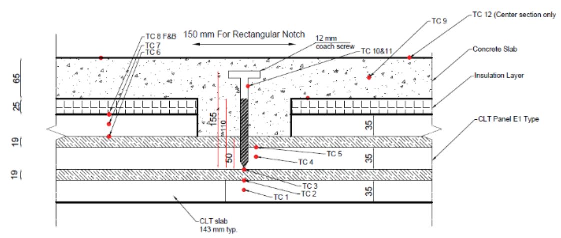

Figure 2: *Distribution of thermocouples around one of the strip notches*

3 DESIGN PROCEDURE

The current design method of timber structures is based on the limit states design (LSD) philosophy in Canada. It takes three design categories into account: Serviceability Limit States (SLS), Ultimate Limit States (ULS), and Fire resistance conditions. The serviceability limit states intend to guarantee the structural components be capable of sustaining the applied loads without any significant defects and/or service disruptions, including excessive deflection, vibration, permanent deformation, and local structural damage such as cracking [15].

3.1 NOTCH CONNECTION DESIGN

Design Guide of Timber Composite Floors in Canada [10] provides concrete crushing and shear failure strength capacity by Equations (1) and (2). These equations are much more conservative than their counterparts in the design guideline provided by Yeoh et al. [16]. Therefore, several strip notch connections need to be designed and implemented along the span of the TCC floor slabs tested in this study to achieve the targeted 2-hour fire resistance. However, cutting into the entire thickness of the utmost longitudinal ply of the CLT panel in the direction of major strength axis to accommodate the strip notch depth can reduce the overall flexural strength of the TCC section in fire conditions once the natural axis of the composite section escalates up and be relocated within the thickness of the concrete top layer. In addition, having a whole-wide notch connection would influence the initial deflections of the supporting CLT panels while poured concrete is still wet if no shoring is provided in the middle of the slabs. Thus, to avoid excessive initial mid-span deflections and to meet the design serviceability requirements, intermediate support needs to be provided until concrete is hardened. Alternatively, two-stage concrete casting procedure shall be followed. First, concrete shall be poured in the strip notch grooves prepared in the CLT panel until it reaches certain strength with rough surface condition and then, concrete could be poured over the entire floor CLT slab as a second stage.

$$V_{\text{r, Conc. Comp.}} = \alpha_1 \phi_c f'_c d_n b_n, \quad \alpha_1 = 0.85 - .0015 f'_c \qquad (1)$$

$$V_{\text{r, Conc. Shear}} = 0.8P_{r,w} + 2.76\phi_c b_n (2d_n \tan(\theta) + L_n) \leq 0.5\phi_c f'_c b_n (2d_n \tan(\theta) + L_n) \qquad (2)$$

Where, d_n is notch depth, b_n is notch width, $P_{r,w}$ is lag screw withdrawal resistance, L_n is notch length, and ϕ_c is the concrete resistance factor, Figure 3.

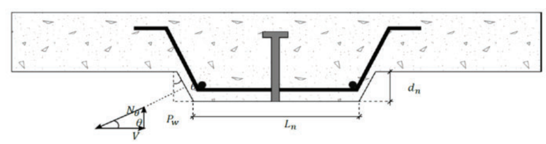

Figure 3: *Force equilibrium at notch connection*

3.2 ELASTIC DESIGN METHOD (γ-method)

As the shear connection performance determines the degree of composite action in a TCC floor systems, such sections shall be designed with this consideration whether the connection yielded before reaching the ultimate limit state condition or not. The γ method can predict the behaviour of TCC floor systems as long as the behaviour of the shear connection is still within the elastic region, such as those utilized nails, HBV steel plates, and notches. Alternatively, the Design Guide for Timber-Concrete Composite Floors in Canada [10] provides an elasto-plastic model (EPM) to capture the behaviour of TCC floor systems at the ultimate state limit with shear connections that can even sustain plastic deformations. However, since notch shear connections normally exhibit elastic behaviour, the γ method is accurate enough to estimate the flexural strength of TCC systems with strip notch shear connections.

4 RESULTS AND DISCUSSION

4.1 DEFLECTIONS

Figures 4 and 5 show the time-deflection curves developed based on deflection values measured at the midspan and left-side loading point for both floor assemblies, Slab 1 and Slab 2, respectively. Due to electronic malfunction in one of the displacement transducers, the floor deflections at the right-side loading point were not recorded. According to the presented time-deflection curves, both slabs experienced gradual increase in their vertical deflection until approximately 25 mins into the fire tests with a slop that is slightly higher than that experienced by both slabs for the next 25 mins (25 to 50 mins into the fire tests). It is worth mentioning that at 25 mins into the fire tests less than half the thickness of the first ply charred in both slabs according to the thermal measurements obtained. While at 50 mins into the fire tests the entire thickness of the first ply charred, which can

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be correlated to the bounce back of higher slops exhibited by the time-deflection curves started at that time mark. Both slabs maintained that relatively linearly increased slop until almost the end of the fire tests when both tests were deliberately terminated a few mins after surpassing the targeted 90 mins fire resistance time mark.

At the termination time of the first tests (90 mins), the mid-span recorded deflections were 35 and 30 mm in Slab 1 and Slab 2, respectively, including the initial deflections due to the pilot loading applied before the start of the fire tests, Figures 4 and 5.

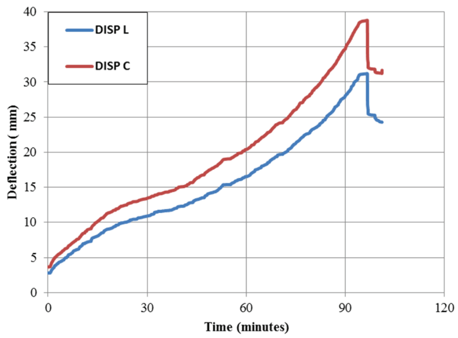

Figure 4: *Time-deflection curves of Slab 1*

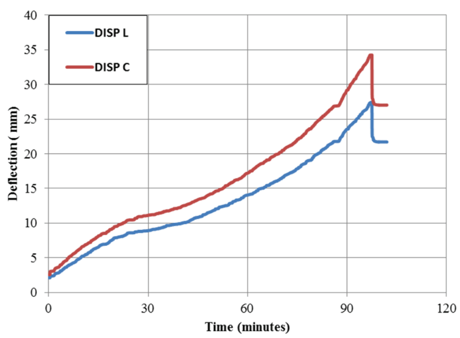

Figure 5: *Time-deflection curves of Slab 2*

Throughout the duration of the fire test, the char front progressed closer to the top plys. In particular, the top three plys in the CLT panel. The bottom of the middle longitudinal ply was the location of the thermocouple labelled TC3. The middle longitudinal ply was deemed critical for the targeted 90-min fire resistance under standard fire exposure if it burned away.

Figure 6 shows the time-temperature curves of the thermal measurements of the critical thermocouple (TC2) installed at the bottom of the first transverse ply and those measured by thermocouple TC3 installed at the bottom of the middle longitudinal ply at three different sections (L, M, and R) along the span of Slab 1. The left and right-side sections were 1100 mm offset from the midspan, as shown in Figure 1. As shown in Figure 6, as per the design of the TCC floor specimens, the bottom transverse ply began to char at approximately 55 mins as the temperature measured by TC2 reached 300 °C at this time mark. While the temperature measured by TC3 was less than 200 °C at the end of the fire test.

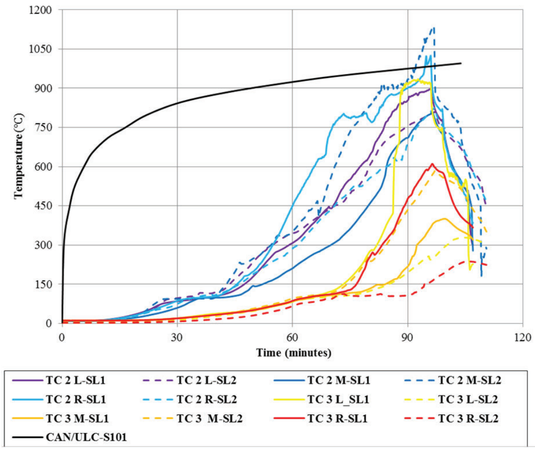

Figure 6: *Time-temperature curves of thermocouples TC2 and TC3 located at the three different sections in both slabs*

Figure 7 shows one of the floor test specimens (Slab 1) still burning right after the termination of the fire test and before extinguishing the specimen by spraying it with pressurized water mist.

Figure 7: *Slab 1 with its CLT panel still burning right after the termination of the fire test*

Table 1 presents the charring rate calculations based on the temperatures measured by the critical thermocouple (TC2) installed at the bottom of the first transverse ply and those measured by thermocouple TC3 installed at the bottom of the middle longitudinal ply at three different sections (L, M, and R) along the span of Slab 1. The average charring rates according to the calculations performed based on the thermal measurements of the selected thermocouples located at the three sections are 0.63 and 0.61 mm/min for Slab 1 and Slab 2, respectively. It is worth mentioning that there was no delamination observed due to adhesive melting in the CLT panel of any of the two test specimens. Thus, the calculated charring rates based on actual thermal measurements meet those rates provided in ANSI/APA-PRG-320 [6] as a requirement of reaching 250 ºC temperature at the glue line without excessive delamination.

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Table 1: *Calculated charring rates based on measured temperatures at the three different sections in both slabs*

TC No.	Section along the span	Ply used for the charring rate calculations	Charring rate (mm/min) Slab 1	Slab 2
TC 2	Left	1st long. ply	0.59	0.64
TC 3		1st trans. ply	0.83	0.54
		1st long. & trans. plys	0.66	0.60
TC 2	Middle	1st long. ply	0.50	0.64
TC 3		1st trans. ply	0.85	0.63
		1st long. & trans. plys	0.58	0.64
TC 2	Right	1st long. ply	0.64	0.57
TC 3		1st trans. ply	0.67	0.66
		1st long. & trans. plys	0.65	0.60

5 CONCLUSIONS

Two identical full-size, one-way CLT-concrete composite floor slabs have been fire tested at Lakehead University Fire Testing and Research Laboratory (LUFTRL). Based on the design equations provided in the Design Guide for Timber-Concrete Composite Floors in Canada [14], the strip notch connections of the two test specimens were designed.

As a result of the activation of the composite action between the concrete top layer and CLT panel, both TCC floor slabs sustained the applied service loads for the 90 min duration of standard fire exposure. This show at least 30 mins added to the 1-hr fire resistance that those CLT panels with the same span (5000 mm) can have under the same applied load (4.8 kPa), as per the data provided by their manufacturer.

According to the outcomes of this new experimental research study, it is recommended that for strip notch connections in TCC floor assemblies like the ones examined under standard fire exposure in this study, at least one longitudinal ply in the major strength direction other than the utmost longitudinal ply that was cut due to the implementation of the six rectangular notches along the length of the CLT panel needs to stay unburned and remain in the residual section of the TCC after fire.

Another important observation is that having a whole-wide strip notch connection would influence the initial deflections of the supporting CLT panels while poured concrete is still wet if no shoring is provided in the middle of the slabs. Thus, to avoid excessive initial mid-span deflections and to meet the design serviceability requirements, intermediate support needs to be provided until concrete is hardened.

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