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FIRE RESISTANCE TESTING OF CLT-CONCRETE COMPOSITE FLOOR SLABS UTILIZING GLUED-IN STEEL PLATES AS SHEAR CONNECTORS

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ABSTRACT: Timber-concrete composite (TCC) sections have shown desirable mechanical characteristics for use in the structural design of mass timber buildings at both ambient and elevated temperatures. TCC sections have advantages over conventional steel-reinforced concrete elements or timber elements on their own. While some recent performance-based design guidelines have been developed to aid in the design of TCC sections, they primarily rely on experimental data from specific TCC arrangements with certain types of shear connectors (e.g., steel plates, metal screws, etc.). The study presented in this paper involves experimental testing of two full-size CLT-concrete composite one-way floor slabs that were exposed to elevated temperatures of the CAN/ULC-S101 standard fire time-temperature curve, while being subjected to four-point flexure bending that is equivalent to the moment developed by a uniformly distributed 4.8 kPa service load. Each TCC slab assembly had a clear, simply supported span of 5000 mm and a width of 900 mm. The CLT panel composition (5 plys) and thickness (143 mm) were chosen to investigate how its one-hour fire resistance under the applied service loads could be increased to two hours by developing the composite action with the added concrete layer (90 mm thick) that otherwise would impose |dead load on the CLT panel without contributing to the overall strength of the floor system. Shear connectors utilized in these two TCC floor assemblies were perforated steel plates installed in prepared longitudinal slots using epoxy.

KEYWORDS: Timber-concrete composite (TCC) sections, Glued-in steel plates, Shear connectors, Fire performance

1 INTRODUCTION

Timber-concrete composite (TCC) systems were initially developed and used before being replaced by reinforced concrete slabs several decades ago. Nowadays, such composite systems are experiencing increased use in new construction and rehabilitating existing timber structures. TCC systems are developed by creating a shear connection between a timber section carrying the tensile forces and a concrete topping layer to carry the compressive forces. The behaviour of a TCC section is defined mainly by the rigidity of the connection between the two materials. Failure in such composite systems can occur as brittle failure in the wood section or a brittle or ductile failure at the interface of the connection between the two materials [1]. While mechanical shear connectors, such as screws and steel plates, are approved for specific composite systems in the EU, there are no provisions in the current Canadian standard for *Engineering design in wood* [2]. The only guidance available for engineers in Canada is the recently developed *Design guide for timber-concrete composite floors in Canada* [3], which provides some guidance for the performance-based design of TCC systems at normal and elevated temperatures with mechanical connectors such as screws, plates, and notches in the timber section.

Recent changes in the National Building Code of Canada [4] have allowed for the construction of timber buildings up to 12 storeys if a solid core is designed for lateral loads, such as the recently completed Brock Commons building at the University of British Columbia [5]. The two-way CLT floor slabs were designed to be point-supported on glulam columns with a concrete layer on top in the said building. However, no composite action was developed between the two materials. Thus, the concrete's compressive strength was not fully utilized to increase the stiffness of the floor system or its fire resistance; both are observed benefits of TCC systems [6]. Due to the non-homogenous nature of timber, extensive testing is required on the shear connectors to determine their stiffness, strength, and ductility ratio. Once those characteristics are defined, large-size samples are tested to validate the small-size experimental results and then evaluate how the characteristics of the examined shear connectors can influence the overall behaviour of TCC systems. Ultimately, TCC systems with certain engineered wood products and selected types of shear connectors/connections undergo standard fire testing. The experimental results of a very limited selection of shear connections in CLT-concrete composite floor systems can be found in the available literature, especially in the context of large-scale specimens. The focus has been primarily on notched connections [7] or dowel type

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fasteners and nailed plates [8-10]. Thus, there is a lack of studies on longitudinal connectors secured by adhesive in CLT floor panels, such as the glued-in steel plates utilized in the floor assemblies tested in the current study.

This paper presents the experimental results of two full-size CLT-concrete composite, one-way floor slabs exposed to elevated temperatures of CAN/ULC-S101 standard fire [11], while being subjected to four-point flexure bending that is equivalent to the moment developed by a uniformly distributed 4.8 kPa service load, are presented. The TCC floor slabs involved in this study utilized glued-in perforated steel plates as shear connectors.

2 EXPERIMENTAL PROGRAM

2.1 SPECIMEN DESIGN AND DESCRIPTION

For the design of the TCC floor test specimens of the present study, the gamma and elastoplastic methods were used to determine their flexure bending strength. Hence, their time to failure under standard fire exposure was determined before conducting the fire endurance experiments. Both test specimens were 5300 mm long x 900 mm wide, with a 5000 mm clear simply supported span. The TCC floor assemblies were composed of 5-plys CLT panels of 143 mm thickness, alternating between 35-mm thick lamina in the major axis direction and 19-mm thick lamina in the minor axis direction. A regular strength concrete layer, with a thickness of 90 mm and a 28-day strength of approximately 40 MPa was cast on top of the CLT panel and reinforced with the minimum required steel reinforcement to prevent shrinkage cracking. According to the design, the shear connectors utilized to develop the composite action in the TCC sections were longitudinal glued-in perforated steel plates that measured 254 mm long x 90 mm high. The plates were embedded inside 40-mm deep longitudinal kerf cuts of approximately 3 mm width prepared in the CLT panel. Steel plates were affixed to the CLT panel using a two-component epoxy. The remaining 50 mm depth of the steel plates was embedded within the concrete layer. It is worth mentioning that the mechanical characteristics of the utilized proprietary glued-in Holz-Beton-Verbund (HBV) steel plates are documented, and those types of shear connectors are already installed in a few mass timber buildings recently constructed in North America. A plan view of the layout of the longitudinal steel plate shear connectors in one of the TCC floor assemblies is shown in Figure 1.

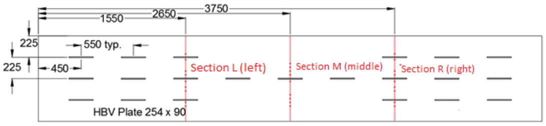

Figure 1: *Plan view of the layout of the steel plate shear connectors in a typical TCC floor assembly*

The relevant design and mechanical properties of the TCC components are summarized in Tables 1 through 3. Based on the listed values, the CLT slabs deflection under simply supported conditions (to mimic the in-site use of the CLT panels as form work) from the curing concrete was calculated and checked against the allowable deflection of *Span/360* and found to be within the allowable design serviceability limits.

Table 1: *Mechanical properties of the utilized CLT panels*

CLT floor panel properties	
M_r	65.0 kN.m
T_r	1780.0 kN
V_r	43.0 kN/m
EA	1480.0 x10^3 kN

Table 2: *Concrete properties*

Concrete slab properties		
	Test 1	Test 2
f'_c	36.94 MPa	40.43 MPa
ρ_c	2477 kg/m^3	2458 kg/m^3
Slump	90 mm	85 mm
Maximum aggregate size	13 mm	13 mm

Table 3: *Mechanical properties of the utilized steel plates*

HBV steel plate shear connector	
V_r	24.4 kN
k_s	209 kN/mm
k_u	139.3 kN/mm

Using the CSA-O86 Standard [2] and the FPI Design Guide for TCC Floors in Canada [3], the design of the TCC floor test assemblies was checked for vibration criteria and SLS and ULS limits under 2.4 kPa dead load (including slab's own weight) and 2.4 kPa live load combinations, and was found to be adequate. Also, based on an assumed notional charring rate of 0.65 mm/min, the TCC test assemblies were determined to safely achieve a 2-hr fire resistance time before failure.

2.2 INSTRUMENTATION

Each specimen had 37 Type-K thermocouples installed at varying depths at three sections (namely Sections L, M and R), as shown in Figure 1. The layout of the thermocouples installed at Section L (near the left side of the specimen within the maximum shear force zone) is shown in Figure 2. While Figure 3 illustrates the distribution of the thermocouples installed at different depths at Section M (at the middle of the specimen within the maximum bending moment zone).

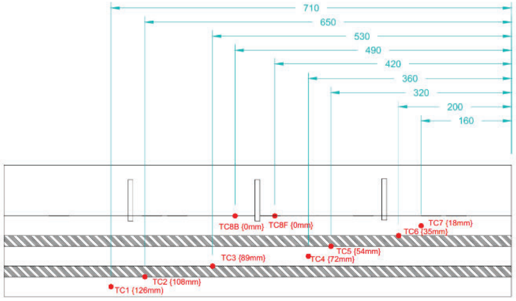

Figure 2: *Thermocouples layout at Section L, where the maximum shear exists (cross-section view)*

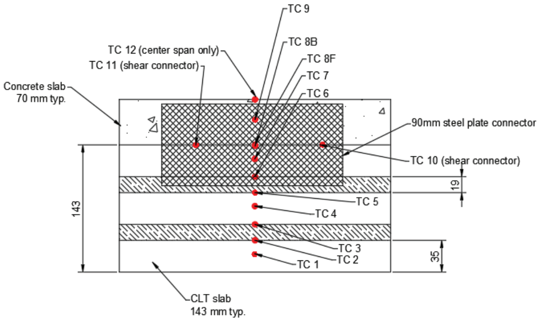

Figure 3: *Thermocouples layout at Section M, where the maximum bending moment exists (sectional-elevation view)*

Thermocouples were distributed to capture a representative sampling of the thermal measurements due to standard fire exposure over the width and along the length of the floor slabs. Also, careful attention was given to ensure that thermocouples were installed in their respective holes drilled to the correct depth, Figure 4.

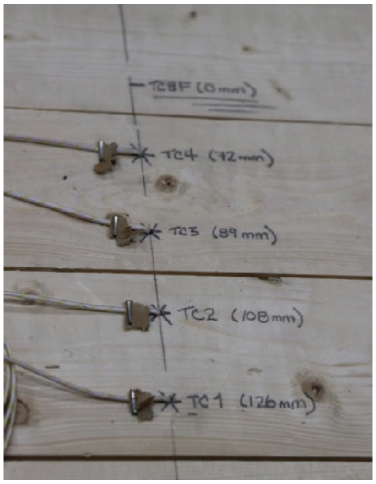

Figure 4: *Thermocouples installed and labelled in one of the two CLT panels*

The temperature readings were used to monitor the test specimens during fire testing and thus, thermal measurements were used to calculate the charring rates which were then compared to the thicknesses of the residual CLT sections measured after the completion of the fire tests.

In addition to the thermal measurements, it was essential to evaluate the mechanical behaviour of the test assemblies by measuring their vertical deflections at three different locations: at the midspan of the specimen and at each of the two applied load points. Thus, three draw-wire displacement transducers were installed above the furnace and safely connected to the top surface of each test specimen.

2.3 TEST SETUP

The two full-size TCC one-way floor slab assemblies were experimentally examined at elevated temperatures following the CAN/ULC-S101 standard fire time-temperature curve. During fire tests, floor assemblies were subjected to four-point flexure bending equivalent to a 4.8 kPa service load (2.4 kPa dead load including the slab's own weight, and 2.4 kPa live load). The loading equals the maximum service load applied to the CLT panels with the same span designed to have a 1-hr fire resistance. The study parameters and matrix of the fire experiments presented in this paper are summarized in Table 4.

Table 4: *Study parameters and matrix of fire experiments*

Test ID.	TCC-HBV-CC
Number of tests	2
Shear connector	254 x 90 mm, HBV steel plates
Wood material	900 mm wide x 143 mm thick x 5000 mm span (5-ply) E1-grade CLT
Concrete material	90 mm conventional concrete, ~ 40 MPa, with 6-mm dia. welded wire mesh
Designed fire resistance time	120 min

A sectional-elevation view of the test set-up applied for the fire experiments of this study is illustrated in Figure 5.

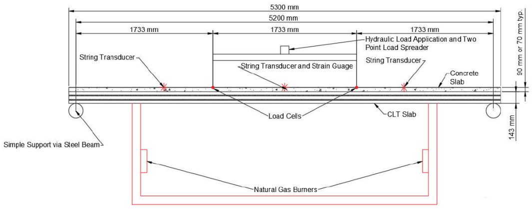

Figure 5: *A typical TCC floor assembly test setup and mechanical instrumentation layout*

TCC floor test assemblies were subjected to monotonic loading throughout the entire duration of the standard fire endurance tests. Shortly after each floor assembly achieved the 2-hr fire resistance time mark, test was deliberately terminated. Figure 6 shows one of the TCC floor test assemblies installed on top of the large-size furnace accommodated at Lakehead University Fire Testing and Research Laboratory (LUFTRL).

Figure 6: *A TCC floor assembly installed on top of the large-size furnace accommodated at LUFTRL*

Throughout the entire duration of each fire test, the applied transverse load was kept constant as the floor slab continued deflecting. Vertical deflections, applied load, and external and internal temperatures were all monitored and logged over the course of each fire test via a data acquisition system connected to a computer. Also, the test specimens were periodically monitored visually through the two observation viewports on the furnace front door. The underside of the first test specimen undergoing fire testing is shown via one of the viewports in Figure 7.

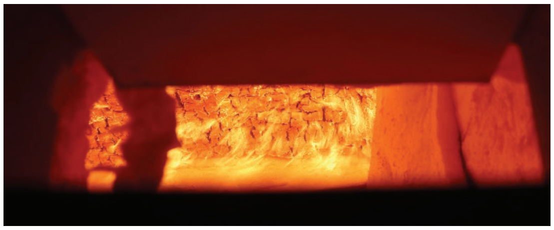

Figure 7: *The underside of a TCC floor assembly undergoing fire testing captured via one of the furnace's viewports*

After the termination of the fire tests, the underneath of the TCC slabs, which were still burning, were sprayed with pressurized water mist. Then, the specimens were removed out of the furnace for examination and visual inspection to determine the thickness of the remaining uncharred CLT section once the char layer was removed.

3 RESULTS

Test specimens were exposed to the CAN/ULC-S101 standard time-temperature curve for a few additional minutes beyond the two hours, exactly 126 minutes, to ensure satisfaction of the designed 2-hr fire resistance rating required by applicable building codes for the construction of tall timber buildings in Canada. Both samples sustained a 28.0 kN.m bending moment applied at their midspans under simply supported end conditions for the entire duration of the 2-hr standard fire exposure with no run-away deflection or any other characteristics of failure. This shows that a significant increase (more than 1 hr) in fire resistance time can be achieved for CLT floor slabs like the ones utilized in this study with the addition of a top layer of concrete that can work in composite action with the supporting mass timber section as a results of the utilization of the HBV glued-in steel plates as shear connectors between the timber and concrete elements in such TCC floor systems.

3.1 MECHANICAL BEHAVIOUR

After casting the concrete layer on top of the CLT slab, the initial mid-span deflections of the prepared test specimens due to the weight of wet concrete were measured and found to be 6.7 mm and 9.3 mm for Slabs 1 and 2, respectively. Afterwards, the test specimens were stored indoors for at least 28 days for full concrete curing, before each TCC floor assembly was installed on top of the furnace. Before the commencement of the fire test, a two-point load causing a maximum bending moment of 28.0 kN.m at the specimen midspan was applied in four increments, each of 25%, with the total applied load maintained stable for at least 30 minutes in conformity with CAN/ULC-S101. Then, the vertical deflections were measured due to the pilot loading prior to the start of the fire test. The applied bending moment maintained relatively constant throughout the entire duration of the fire test, while the gradually increased vertical deflections of the specimens were measured and recorded. The time-deflection curves for both floor slabs are shown in Figure 8.

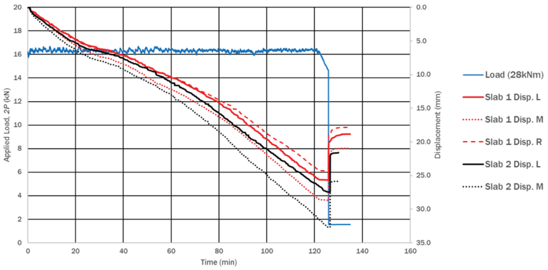

Figure 8: *Time-deflection curves for Slab 1 and Slab 2*

A summary of the maximum vertical deflections measured at the slab midspan and each point-load location is provided in Table 5. Readings for the right-side deflections of Slab 2 were not recoded due to a malfunction that occurred with the displacement transducer prior to the start of the fire test.

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***Table 5:** Summary of the maximum vertical deflections measured for Slab 1 and Slab 2*

Test specimen	Initial deflections due to weight of wet concrete (mm)		
Slab 1	6.7		
Slab 2	9.3		
	Deflections due to pilot loading (mm)		
	L	M	R
Slab 1	2.9	3.9	3.7
Slab 2	2.6	3.0	Error
	Final deflections right before terminating the fire tests		
Slab 1	29.1	32.1	28.4
Slab 2	32.7	38.7	Error

Generally, the vertical deflection values were found to be in good agreement with each other and consistent over the two slabs. From the time-deflection curves previously shown for both slabs in Figure 8, the floor slab deflection behaviour was more of a linear increase, which is characteristic of the reduction of the CLT cross-section over time due to charring. No exponential trend or run-away deflection was observed for the time-deflection curves for any of the two floor slabs throughout the entire duration of the 2-hr fire tests. It is worth mentioning that the deflection values rebounded a noticeable amount when the load was removed at the termination of the fire test. This behaviour is aligned with the TCC sections still undergoing elastic deformations and not exhibiting any plastic deformations in their shear connectors or brittle failure in the timber nor concrete components.

3.2 THERMAL BEHAVIOUR

Over the course of the 2-hr fire test, 37 thermocouples measured the internal temperatures of each test specimen at different locations with various depths. As the CLT bottom plys burned away, the exposed thermocouples were found to reach and follow the time-temperature profile of the followed standard fire as anticipated.

As the fire test progressed, the charring front moved closer to the more critical plys. These plys were the last two remaining plys in the CLT panel (one transverse with a 19 mm thickness and the very top longitudinal ply with a 35 mm thickness). The bottom of the last transverse ply was the location of the thermocouple labelled TC5. The transverse ply was deemed critical for the 2-hr standard fire exposure, not because the assembly could no longer sustain the load if it burned away, but for two reasons:

1) As per the composition of the utilized CLT panels, the transverse glued layer transfers the load to the remaining longitudinal plys, which were not edge glued. If the said transverse ply burned away, the CLT slab would no longer be in a composite action with the top concrete layer and thus, the behaviour of the remaining very top longitudinal ply solely supporting the concrete layer could no longer be as accurately predicted with either the gamma method or the elastoplastic method;

2) Since the HBV steel plate shear connectors were installed into the CLT panels using an epoxy material that is sensitive to elevated temperatures a minimum wood cover needed to be maintained to ensure the integrity of the adhesive and accuracy of the predicted behaviour of the shear connection with no failure in the adhesive due to fire exposure.

Figure 9 shows the time-temperature curves of the thermal measurements of the critical thermocouple (TC5) installed at the bottom of the top transverse ply and those of the thermocouple installed at the mid thickness of the said ply (namely TC6) in one of the slabs (i.e., Slab 1). As shown in the figure, as per the design of the TCC floor specimens, the top transverse ply began to char near the end of the fire test at approximately 123 minutes as the temperature measured by TC5 reached a temperature of 300 °C at this time mark.

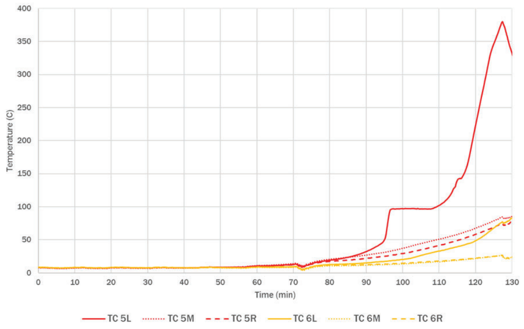

***Figure 9:** Time-temperature curves of thermocouples TC5 and TC6 installed in Slab 1*

Generally, it was observed from the thermal results that the internal temperatures measured at the midspan of the floor slabs (Section M) increased with time to reflect a charring rate that is close to the notional rate of 0.65 mm/min that is standard for the utilized CLT panels. However, in the maximum shear zones of the floor slab, near the walls of the furnace, steeper temperature gradients were observed. Due to the non-combustible nature of the furnace insulated walls, fire vortexes formed at the corner where the furnace wall intersects with the underneath surface of the test specimen at each end. While this phenomenon unrealistically increased the charring rates near the left and right-side walls of the furnace, it did not affect the fire resistance of the test specimens or prematurely fracture the remaining longitudinal ply at the midspan where the maximum bending moment exists. This confirmed a continued composite action between the CLT plys remained after charring and the concrete layer until the termination of the fire resistance test at 126 minutes.

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3.3 CHARRING RATE

After the TCC floor slabs were taken out of the furnace, they were securely positioned on their back longitudinal edge to allow for the removal of the developed char layer as shown in Figure 10 for Slab 1. The char layer was removed on the entire bottom surface of each test specimen using a wire brush on an electrical drill. Figure 11 shows the residual CLT section at the midspan of Slab 2 after removing the char layer.

Figure 10: *Char layer removed on the entire bottom surface of Slab 1*

Figure 11: *Residual CLT section at the midspan of Slab 2 after removing the char layer*

Once the char layer was removed, small holes were drilled into the CLT residual section at different locations until the drill bit touched the concrete slab. A digital calliper was inserted into the drilled holes to measure the residual thickness of the CLT section. The average thickness of the CLT residual section from various locations near the midspan of the test specimens were found to be 57 mm and 59 mm for Slab 1 and Slab 2, respectively.

The CLT residual thicknesses are reflective of a 2hr and 6-minute standard fire exposure, followed by approximately 5 minutes of a cool down phase before extinguishing of the test specimens started. Therefore, the charring rate was found to be between 0.65 mm/min and 0.68 mm/min assuming a time of either 131 minutes or 126 minutes, respectively. Based on the thermal measurements taken by the thermocouples implemented inside each test specimen (discussed in Section 3.2), the average charring rate was calculated at approximately 0.65 mm/min based on the assumption that the location of the char front in the CLT slab corresponded to a thermocouple reading of 300 °C.

4 DISCUSSION

The new results of the fire resistance tests of the two full-size one-way TCC floor slabs show that both test specimens achieved the targeted two-hour fire resistance time. Neither slab experienced failure while loaded with a total service load equivalent to 4.8 kPa over the course of exposure to two hours of a CAN/ULC-S101 standard fire. The CLT slab itself, under the same loading conditions, which could include a poured concrete layer without composite action with the supporting CLT slab, was only rated for a 60-minute fire resistance. The experimental results were found to be in good agreement with the predicted design calculations and the assumed charring rate used in the design of the CLT residual sections at the 2-hr fire resistance time mark were confirmed to be accurate. In addition, the fire performance of the HBV steel plates as the shear connectors used in the test specimens of the present study can be accurately predicted using the gamma method or the elastoplastic method based on the following two assumptions:

1. A minimum adequate thickness of a wood layer beneath the kerf saw cut in the CLT floor slab is maintained over the duration of the fire and thus, at no point the adhesive securing the steel plate connector into the timber is exposed to direct fire.
2. That the remaining plys of the CLT floor slab maintain its mechanical properties over the course of the fire. In the case of the CLT panels used in the experiments of the present study, the laminas were not edged glued and thus, it had the bottom underlying transverse layer (second ply from the bottom) burned away completely near the end of the 2-hr fire test. Accordingly, there would have been little to no interaction between the individual longitudinal lamina and the shear connectors would only be interacting with the longitudinal lamina they were embedded in and not

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any adjacent longitudinal lamina without shear connectors in the wood

5 CONCLUSIONS

Using the HBV glued-in steel plates as effective shear connectors enhanced the fire resistance of the two CLT-concrete composite floor slabs tested in this study by creating a near-complete composite action that achieved a minimum fire resistance of two hours as required by applicable building codes for mid-rise residential buildings. The designed TCC floor slabs satisfied deflection limits during the initial concrete curing stage. Also, the stiff shear connectors increased the degree of composite action between the CLT and concrete layer and thus, reduced the mid-span deflections of the TCC slabs under the applied load, keeping the exhibited deflections within the allowable limits for SLS criteria. The TCC slabs were found to satisfy ULS criteria at both ambient and after a 2-hr standard fire exposure. The ambient and fire design outcomes based on the gamma and elastoplastic methods for the experimentally examined TCC floor slabs were found to be supported by the experimental results and thus, their fire behaviour was proven to be accurately predicted.

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