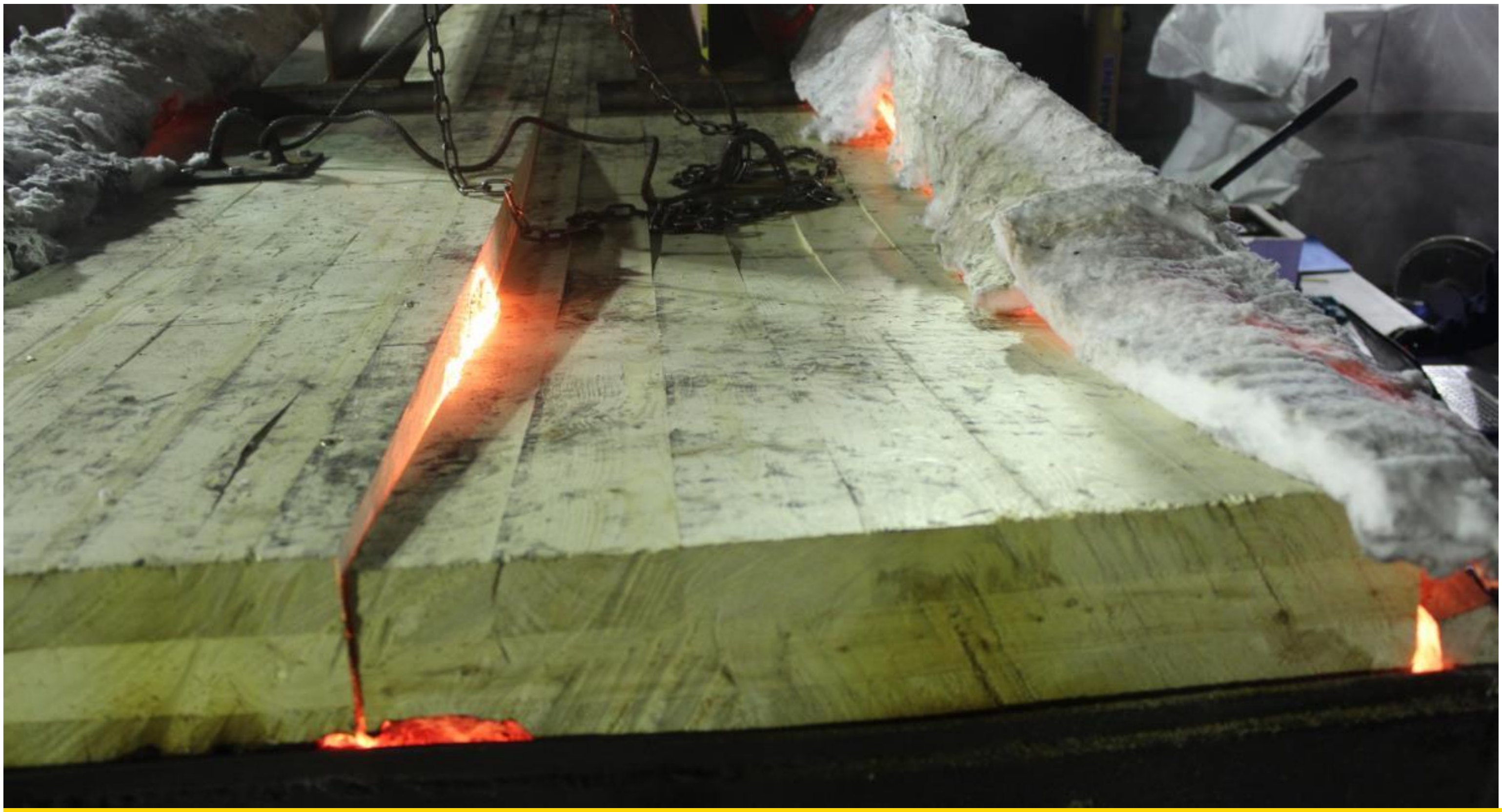

Fire Performance of Cross-Laminated Timber Panel-to-Panel Joints

Date: March 31st 2015

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Report prepared for:

Forestry Innovation Investment Ltd.

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APPROVALS

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Disclosure for Commercial Application: If your mill requires assistance to implement these findings, please contact FPInnovations.

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1. OBJECTIVE

The current study aims at evaluating the integrity failure (i.e. passage of hot gases or flames through the assembly) of CLT assemblies connected together using four types of commonly used panel-to-panel joints when exposed to the standard CAN/ULC S101 "*Standard Method of Fire Endurance Tests of Building Construction Materials*" [1] fire resistance time-temperature curve. The four types of joints include: 1) half-lapped, 2) internal spline, 3) single surface spline and 4) double surface splines.

2. BACKGROUND

Structural fire performance of building assemblies are assessed by conducting fire-resistance tests in accordance with CAN/ULC S101. A fire-resistance rating is defined as the period of time a building element, component, or assembly maintains the ability to perform its separating function (i.e. integrity and insulation), continues to perform a given load-bearing function (mechanical resistance), or both, when exposed to fire under specified conditions of test and performance criteria. Designers should be capable of accurately verifying both the load-bearing and separating functions of cross-laminated timber (CLT) as floor or wall slab assemblies in accordance with fire-related provisions of the building codes.

Integrity is one of the two requirements of the separating function of building assemblies (insulation being the other requirement). The time at which a CLT panel-to-panel joint can no longer prevent the passage of flame or gases hot enough to ignite a cotton pad defines its integrity fire resistance, as per CAN/ULC-S101. This requirement is essential in meeting Code objectives and functional statements, namely with respect to limiting the risk of fire spread to compartments beyond the compartment of fire origin.

As described in the 2014 Chapter 8 of the CLT Handbook [2], CLT panel-to-panel joint performance depends on its configuration and connection details; an integrity failure may occur when the connection detail can no longer withstand the applied load in either shear or withdrawal. CSA O86 "*Engineering Design in Wood*" [3] provides design provisions for connections with respect to minimum fastener penetrations for developing adequate lateral and withdrawal resistance. For instance, when using wood screws to connect CLT panels together, a minimum penetration no less than 5 times the wood screw diameter is required for single shear connections. As such, proper engineering and detailing of connections are fundamental.

So far, half-lapped joints have been evaluated in full-scale fire tests where the joint was located at mid-depth of the CLT panels and overlapped for at least 64 mm [4]. The joints were fastened using self-tapping wood screws of 90 mm (3½ in.), 160 mm (6¼ in.), and 220 mm (8¾ in.) for CLT assemblies made of 3, 5 and 7 plies respectively. A bead of construction adhesive was also used to ensure that the joint was sealed. Full-scale fire testing of CLT assemblies showed that integrity seems to be the predominant failure mode of CLT floor assemblies under load (i.e. flaming through the CLT panel-to-panel half-lapped joint). This failure mode was not observed in CLT wall assemblies under load. Walls usually buckle due to increasing second-order effects (i.e. P-Δ effects) as the section chars. According to the 2014 Chapter 8 of the CLT Handbook [2], the integrity failure time of a half-lapped joint located at mid-depth can be determined from Equation (1)

$$t_{\text{int}} = K_j \cdot \frac{h}{\beta_0} \tag{1}$$

Where K_j is a joint coefficient (taken as 0.35 for half-lapped joints at mid-depth), h is the total initial thickness (mm) and β_0 is the one-dimensional charring rate (mm/min). This model is based on the

European approach given in Eurocode 5:1-2 "*Design of timber structures - Part 1-2: General - Structural fire design*" [5] applicable to the effect of joints in wood-based panels that are not backed by battens (i.e. unexposed side not protected by wood paneling, structural element, concrete topping, etc.). According to this standard, a joint coefficient of 0.3 is assigned for a half-lapped joint and 0.4 for an internal spline. This coefficient currently does not address single or double splines. Furthermore, a joint coefficient of unity (K_j = 1.0) can be taken when panel joints are fixed to a batten of at least the same thickness or to a structural element or when wood paneling is installed on the unexposed side. It is noted that these coefficients have been derived based on the fire behaviour of solid timber components, which may not necessarily be applicable to CLT slabs that may exhibit heat delamination (i.e. increased charring when compared to solid timber).

However, connection details of CLT assemblies may also consist of other configurations such as single or double surface splines or internal spline(s). These tightly fitted joint profiles should provide sufficient fire-resistance provided the loss in depth of the reduced cross-section has not yet reached the spline, but they have yet to be properly evaluated for fire-resistance in CLT assemblies. Therefore, evaluating and developing a joint coefficient (K_j) for these types of joints is needed.

Lastly, O'Neil [6] evaluated the fire performance of timber floors and recommended using a minimum residual thickness of 15 mm to be used as a "safe" approximation for meeting the insulation and integrity criteria simultaneously. Specifying a minimum residual thickness allows for ensuring the unexposed surface to remain within the limits prescribed in standard fire-resistance tests. This value is in agreement with the thermal model developed by Janssens & White [7]. According to their model, the remaining CLT thickness required to keep the average unexposed temperature increase below 140°C (or a temperature of about 160°C at a single point) would be 12 mm.

3. TECHNICAL TEAM

Christian Dagenais, Eng, M.Sc	Scientist, Serviceability & Fire Performance
Lindsay Osborne, M.A.Sc	Scientist, Serviceability & Fire Performance
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	Advanced Building Systems, FPInnovations

Assembly and instrumentation of the CLT panels were done at FPInnovations Materials Evaluation laboratory in Quebec City. Fire testing was conducted at the Fire Research Facilities of Carleton University in Carleton Place, Ontario.

4. MATERIALS AND METHODS

4.1 Fire testing

Intermediate-scale fire-resistance tests were carried out in a furnace recently constructed at the Fire Research Facilities of Carleton University in Ottawa, Ontario (Figure 1). The furnace is designed to accommodate specimens up to 4.8 m long by 1.06 m wide. A hydraulic jack is mounted above which can apply a load on the CLT panels in one-way bending up to a 200 mm maximum deflection. A two-point loading condition was chosen. The loading heads were free to rotate (i.e. roller bearing point) and were located at 1627 mm from the supports. This loading condition generates withdrawal stress at the fasteners located between the loading points (shear-free zone under the maximum bending moment) and longitudinal shear stresses along the fasteners located outside the loading points (constant shear stress). The manually controlled fire exposure followed, as close as possible, the CAN/ULC S101 standard time-temperature curve.

Table 1 summarizes the test matrix in this study. A total of ten specimens were tested using different panel-to-panel joint details. Given the fact that 7-ply CLT are most likely to be used for either long spans or high loading conditions, it was decided not to test the internal and single surface spline details for these 7-ply specimens. This is because the capacities of these details in 7-ply CLT are likely to be limited by the plywood spline capacity. Figure 2 shows the actual joint details evaluated in this study.

Figure 1 – Intermediate-scale furnace at Carleton University

Table 1 – Test matrix

CLT Assembly	Panel-to-panel joint detail			
	Half-lapped	Internal Spline	Single surface spline	Double surface splines
3-ply (105 mm)	X	X	X	X
5-ply (175 mm)	X	X	X	X
7-ply (245 mm)	X	-	-	X

The CLT specimens were two specimens of the E1 stress grade conforming to ANSI/APA PRG-320 standard [8, 9] joined side-by-side using partially-threaded self-tapping screws. For the half-lapped and internal spline configurations, partially-threaded ASSY® 3.0 Ecofast [10] with a 6 mm diameter and in lengths of 100, 160 and 240 mm were used for 3-ply, 5-ply and 7-ply CLT specimens respectively (ϕ6 x 100/60 mm, ϕ6 x 160/70 and ϕ6 x 240/70). The same self-tapping screws, of 70 mm in length (ϕ6 x 70/42), were used for all CLT specimens with the single and double spline configurations. Screws were spaced at 300 mm (12”) on center for all specimens.

It is noted that the fire testing was conducted during winter, thus in very cold and dry conditions as the laboratory is not heated. The CLT specimens were not conditioned prior to the tests and in most tests their initial temperature was below freezing.

a) Half-lapped joint

b) Internal spline

c) Single surface spline

d) Double surface spline

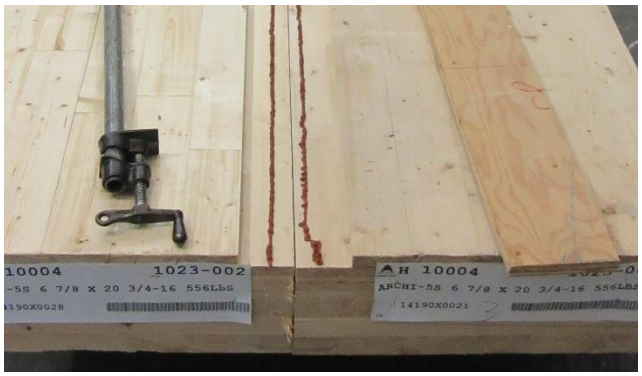
Figure 2 – CLT panel-to-panel joint details

Except for the half-lapped joint configuration, all other panel-to-panel joints required the use of plywood splines to securely fasten the CLT panels together. The plywood splines were cut along the major strength direction of 1.22 x 2.44 m (4 x 8 ft.) sheets of Canadian softwood plywood (CSP) to dimensions of 18.5 mm (¾ in. nominal) in thickness and 130 mm (5⅛ in.) in width. Two plywood splines were butt-jointed together along their length (butt-joint located at mid-span). The CLT panels were machine-grooved at the manufacturing plant to accommodate for the joint details. Temperatures were measured throughout the CLT specimens and in the joints to obtain an accurate understanding of the heat transfer through the assemblies.

All joint assemblies were tightly fit and sealed using a 6 mm bead of Hilti FS-One intumescent firestop sealant [11] to prevent smoke leakage, as shown in Figure 3.

a) Half-lapped

b) Internal spline



c) Single surface spline

d) Double surface spline

Figure 3 – Intumescent sealant used in the panel-to-panel joints

4.2 Spline preliminary evaluation

During the discussion to establish the loading protocol, some concerns were raised with respect to the proper way to achieve the study objective. As mentioned in section 1, the objective is to evaluate the integrity failure (i.e. passage of hot gases or flames through the assembly) of CLT assemblies connected together using four types of commonly used panel-to-panel joints during fire conditions. Typically, floor systems are to be evaluated for fire exposure from below (i.e. representing a fire occurring from a floor below).

Connections between CLT slabs are designed to solely transfer in-plane shear forces resulting from a floor diaphragm action or racking of CLT wall assemblies (for purposes of this report and given the fire test configuration, these will be referred to from this point onward as “horizontal shear forces”). These connections, even if they have some ability to transfer vertical shear forces between the CLT slabs, are not designed for this function. The panel-to-panel joint details proposed in this study are meant to transfer horizontal forces between CLT slabs. The application of any horizontal load will result in a loading that forces horizontal sliding action between each CLT slab. This sliding action is the shear that is resulting from the floor responding as a diaphragm. Fasteners and splines serving as a link between any two CLT slabs are designed to resist this sliding action other loading effects are normally not taken into consideration.

As such, it was suggested to conduct preliminary bending tests under ambient conditions that would help develop a better understand of the behaviour of CLT splines subjected to a bending moment. The intent was to evaluate the potential failure mode and derive an adequate loading level during the fire tests as not to force premature failure of the fasteners or the plywood splines (force flame-through between the CLT panels).

The test setup consisted of a smaller-scale version of the fire test setup, that is a simple span of 3.5 m (138 in.) subjected to a two-point loading conditions. Each loading point was placed at one-third of the span, replicating a similar stress distribution as that used in the fire tests. Three CLT panels were connected side-by-side using the same single surface plywood spline and self-tapping screws as those used in the fire tests, and where the loads were applied only on the middle panel (Figure 4).

Figure 4 – CLT bending test under ambient conditions

Two specimens were evaluated and exhibit very similar behaviour. As expected, the fasteners were the weakest link; the failure mode was the screw heads pulling through the plywood splines (Figure 5). This confirmed that the loading conditions used in the fire-resistance tests need to be such that failure of the fasteners will not occur prematurely (i.e. pull-through should not occur, but withdrawal or lateral crushing could, or simply burn-through at the joints).

Figure 5 – Head pull-through in CLT bending test under ambient conditions

5. RESULTS

The following is a summary of the fire tests conducted on the 10 CLT panel-to-panel joints. In the first two tests (3-ply internal spline and half-lapped), some problems occurred during the testing either with the furnace, the thermocouples voltage reading or the loading jack. Monitoring of the burners as well as the loading jack was highly improved as the test series progressed. Each test is described further in detail in the following subsections.

5.1 Half-lapped joint – 3-ply CLT

The 3-ply CLT with a half-lapped joint located at mid-depth was tested on December 3, 2014. The ambient conditions in the laboratory were -7ºC and 39% relative humidity. The outdoor temperature was -3ºC.

A load of 32 kN, representing a full loading condition, was applied prior to the fire exposure as shown in Figure 6. However, the bending stiffness of a 3-ply CLT floor slab is quickly reduced when the exposed layer in the strength direction chars. As such, the applied load was modified during the test. It can be seen that indeed the maximum 20 cm deflection was reached very early into the test. Nevertheless, the test continued until glowing at the unexposed surface was observed at the portion of the joint located between the loading points. The test failure time was recorded as 45 min.

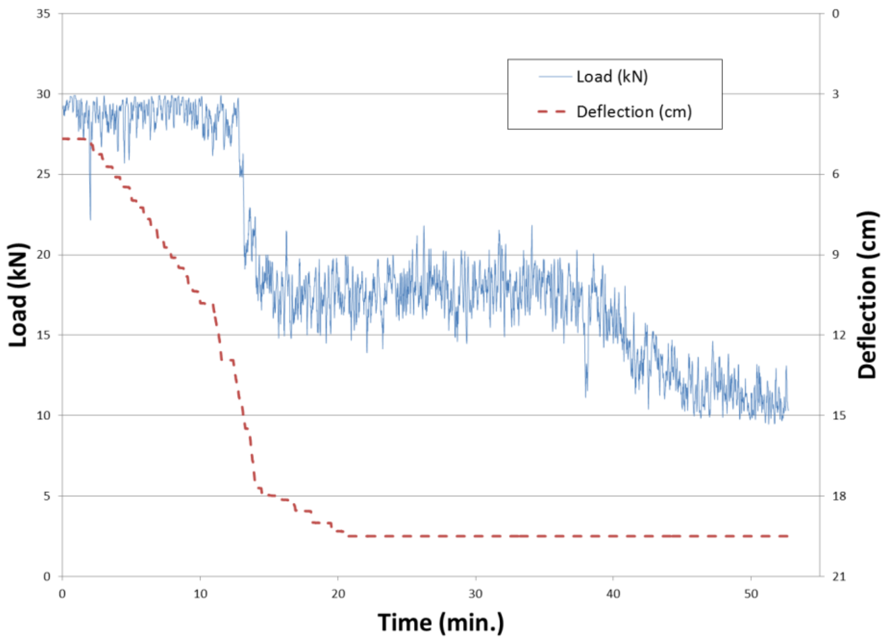


Figure 6 - 3-ply half-lapped joint load and deflection measurements

Figure 7 – Failure of the 3-ply half-lapped joint

Throughout the test, there were significant difficulties trying to properly following the standard fire curve, especially during the first 20 minutes as shown in Figure 8. Figure 9 and Figure 10 show the temperature profiles recorded throughout the CLT and at the junction of the half-lapped joint. The 300ºC isotherm was reached at 17.5 mm after 28 min, yielding a charring rate of 0.63 mm/min. At the end of the test (at 53 min), the maximum temperature reading at the joint was 290ºC, indicating that the char front (300ºC isotherm) was very close to this point; this result gives a charring rate of 0.99 mm/min.

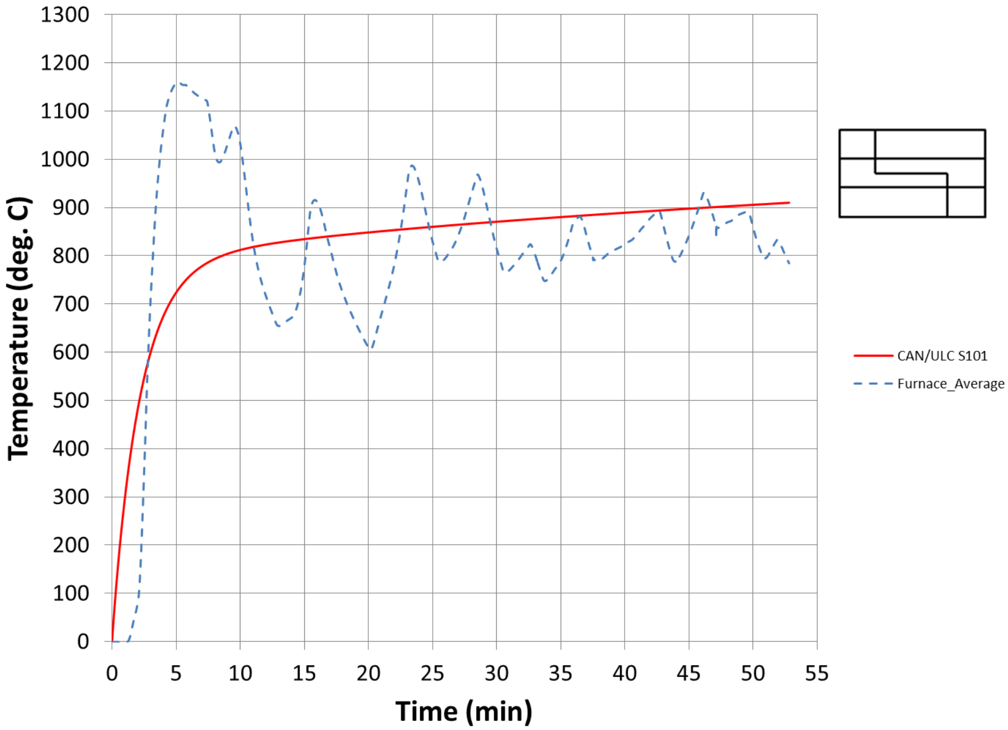


Figure 8 – Furnace temperature for the 3-ply half-lapped joint (average values)

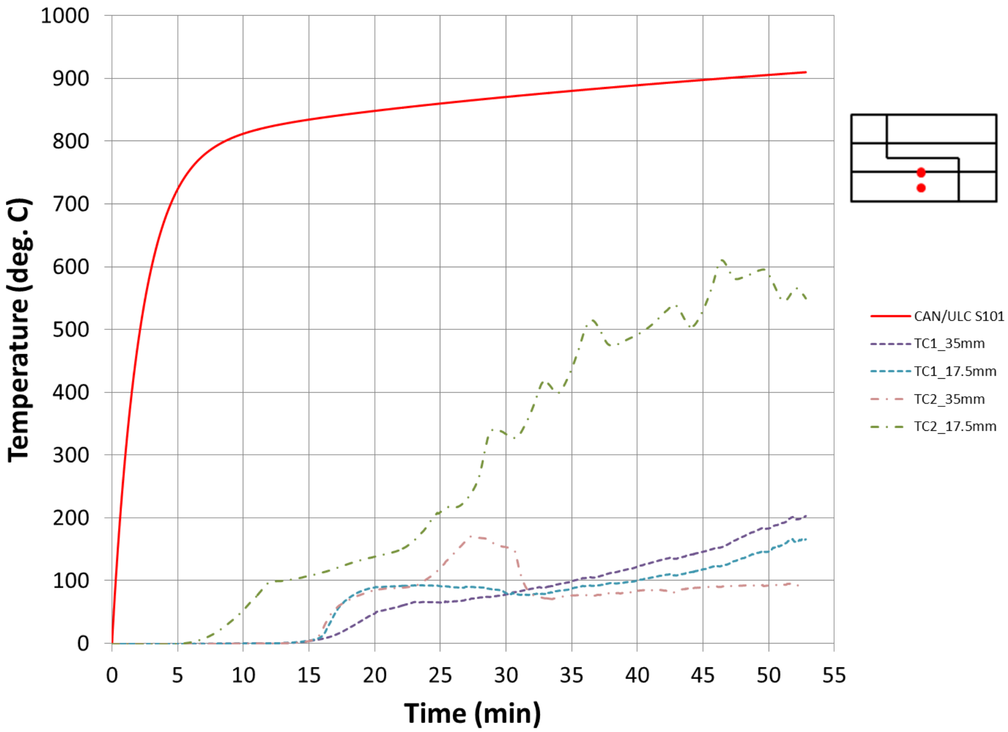


Figure 9 – Temperature profiles for the 3-ply half-lapped joint

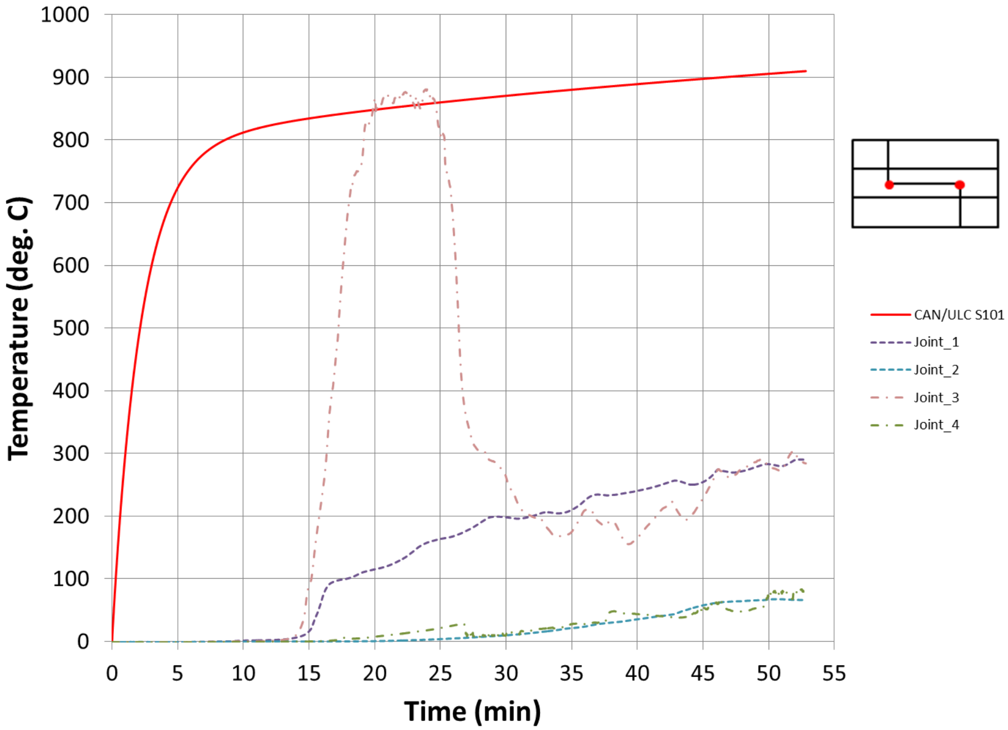


Figure 10 – Temperature profiles at the half-lapped joint of the 3-ply CLT

5.2 Half-lapped joint – 5-ply CLT

The 5-ply CLT with a half-lapped joint located at mid-depth was tested on February 6, 2015. The ambient conditions in the laboratory were -7ºC and 43% relative humidity. The outdoor temperature was -7ºC.

A load of 41 kN, representing a 54% loading condition determined from an initial 20 mm deflection, was applied prior to the fire exposure as shown in Figure 11. The test continued until differential deflection occurred between the 2 CLT panels (Figure 12). The test failure time was recorded as 98 min.

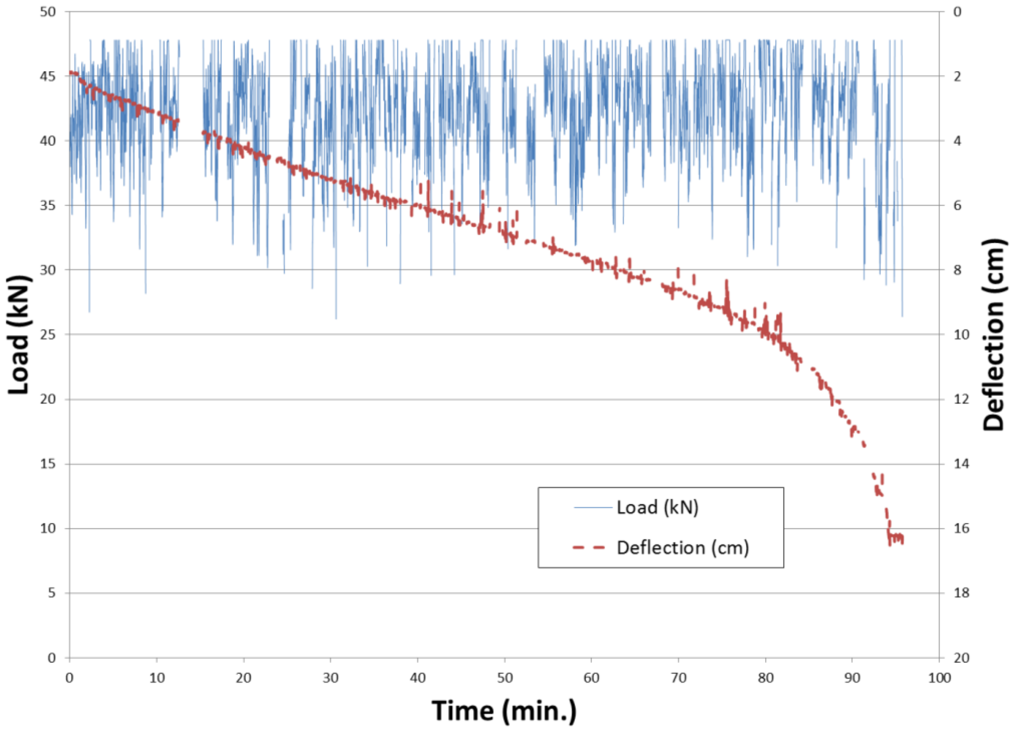


Figure 11 - 5-ply half-lapped joint load and deflection measurements

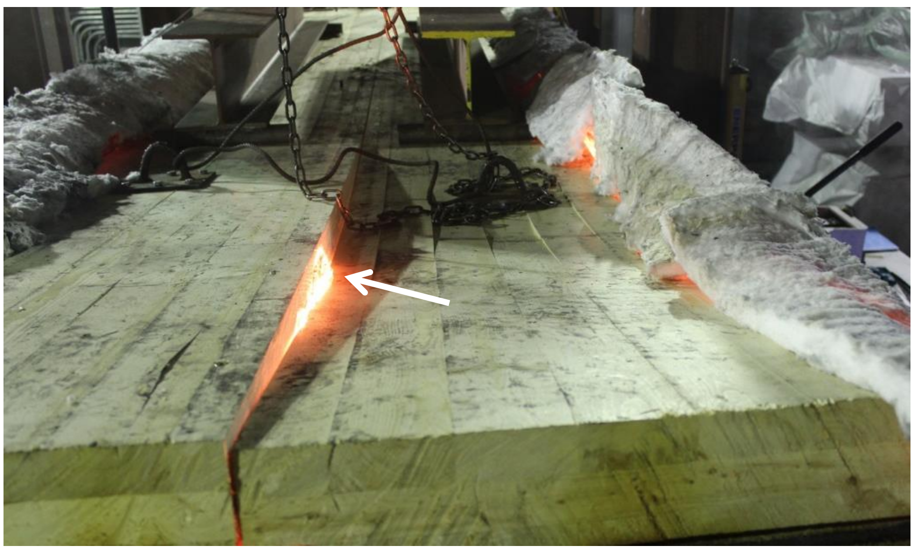


Figure 12 – Failure of the 5-ply half-lapped joint

Figure 13 illustrates the temperature recorded inside the furnace during the test. It can be seen that the temperature, although lower for most of the test, followed closely the standard curve. Figure 14 and Figure 15 show the temperature profiles recorded throughout the CLT and at the junction of the half-lapped joint. The 300ºC isotherm was reached at 17.5 mm and 35 mm after 51 min and 74 min, yielding a charring rate of 0.34 and 0.47 mm/min, respectively. As shown in Figure 15, no significant temperature rises were recorded at the 2nd glue line (70 mm) or at the joint interface.

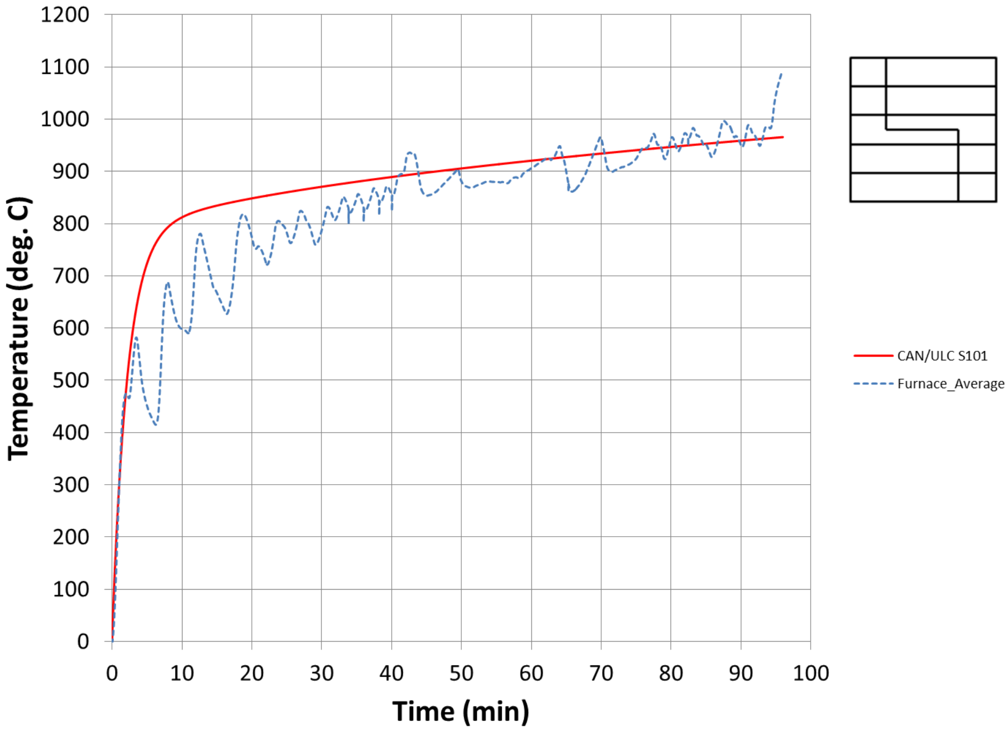


Figure 13 – Furnace temperature curve for the 5-ply half-lapped joint (average values)

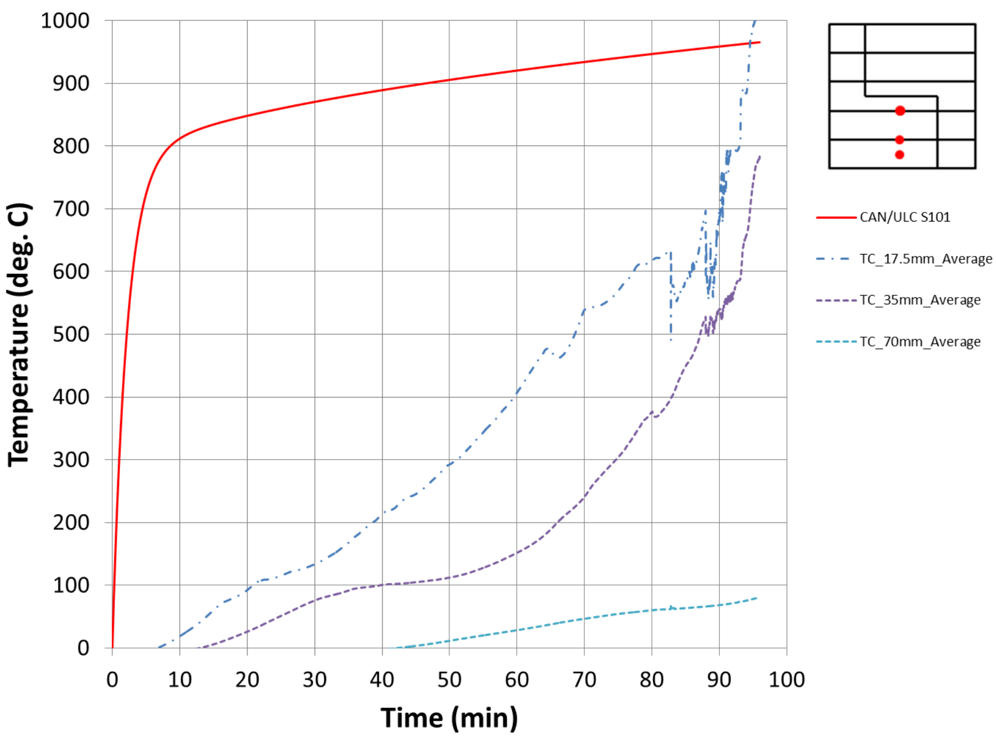


Figure 14 – Temperature profiles for the 5-ply half-lapped joint (average values)

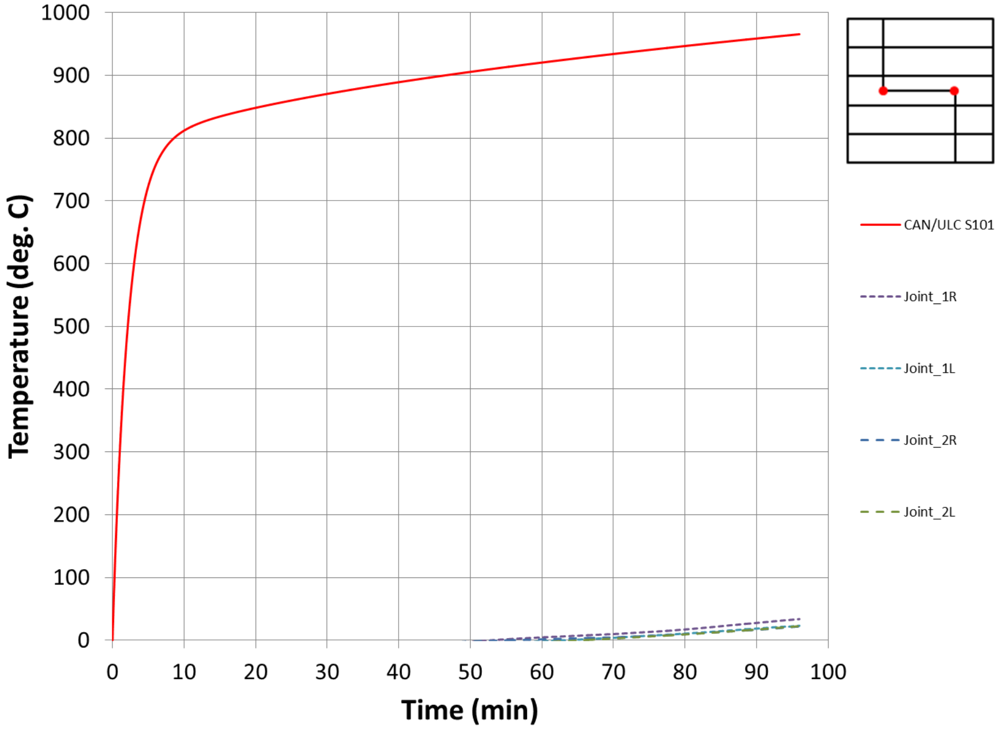


Figure 15 – Temperature profiles at the half-lapped joint of the 5-ply CLT

5.3 Half-lapped joint – 7-ply CLT

The 7-ply CLT with a half-lapped joint located at mid-depth was tested on March 12, 2015. The ambient conditions in the laboratory are unknown, but the outdoor temperature was -6ºC.

A load of 50 kN, representing a 37% loading condition limited by the load cell capacity, was applied prior to the fire exposure (Figure 16). The test continued until glowing at the unexposed surface was observed at the portion of the joint located between the loading points, as shown in Figure 17. As with the 5-ply half-lapped test, differential deflection also occurred between the 2 CLT panels (Figure 18). The test failure time was recorded as 140 min.

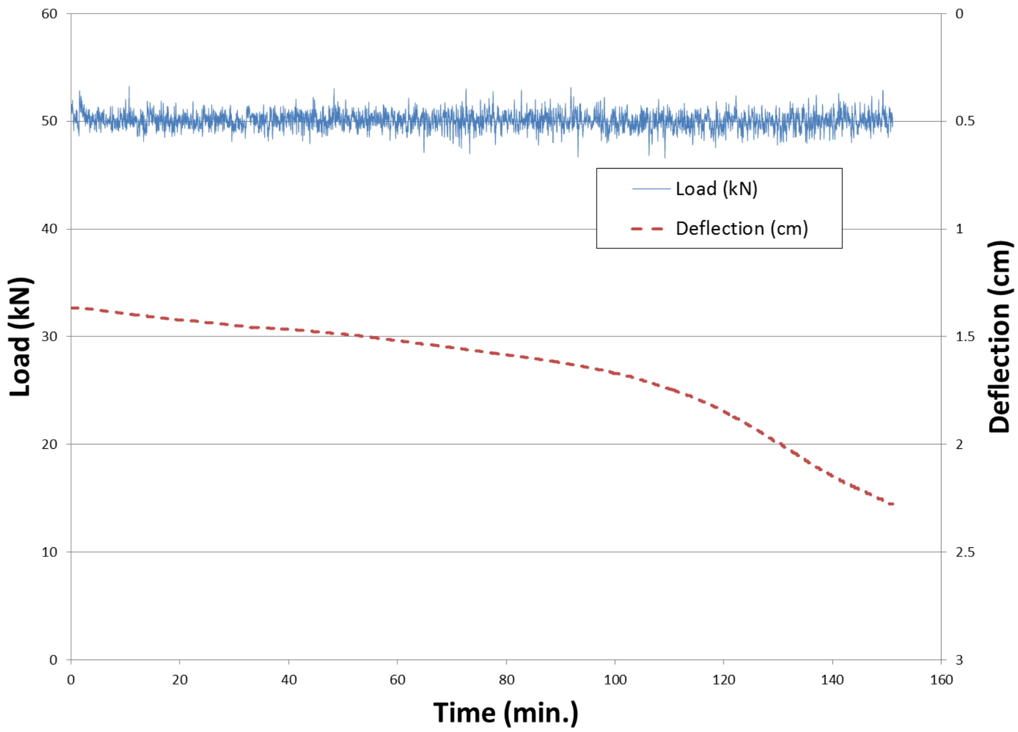


Figure 16 - 7-ply half-lapped joint load and deflection measurements

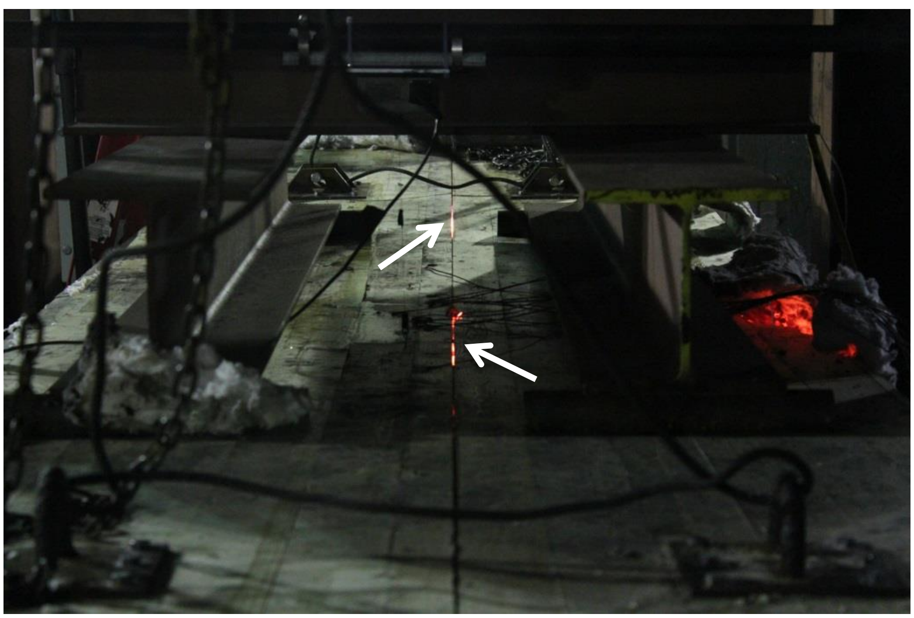


Figure 17 – Failure of the 7-ply half-lapped joint

Figure 18 – Differential deflection of the 7-ply half-lapped joint

Figure 19 illustrates the temperature recorded inside the furnace during the test. It can be seen that the temperature followed closely the standard curve. Figure 20 and Figure 21 show the temperature profiles recorded throughout the CLT and at the junction of the half-lapped joint. The 300ºC isotherm was first reached at 17.5, 35, 70 and 105 mm after 47, 74, 117 and 144 min, yielding a charring rate of 0.37, 0.47, 0.60 and 0.73 mm/min respectively. The half-lapped interface reached 300ºC at 96 min.

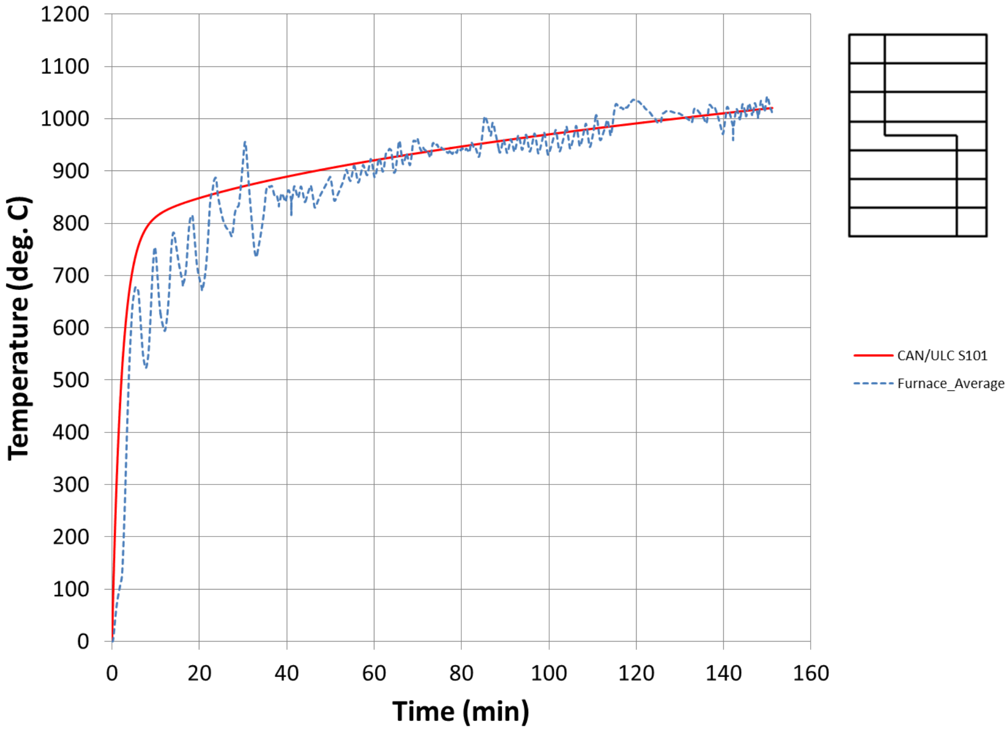


Figure 19 – Furnace temperature curve for the 7-ply half-lapped joint (average values)

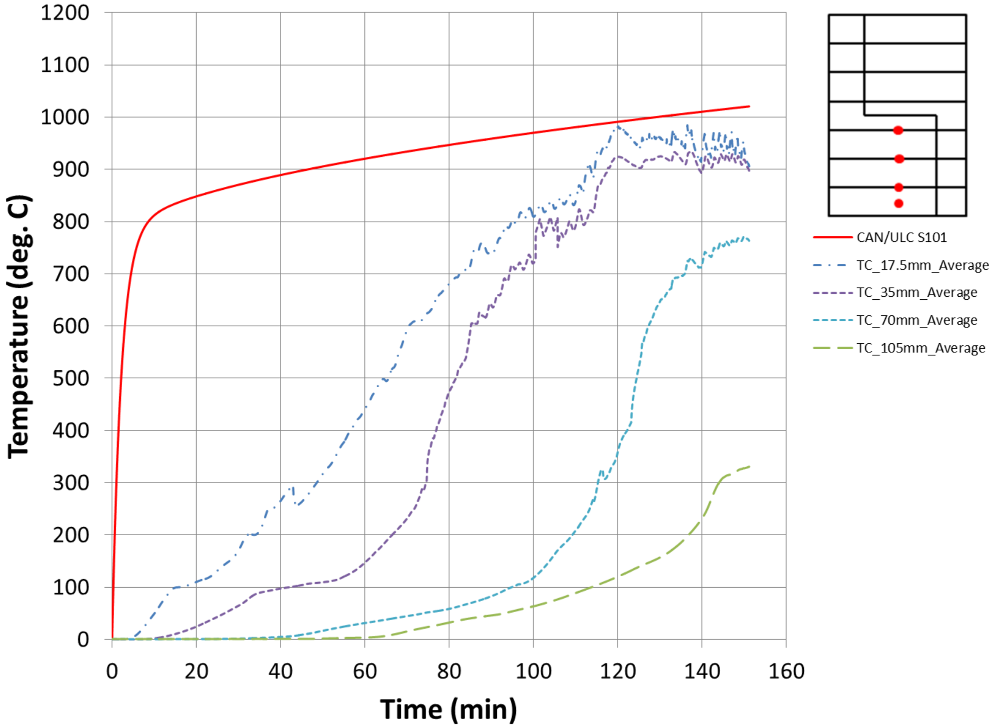


Figure 20 – Temperature profiles for the 7-ply half-lapped joint (average values)

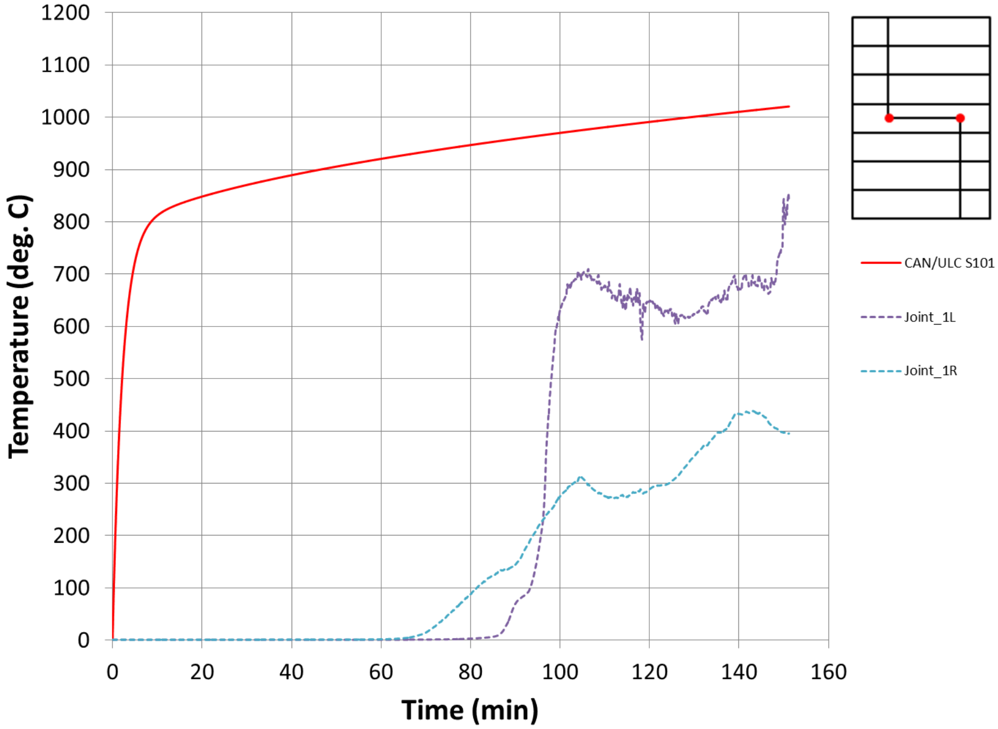


Figure 21 – Temperature profiles at the half-lapped joint of the 7-ply CLT

5.4 Internal spline – 3-ply CLT

The 3-ply CLT with an internal spline located at mid-depth was tested on November 19, 2014. The ambient conditions in the laboratory are unknown, but the outdoor temperature was -6ºC.

A load of 32 kN, representing a full loading condition, was applied prior to the fire exposure (Figure 29). Significant problems occurred throughout the test, namely with the burners due to the very cold indoor conditions (problem in the air/propane mixture). In addition, problems with the data acquisition system occurred. As such, no data has been properly recorded for this specific test, including the furnace temperature.

However, from visual observations and manual timing, glowing at the surface (unexposed) was observed at the joint around 35 min after the test (Figure 23). The burn-through was located close to mid-span where the spline was butt-jointed. It is noted that since the burners were not controlled properly, the furnace temperature could not be verified.

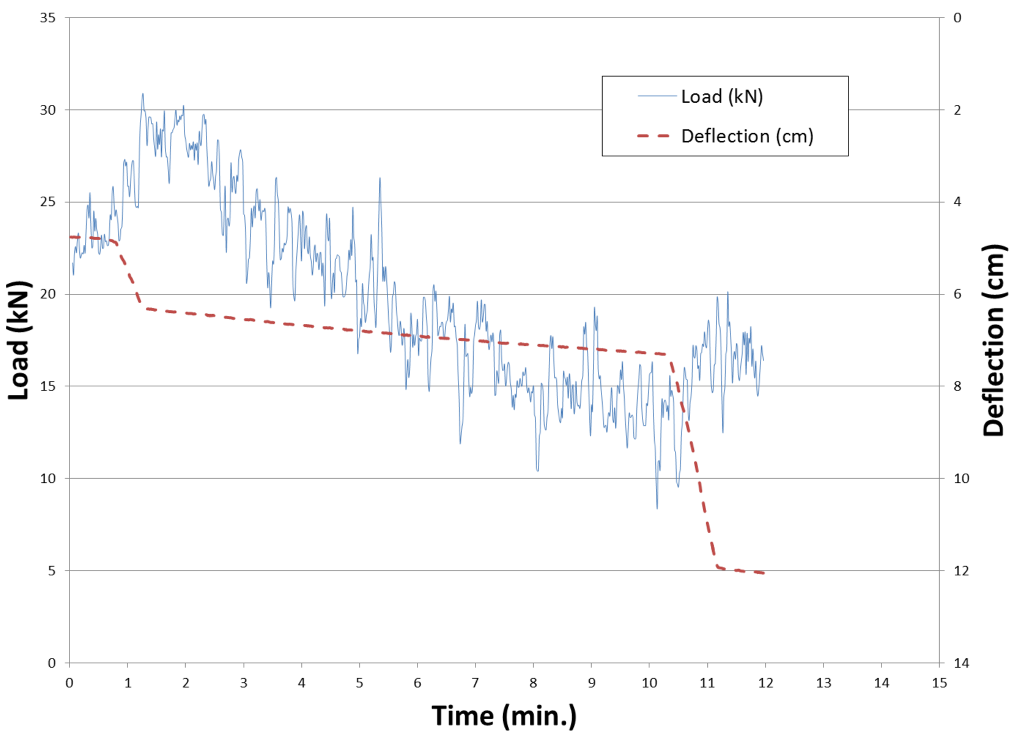


Figure 22 - 3-ply internal spline load and deflection measurements

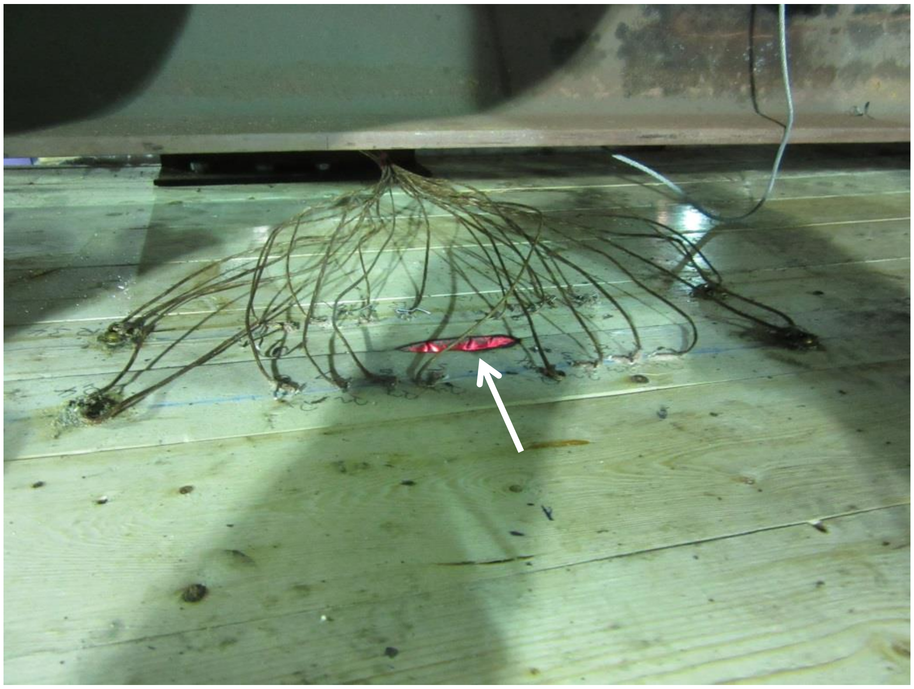


Figure 23 – Failure of the 3-ply internal spline

5.5 Internal spline – 5-ply CLT

The 5-ply CLT with an internal spline located at mid-depth was tested on January 30, 105. The ambient conditions in the laboratory are unknown, but the outdoor temperature was -13ºC.

A load of 42 kN, representing a 55% loading condition determined from an initial 20 mm deflection was applied prior to the fire exposure as shown in Figure 24. The test continued until glowing at the unexposed surface was observed at the joint, located at mid-span where the spline was butt-jointed, as shown in Figure 25. The test failure time was recorded as 76 min.

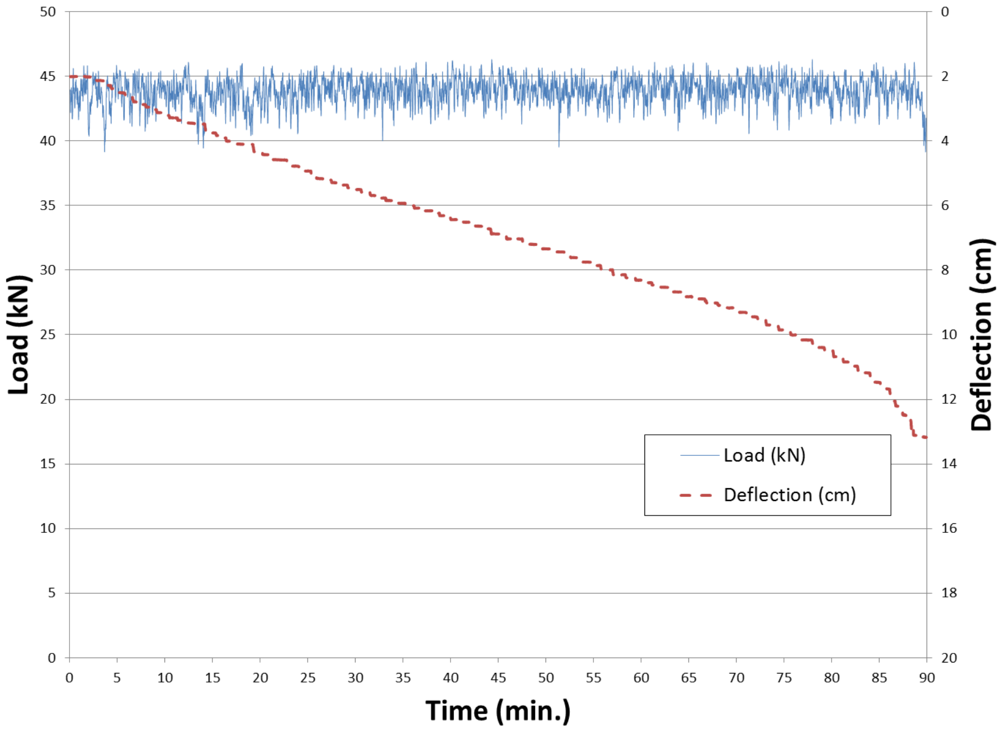


Figure 24 - 5-ply internal spline load and deflection measurements

Figure 25 – Failure of the 5-ply internal spline

Figure 30 illustrates the temperature recorded inside the furnace during the test. It can be seen that the temperature was lower for most of the test but followed closely the standard curve. Figure 27 and Figure 28 show the temperature profiles recorded throughout the CLT and at the junction of the internal spline. The 300ºC isotherm was reached at 17.5, 35 and 70 mm after 29, 61 and 85 min, yielding a charring rate of 0.60, 0.57 and 0.82 mm/min respectively. The bottom and the top of the internal spline reached 300ºC respectively at 75 and 81 min.

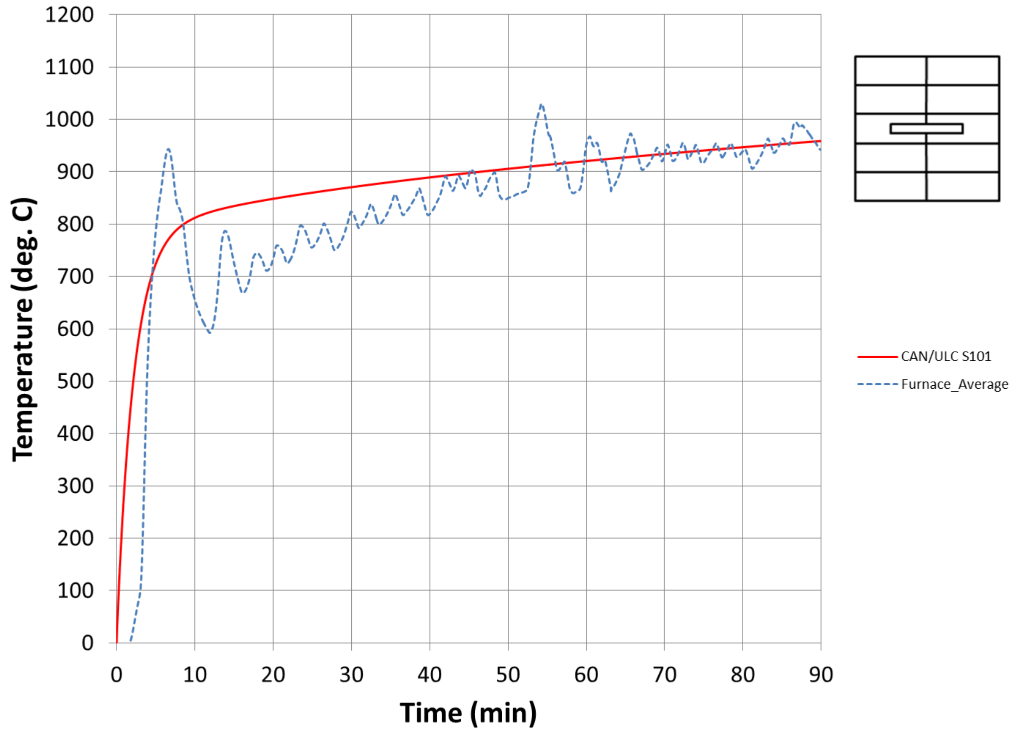


Figure 26 – Furnace temperature curve for the 5-ply internal spline (average values)

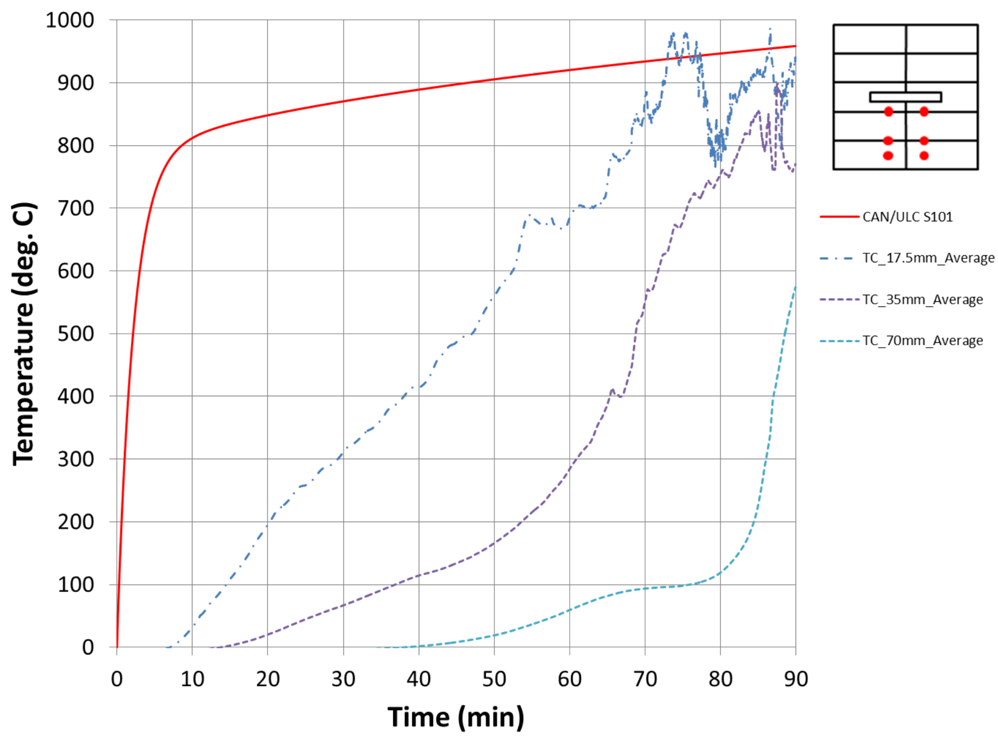


Figure 27 – Temperature profiles for the 5-ply internal spline (average values)

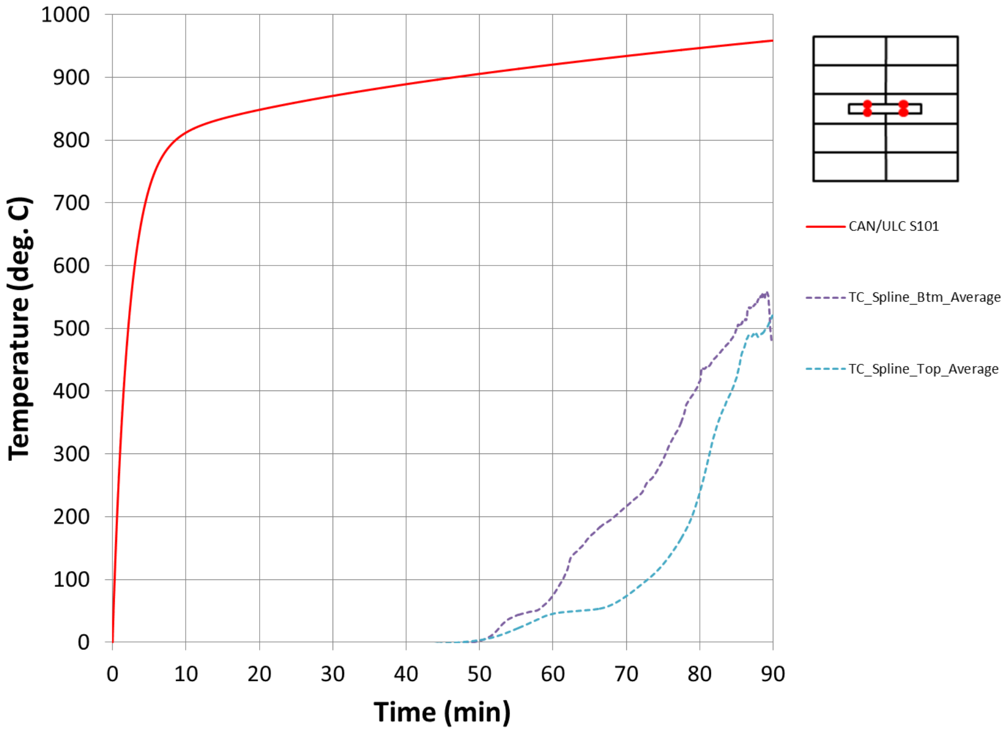


Figure 28 – Temperature profiles at the internal spline of the 5-ply CLT (average values)

5.6 Single surface spline – 3 ply CLT

The 3-ply CLT with a single surface spline was tested on December 9, 2014. The ambient conditions in the laboratory were 2ºC and 58% relative humidity. The outdoor temperature was -3ºC.

A load of 32 kN, representing a full loading condition, was applied. As explained in subsection 5.1 of this report, the maximum deflection (20 cm) was reached early in the test. After 54 min into the test, it was decided to end the test due to laboratory equipment safety concerns. As such, no failure time was recorded.

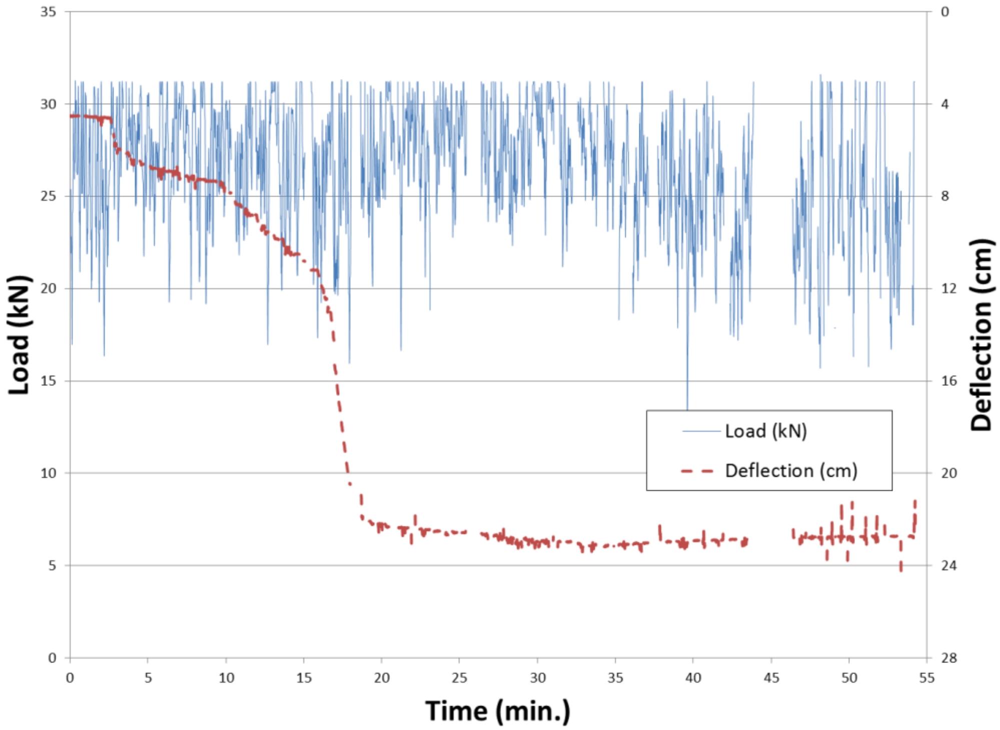


Figure 29 - 3-ply single surface spline load and deflection measurements

Throughout the test, there were significant difficulties in properly following the standard fire curve (Figure 30). Figure 31 and Figure 32 show the temperature profiles recorded throughout the CLT and at the junction of the half-lapped joint. The 300ºC isotherm was reached at 17.5 and 35 mm after 30 and 52 min, yielding a charring rate of 0.58 and 0.67 mm/min. No significant temperature rises were recorded at the 2nd glue line (70 mm) and at the joint interface, as shown in Figure 32.

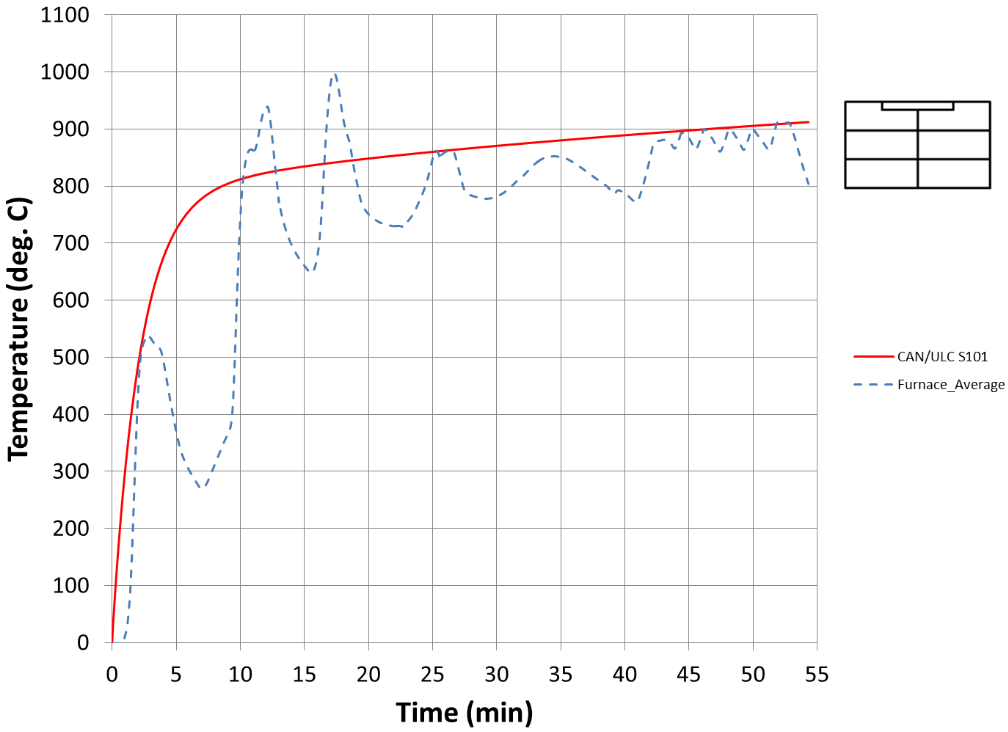


Figure 30 – Furnace temperature for the 3-ply single surface spline (average values)

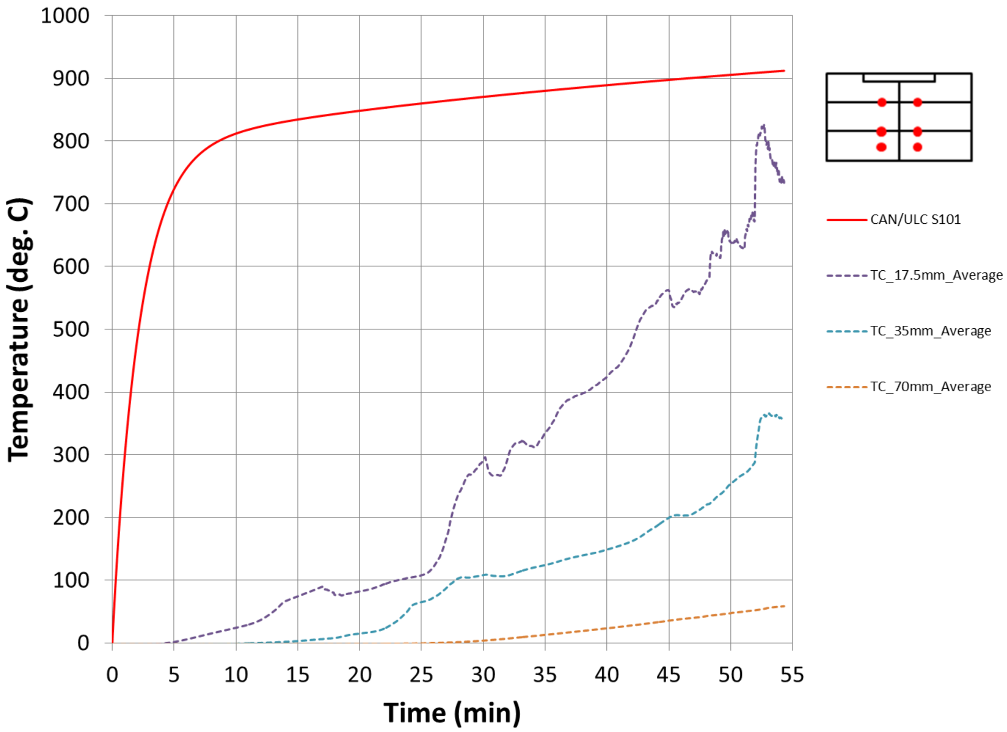


Figure 31 – Temperature profiles for the 3-ply single surface spline (average values)

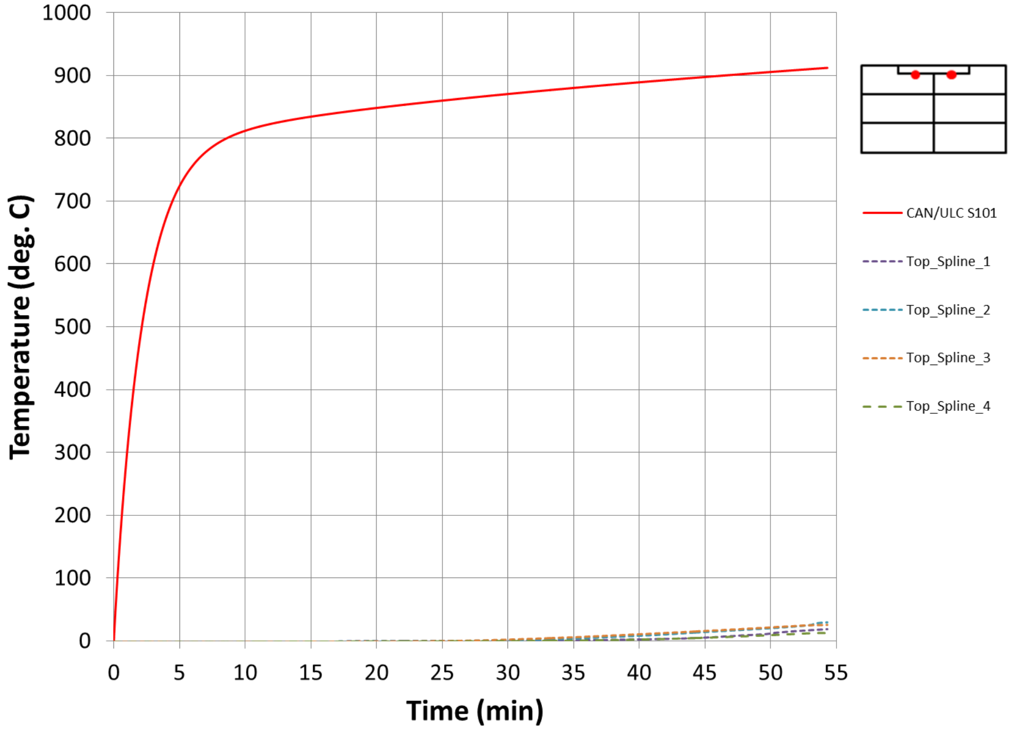


Figure 32 – Temperature profiles at the single surface spline of the 3-ply CLT

5.7 Single surface spline – 5 ply CLT

The 5-ply CLT with a single surface spline located at the unexposed (top) surface was conducted on February 17, 2015. The ambient conditions in the laboratory were -11ºC and 29% relative humidity. The outdoor temperature was -12ºC.

A load of 42 kN, representing a 55% loading condition determined from an initial 20 mm deflection was applied as shown in Figure 11. After roughly 98 min, it was decided to end the test due to laboratory equipment safety concerns (several burn-through locations occurred along the sides of the specimen). As such, no failure time was recorded.

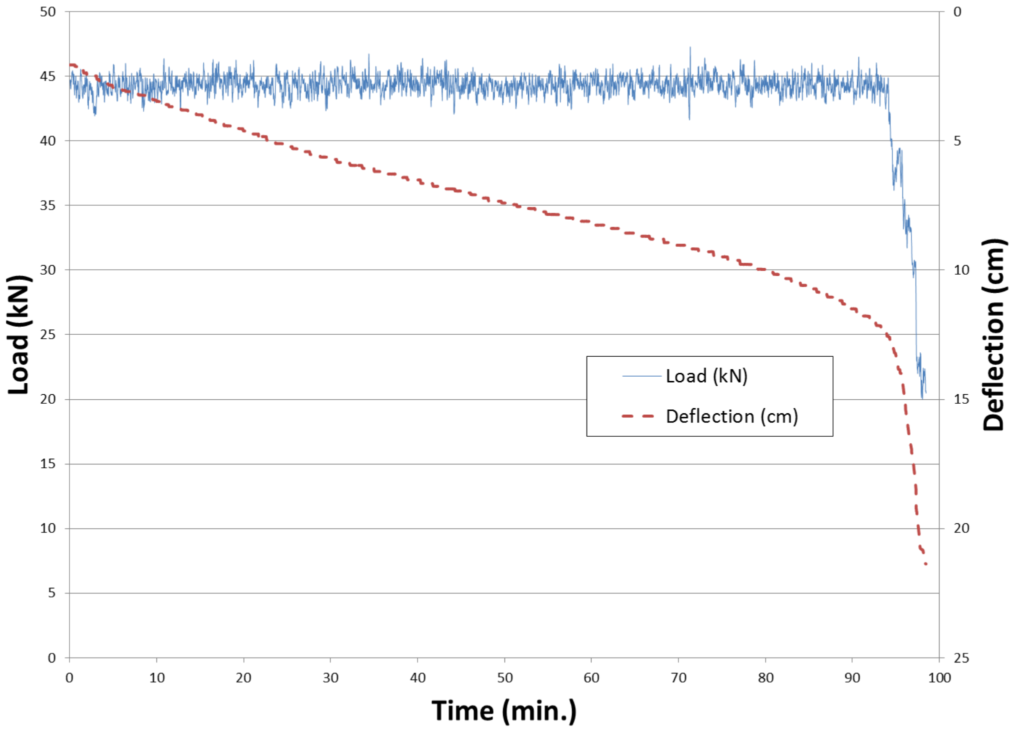


Figure 33 - 5-ply single surface spline load and deflection measurements

Figure 34 illustrates the temperature recorded inside the furnace during the test. It can be seen that the temperature was slightly lower in general but followed closely the standard curve. Figure 35 shows the temperature profiles recorded throughout the CLT and at the junction of the surface spline. The 300ºC isotherm was reached at 17.5 and 35 mm after 45 and 78 min, yielding a charring rate of 0.39 and 0.45 mm/min respectively. No significant temperature rises were recorded at the 2nd glue line (70 mm) and at the spline-CLT interface (thus not shown in Figure 35 beyond 70 mm).

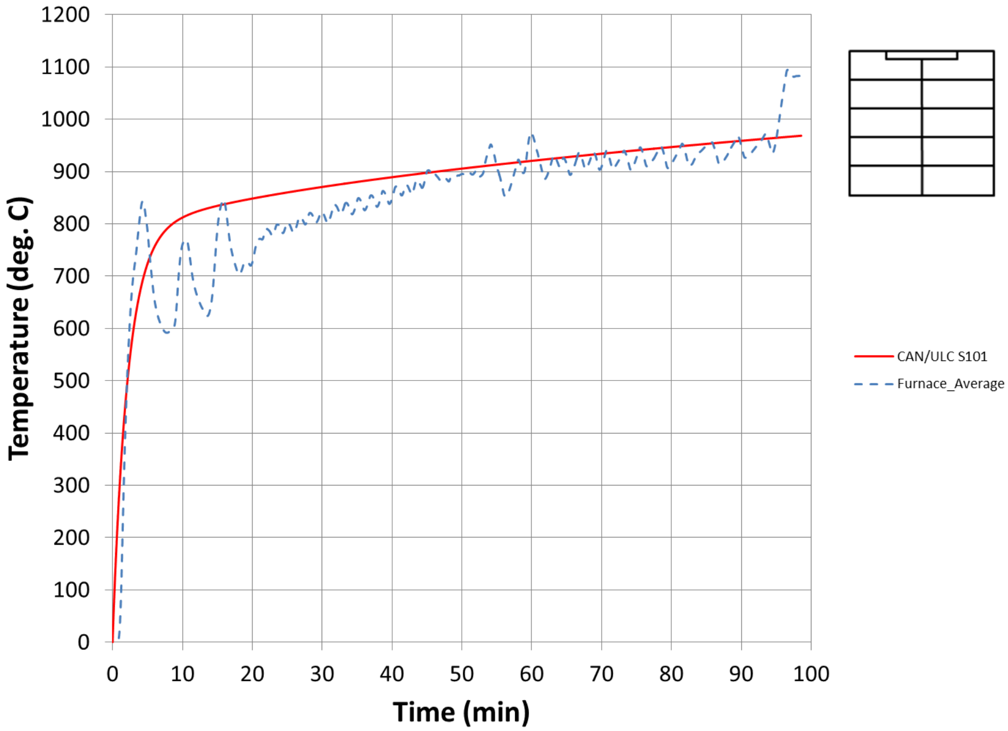


Figure 34 – Furnace temperature curve for the 5-ply single surface spline (average values)

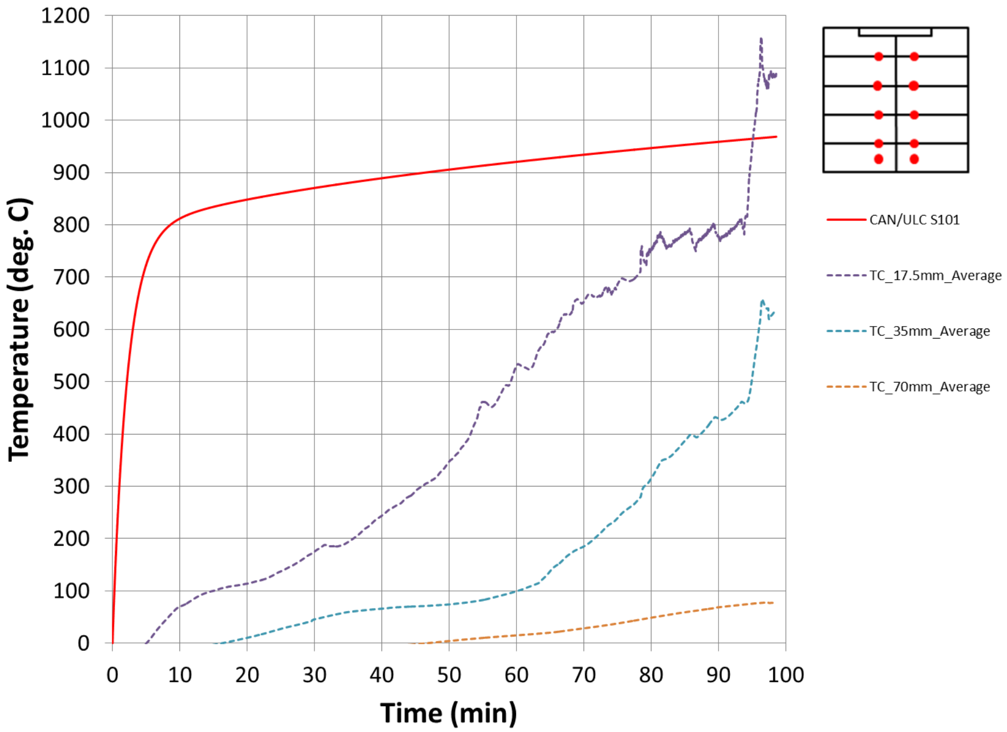


Figure 35 – Temperature profiles for the 5-ply single surface spline (average values)

5.8 Double surface spline – 3 ply CLT

The 3-ply CLT with double surface splines was tested on December 16, 2014. The ambient conditions in the laboratory were 3ºC and 75% relative humidity. The outdoor temperature was -2ºC.

A load of 32 kN, representing a full loading condition, was applied (Figure 36). The test continued until glowing at the surface (unexposed) was observed at the portion of the joint located between the spline and the CLT, close to a loading point, as shown in Figure 37. The test failure time was recorded as 43 min.

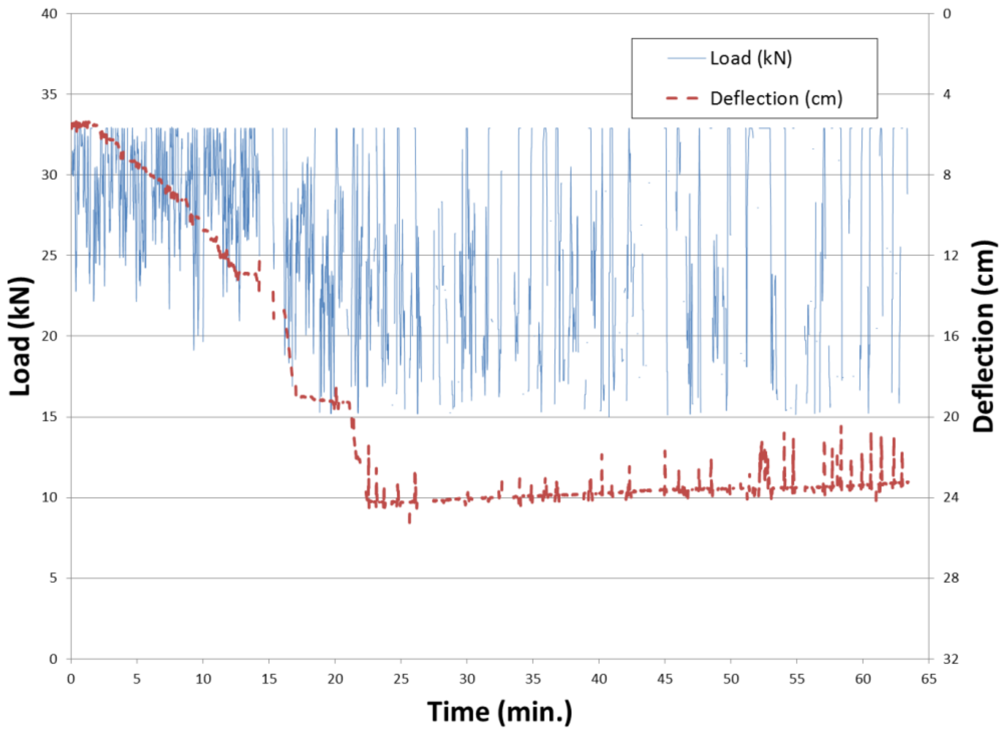


Figure 36 - 3-ply double surface spline load and deflection measurements

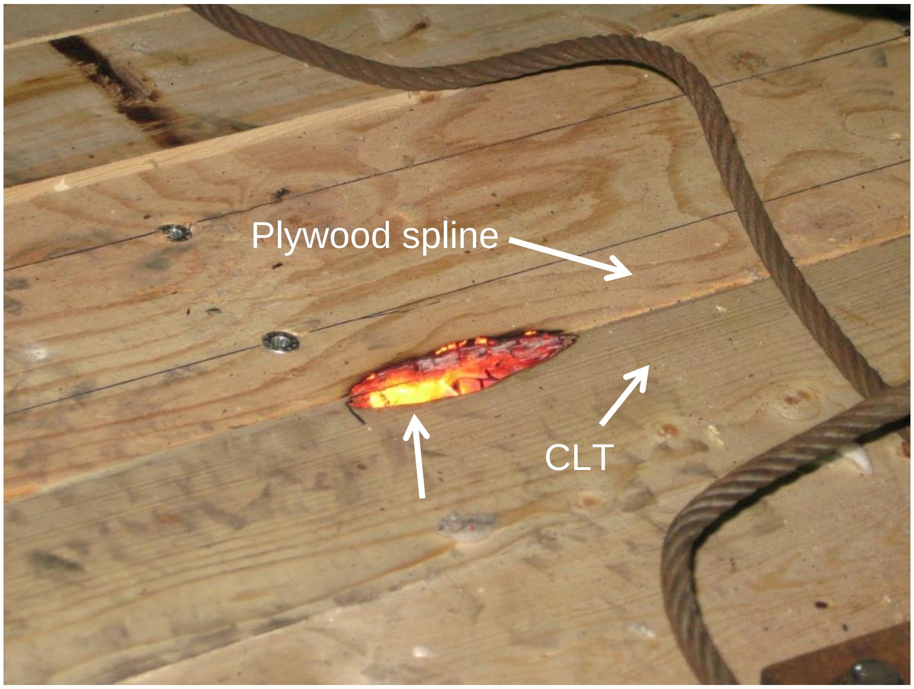


Figure 37 – Failure of the 3-ply double surface splines

There were difficulties in attempting to properly follow the standard time-temperature curve as shown in Figure 38. Figure 39 and Figure 40 show the temperature profiles recorded throughout the CLT and at the junction of the surface splines (top and bottom). The 300ºC isotherm was reached at 17.5 and 35 mm after 46 and 60 min, yielding to a charring rate of 0.38 and 0.58 mm/min. No significant temperature rises were recorded at the 2nd glue line (70 mm). The bottom spline reached 300ºC at 28 min. No significant temperature rise was recorded underneath the top surface spline.

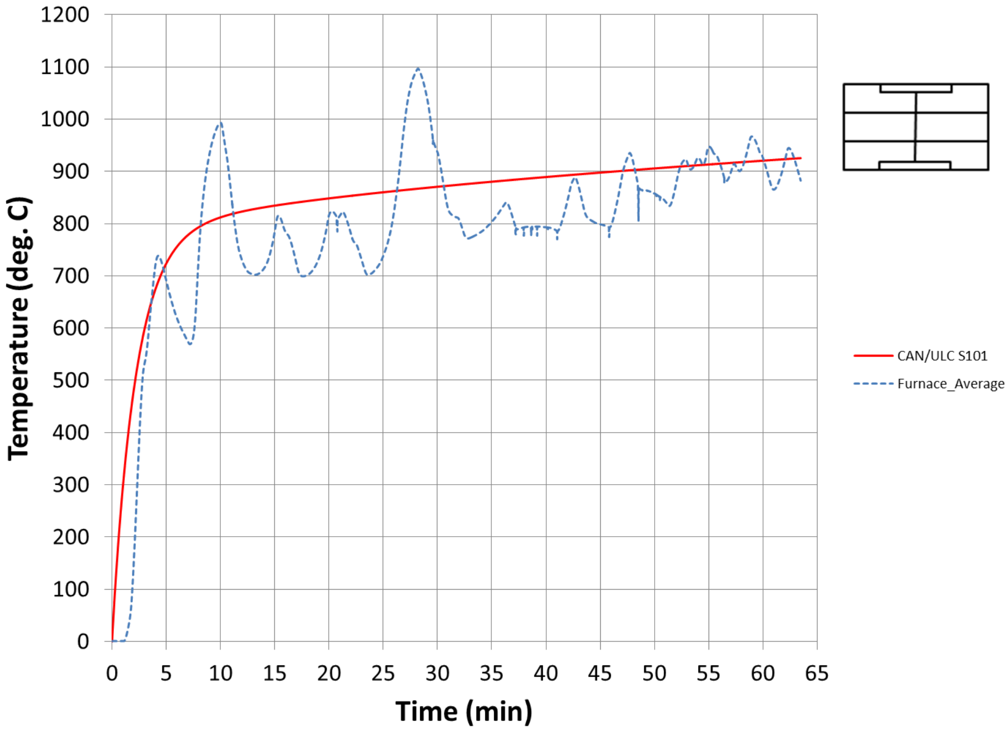


Figure 38 – Furnace temperature curve for the 3-ply double surface spline (average values)

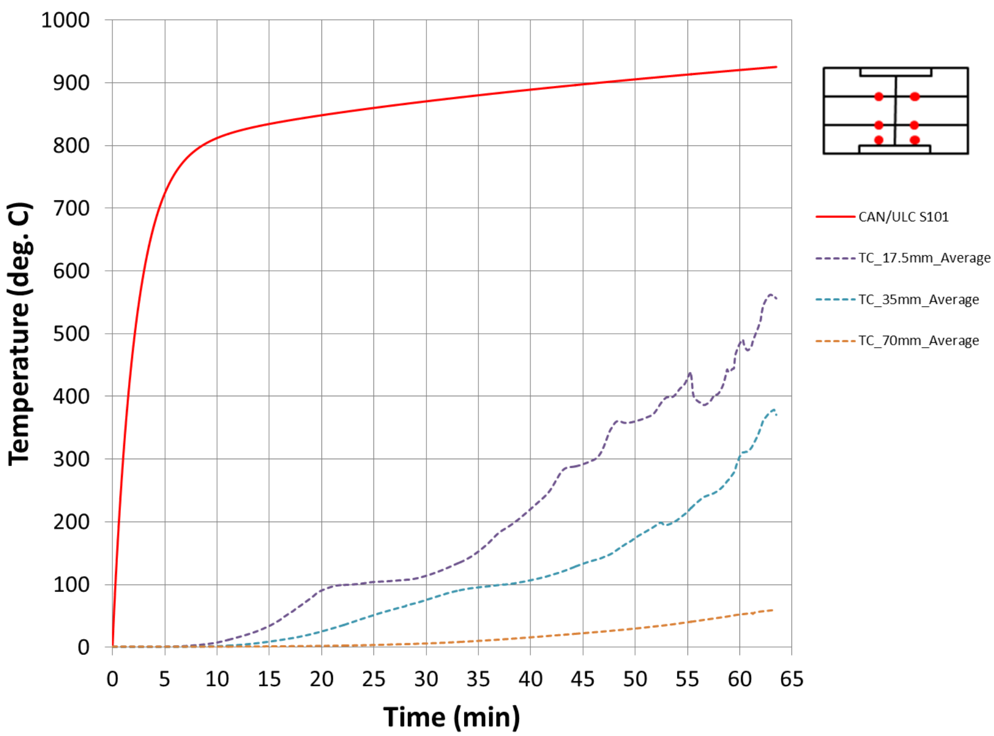


Figure 39 – Temperature profiles for the 3-ply double surface spline (average values)

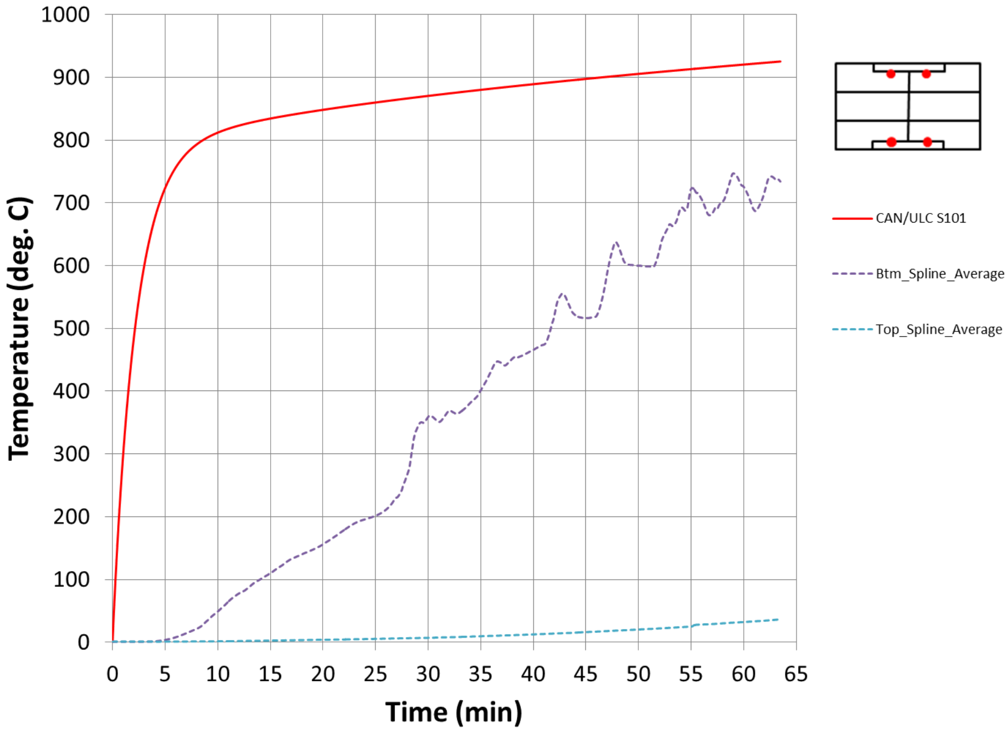


Figure 40 – Temperature profiles at the surface splines of the 3-ply CLT (average values)

5.9 Double surface spline – 5 ply CLT

The 5-ply CLT with double surface splines was tested on February 11, 2015. The ambient conditions in the laboratory were -5ºC and 30% relative humidity. The outdoor temperature was -14ºC.

A load of 42 kN, representing a 55% loading condition determined from an initial 20 mm deflection, was applied (Figure 41). After 90 min, it was decided to end the test due to laboratory equipment safety concerns (several burn-through locations occurred along the sides and ends of the specimen). However, it was noted that a small burn-through occurred close to the surface spline (but within the CLT, not at the joint interface) at 82 min as shown in Figure 42. The actual reason for this burn-through is unclear as it occurred at a distance from the panel-to-panel joint and close to an end support.

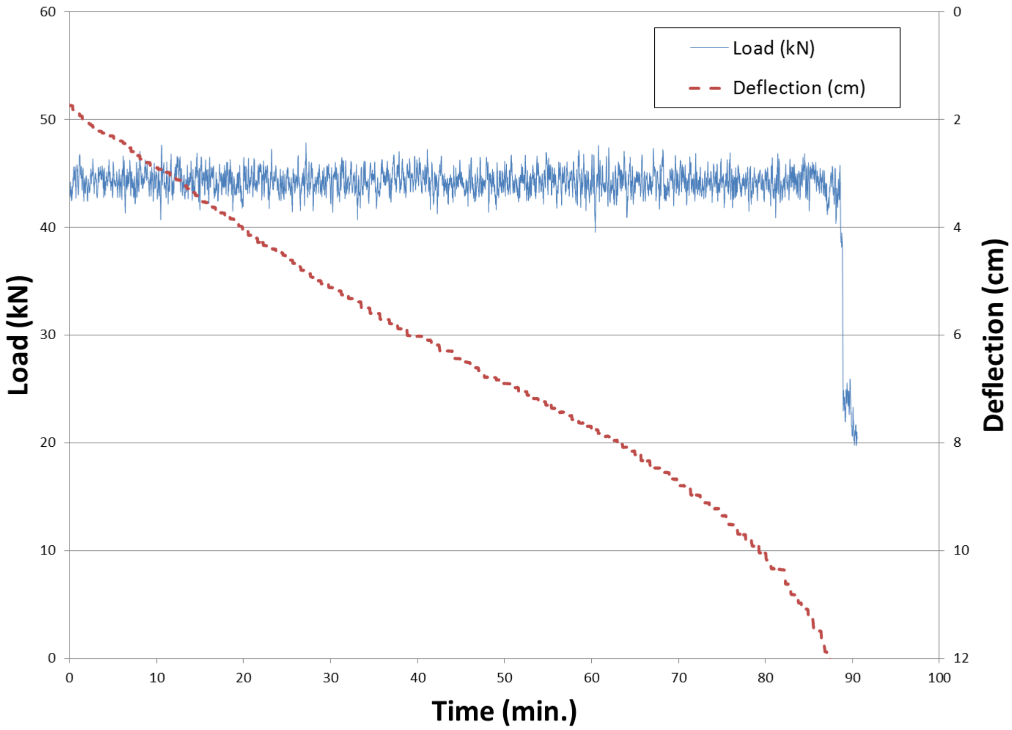


Figure 41 - 5-ply double surface spline load and deflection measurements

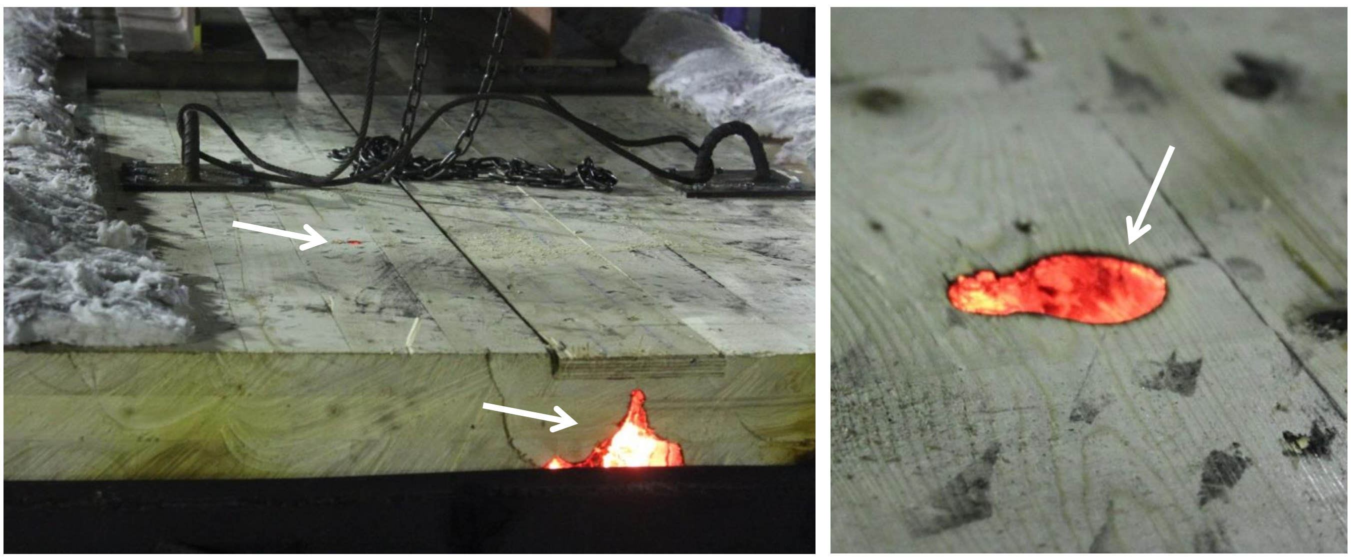


Figure 42 – Failure of the 5-ply double surface spline

The furnace temperature, although lower for most of the test as shown in Figure 43, accurately followed the standard time-temperature curve. Figure 44 and Figure 45 show the temperature profiles recorded throughout the CLT and at the junction of the surface splines (top and bottom). The 300ºC isotherm was reached at 17.5, 35 and 70 mm after 32, 43 and 89 min, yielding a charring rate of 0.55, 0.81 and 0.79 mm/min, respectively. No significant temperature rises were recorded at the 3rd glue line (105 mm) and beyond (thus not shown in Figure 44 and Figure 45 beyond 105 mm). The top of the bottom spline reached 300ºC at 25 min.

As mentioned previously, the reason for the failure time (82 min) is unclear since very little temperature rise was recorded at the 4th glueline (140 mm) (Figure 44) and none underneath the top surface spline (Figure 45).

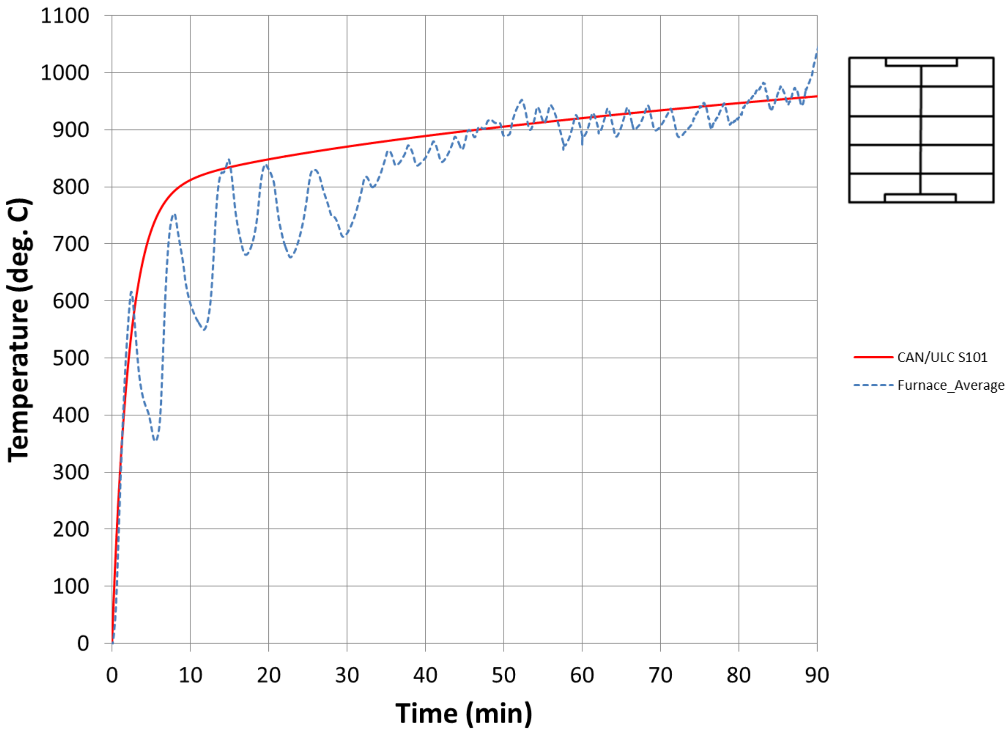


Figure 43 – Furnace temperature curve for the 5-ply double surface spline (average values)

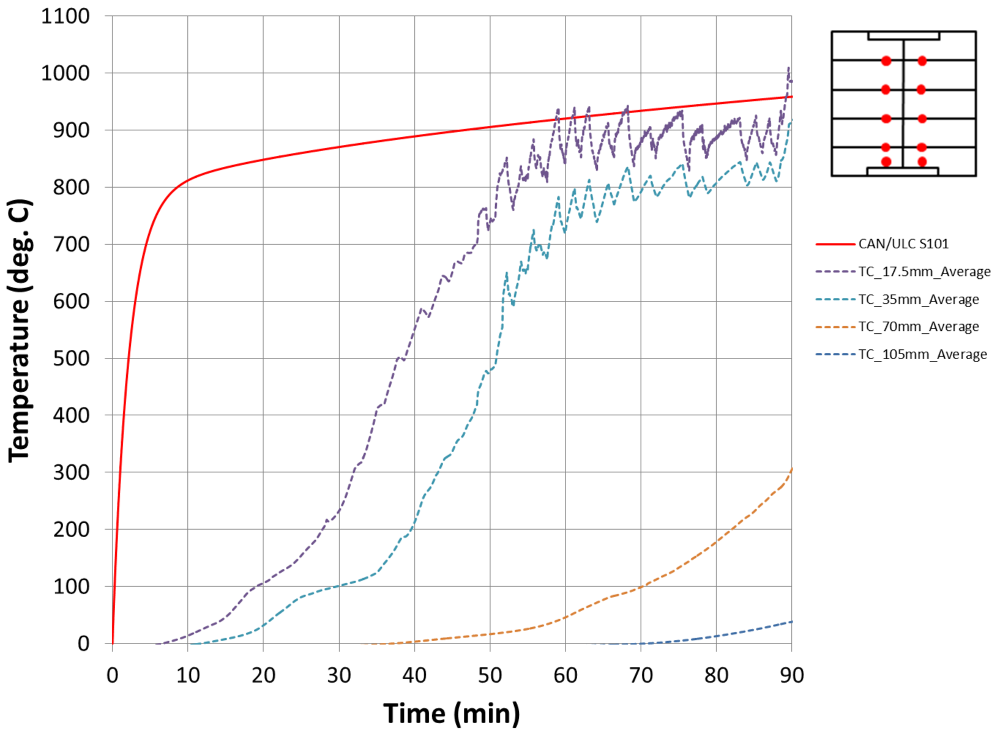


Figure 44 – Temperature profiles for the 5-ply double surface spline (average values)

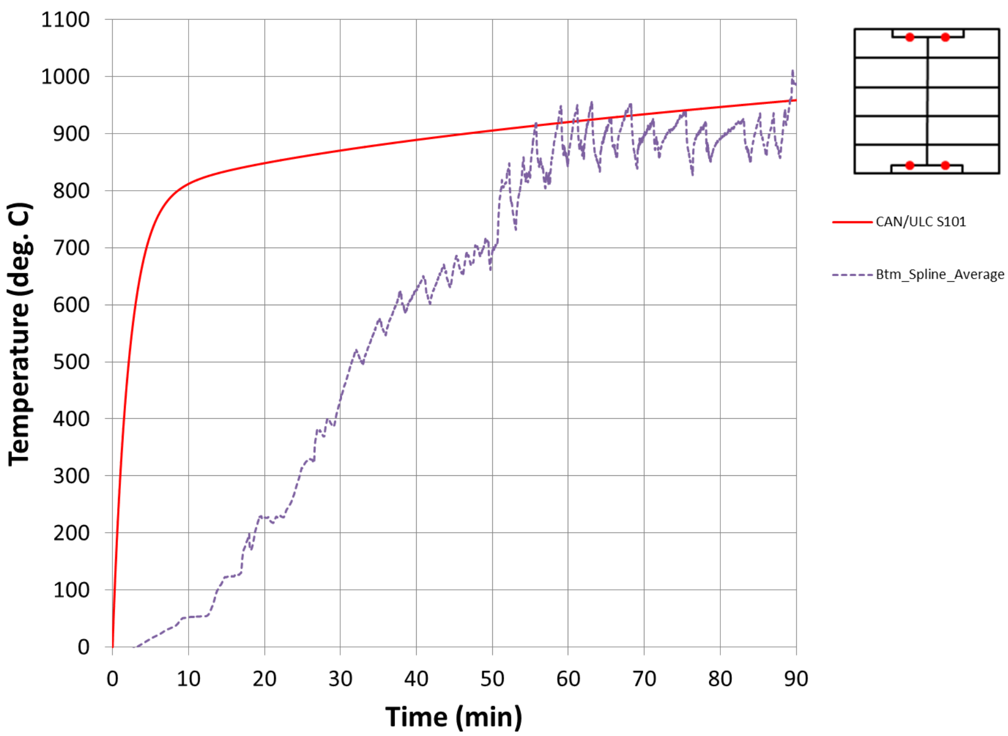


Figure 45 – Temperature profiles at the surface splines of the 5-ply CLT (average values)

5.10 Double surface spline – 7 ply CLT

The 7-ply CLT with double surface splines was tested on February 27, 2015. The ambient conditions in the laboratory were -7ºC and 27% relative humidity. The outdoor temperature was -16ºC.

A load of 50 kN, representing a 37% loading condition limited by the load cell capacity, was applied (Figure 46). Shortly after 180 min into the test, a loud sound was heard due to a structural failure. As such, it was decided to end the test due to laboratory equipment safety concerns. Several burn-through locations occurred along the sides and ends of the specimen. However, no burn-through was observed at the unexposed surface or next to the panel-to-panel joint. No failure time was recorded.

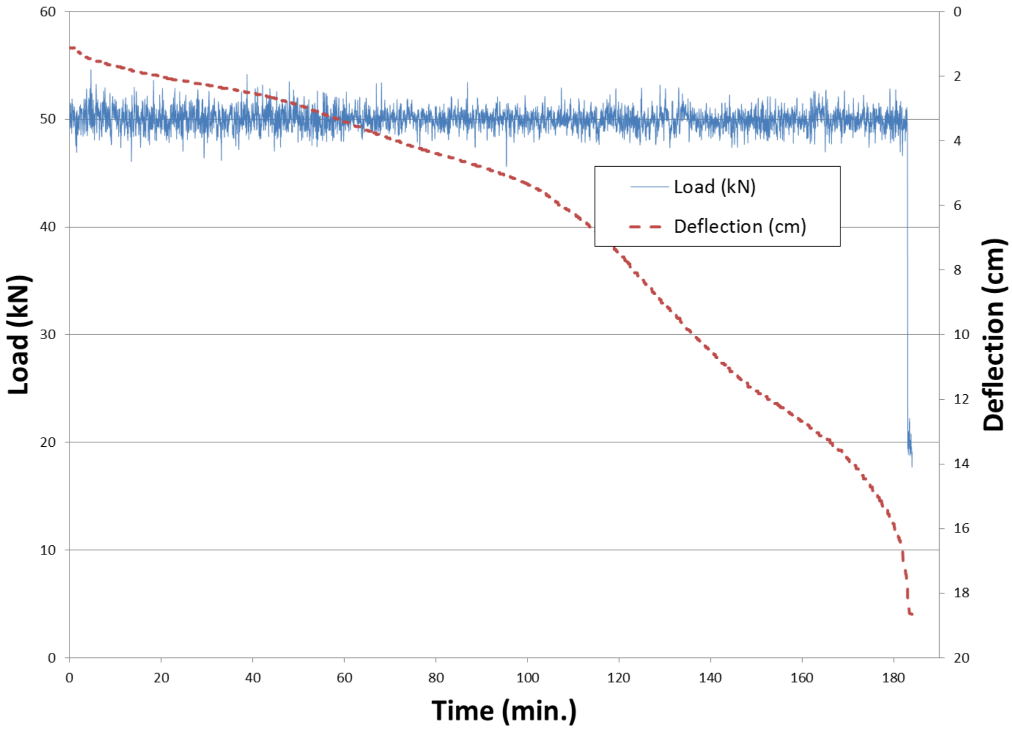


Figure 46 - 7-ply double surface spline load and deflection measurements

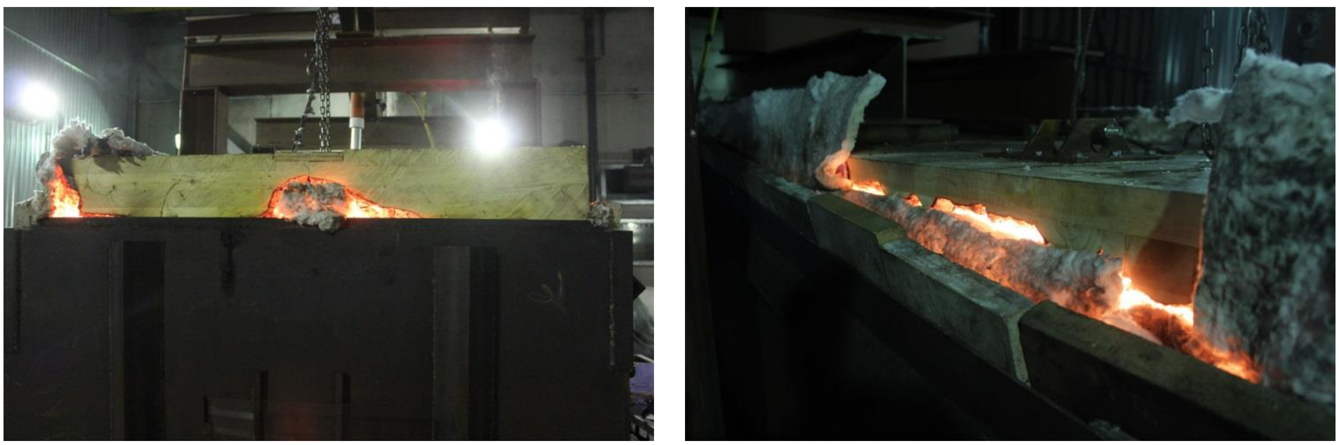


Figure 47 – Burn-through along the perimeter of the 7-ply double surface spline

The furnace temperature, although being lower in the early stage of the test, followed well the standard time-temperature curve(Figure 48). Figure 49 and Figure 50 show the temperature profiles recorded throughout the CLT and at the junction of the surface splines (top and bottom). The 300ºC isotherm was reached at 17.5, 35, 70 and 105 mm after 52, 51, 114 and 167 min, yielding to a charring rate of 0.34, 0.69, 0.61 and 0.63 mm/min, respectively. No significant temperature rises were recorded beyond the 3rd glue line (105 mm) and at the top surface spline (thus not shown in Figure 49 and Figure 50 beyond 140 mm). The top of the bottom spline reached 300ºC at 46 min.

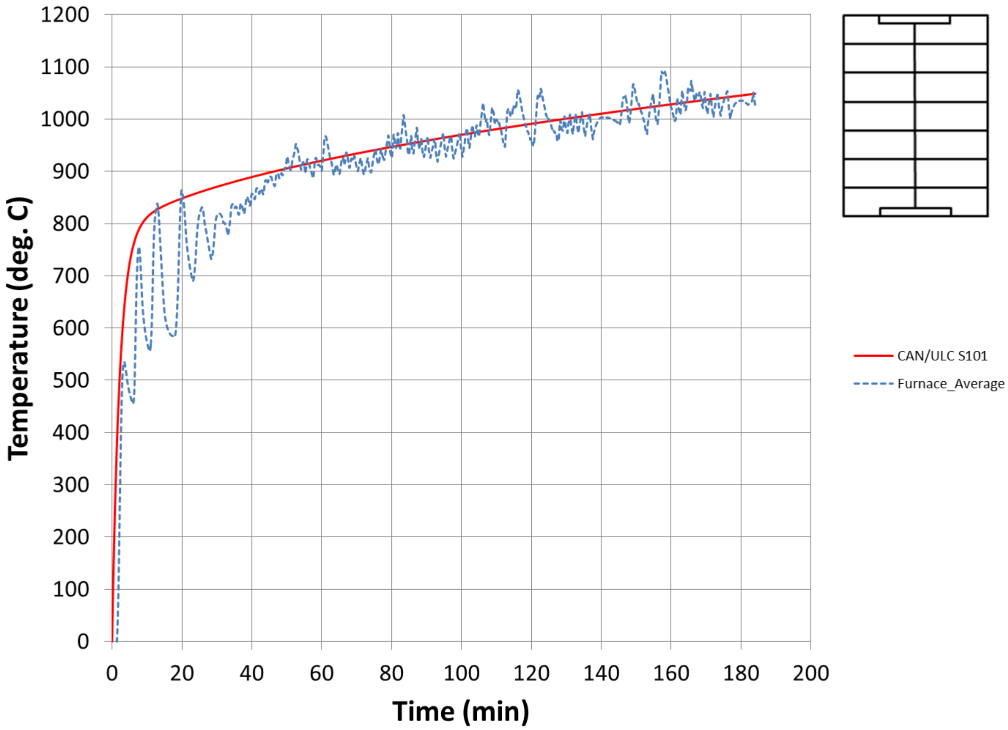


Figure 48 – Furnace temperature curve for the 7-ply double surface spline (average values)

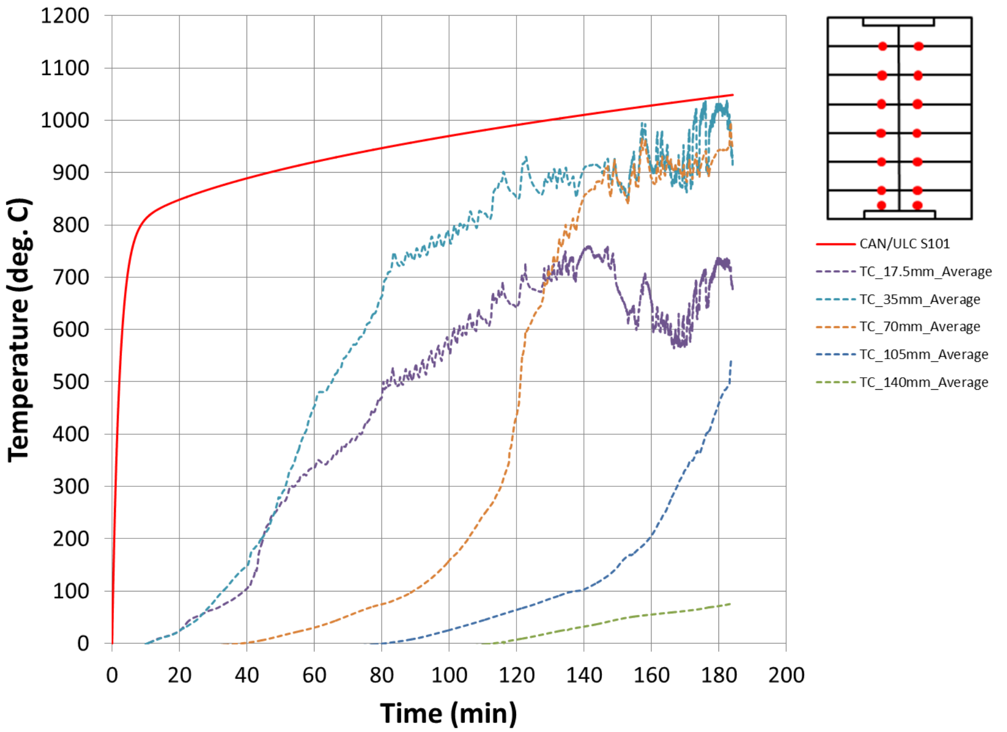


Figure 49 – Temperature profiles for the 7-ply double surface spline (average values)

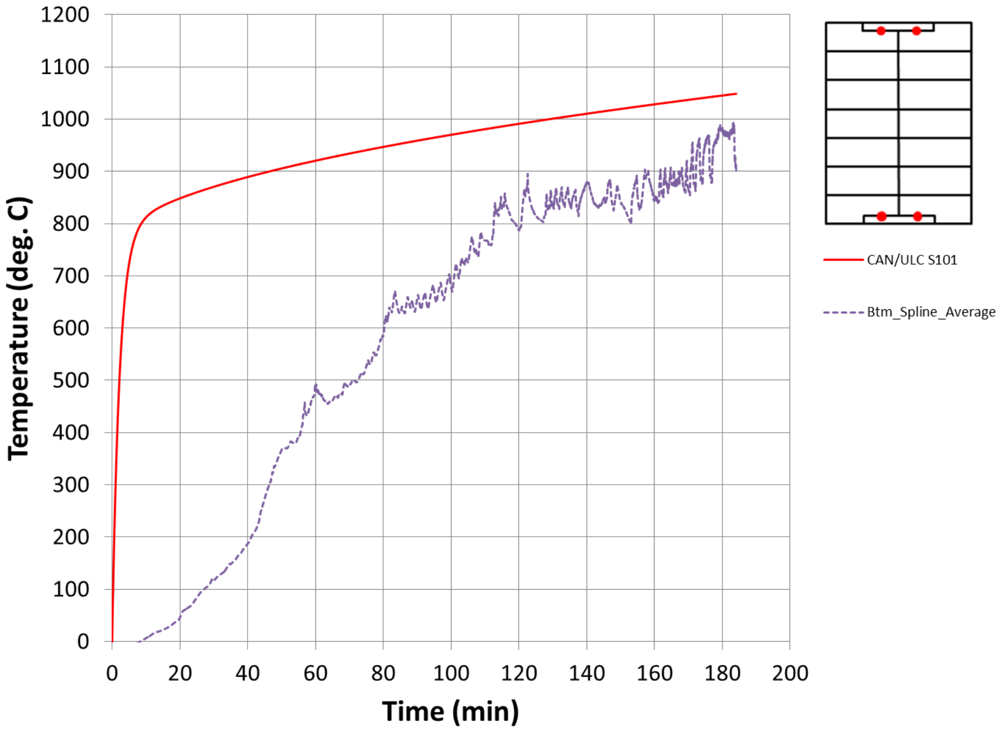


Figure 50 – Temperature profiles at the surface splines of the 7-ply CLT (average values)

6. DISCUSSION

As suggested in section 2 of this report, a panel-to-panel joint profile should provide sufficient fire-resistance provided the loss in depth of the reduced cross-section has not yet reached the spline or the half-lapped joint. The following subsections provide a discussion on the actual integrity failure models, as given in Equation (1) and Eurocode 5:1-2 which are detailed in section 2 of this report. A proposal for developing joint coefficients for other types of CLT panel-to-panel joints is also presented.

6.1 Half-lapped joint

According to Equation (1), an integrity failure of 56, 94 and 132 min would be predicted for a 3-ply, 5-ply and 7-ply CLT, respectively, manufactured with laminates of 35 mm. Eurocode 5:1-2 would predict failure times of 48, 81 and 113 min.

The test failure times observed in this series are 45, 98 and 140 min, which agree well with the predicted failure times and suggest that current models for predicting integrity failure are appropriate (provided the standard time-temperature is actually being closely followed, which was not the case for the 3-ply specimen).

6.2 Internal spline

The test failure times observed in this series were 35 and 76 min for the 3-ply and 5-ply specimens respectively. These times were much faster than the predicted 64 and 107 min using Eurocode 5:1-2. Except for the 3-ply specimen, of which no furnace temperature data is available, the 5-ply exhibited reasonable charring rates when compared to those suggested in the 2014 Chapter 8 of the CLT

Handbook. It is however unclear as to why the char front reached the spline quicker than at the 2nd glueline (70 mm). The spline is located at 78 mm from the exposed surface. According to Figure 27 and Figure 28, the char front reached the spline at 75 min while thermocouple readings at the 2nd glueline indicate a time of 85 min. Nevertheless, the burn-through failures obtained from both tests occurred where the spline was butt-jointed. A potential reason for such rapid burn-through may be due to the internal pressure within the furnace, forcing fresh air to flow into the CLT assemblies through relatively small gaps such as one that could be generated when butt-jointing plywood splines.

It can be demonstrated, by engineering analysis, that the European joint coefficient value of 0.4 is appropriate, even though the current two tests do not correlate (probably due to spline butt-joints not being tightly fitted). According to the stepped charring model detailed in the CLT Handbook, a laminate of 35 mm thick would be expected to initiate fall-off after 43 min of standard fire exposure (which is consistent with rates observed from the 5-ply specimen where the char front reached the 2nd glueline at 85 min). Given the joint configuration, 8 mm of the CLT is provided underneath the plywood spline, which would char within 8 min. Eurocode 5:1-2 assigns a charring rate of 1.0 mm/min for plywood of 20 mm with a characteristic density of 450 kg/m³. It is thereby assumed that an 18.5 mm plywood spline would char within 18 min. Assuming that there are no air gaps between the splines, the sum of the time afforded by each layer would yield a failure time of 69 and 112 min for a 3-ply and 5-ply CLT, respectively.

Equation (1) used with a joint coefficient of 0.4 would yield in similar predictions (64 and 107 min).

6.3 Single surface spline

As reported in subsections 5.6 and 5.7, no failure times were recorded for CLT specimens joined together with a single surface spline. There is also no joint coefficient assigned to this configuration in the publicly-available literature.

The 3-ply CLT specimen was allowed to burn for 54 min, at which time the char front had reached the 1st glueline (35 mm). The temperatures at the 2nd glueline (70 mm) and at the interface underneath the surface spline were 58ºC and 25ºC respectively at this time. Using the engineering approach detailed in subsection 6.2, the stepped charring model would predict a time of 102 min for the char front to reach the spline interface (2 layers of 35 mm and a remaining 16 mm in the 3rd ply).

The 5-ply CLT specimen was allowed to burn for 98 min. At that time, the temperature recorded at the 2nd glueline (70 mm) was 78ºC. No temperature rise was recorded at the joint interface underneath the top spline. These very low temperature measurements suggest that the specimen could have lasted much longer. Using the same engineering approach detailed in subsection 6.2, the stepped charring model would predict a time of 188 min for the char front to reach the spline interface (4 layers of 35 mm and a remaining 16 mm in the 5th ply).

Equation (1) used with a joint coefficient of 0.6 would yield in similar predictions (97 and 161 min). It is noted that Eurocode 5:1-2 assigns a joint coefficient of 0.6 to double tongue-&-groove spline between 2 adjacent wood-based panels.

6.4 Double surface spline

The test failure times observed in this series were 43, 82 and more than 180 for the 3-ply, 5-ply and 7-ply CLT specimens respectively. There is also no joint coefficient assigned to this configuration in the publicly-available literature.

The 3-ply CLT specimen was allowed to burn for 43 min. At that time, the char front reached the 1st glueline (35 mm); the temperature at the 2nd glueline (70 mm) and at the interface underneath the top spline were 59ºC and 36ºC respectively. These very low temperature measurements suggest that the specimen could have lasted much longer. Using the engineering approach detailed in subsection 6.2, the stepped charring model would predict a time of 93 min for the char front to reach the spline interface (plywood spline, 2 remaining 16 mm for the 1st and 3rd plies and 35 mm for the middle ply).

The 5-ply CLT specimen was allowed to burn for 90 min. At that time, the char front reached the 2nd glueline (70 mm) and the temperature at the 3rd glueline (105 mm) was 4ºC. No temperature rise was recorded at the joint interface underneath the top spline. These very low temperature measurements suggest that the specimen could have lasted much longer. Using the engineering approach detailed in subsection 6.2, the stepped charring model would predict a time of 179 min for the char front to reach the spline interface (plywood spline, 2 remaining 16 mm for the 1st and 5th plies and 3 layers of 35 mm for the 2nd to 4th plies).

The 7-ply CLT specimen was allowed to burn for more than 180 min. At 180 min, the char front reached the 3rd glueline (105 mm) and the temperature at the 4th glueline (140 mm) was 76ºC. No temperature rise was recorded at the joint interface underneath the top spline. These very low temperature measurements suggest that the specimen could have lasted much longer. Using the engineering approach detailed in subsection 6.2, the stepped charring model would predict a time of 265 min for the char front to reach the spline interface (plywood spline, 2 remaining 16 mm for the 1st and 7th plies and 5 layers of 35 mm for the 2nd to 6th plies).

It is suggested that a similar joint coefficient to the single surface spline be used (K_j = 0.6) for the double surface spline configuration. As such, Equation (1) used with a joint coefficient of 0.6 would yield predictions of 97, 161 min and 226 min for 3-ply, 5-ply and 7-ply CLT of 35 mm laminates, respectively. The advantage from using a double surface spline as opposed to the single surface spline would an improved in-plane shear resistance of CLT floor diaphragm or shearwall assemblies.

7. CONCLUSION AND RECOMMENDATIONS

During full-scale fire testing of CLT assemblies, it has been shown that integrity seems to be the predominant failure mode of CLT floor assemblies under load (i.e. flaming through the CLT panel-to-panel half-lapped joint). This type of failure mode was not observed in CLT wall test assemblies under load. Integrity is one of the two requirements of the separating function of building assemblies (insulation being the other requirement). The time at which the CLT panel-to-panel joint can no longer prevent the passage of flame or gases hot enough to ignite a cotton pad defines its integrity fire resistance.

So far, only half-lapped joints have been evaluated in full-scale fire tests where the joint was located at mid-depth of the CLT panels and overlapped for at least 64 mm. However, connection details of CLT assemblies may also consist of other configurations such as single or double surface splines or internal spline(s). These tightly fitted joint profiles should provide sufficient fire-resistance provided the loss in depth of the reduced cross-section has not yet reached the spline. It was the objective of this study to evaluate the fire performance of these joint details and to provide recommendations to develop a joint coefficient (K_j) for use in a simple equation such as that provided in the 2014 Chapter 8 of the Canadian CLT Handbook.

A total of ten CLT specimens were tested using different panel-to-panel joint details. The testing took place at Carleton University Fire Research Facilities. The CLT specimens were of the E1 stress grade conforming to ANSI/APA PRG-320 standard and were fastened together using self-tapping screws. Except for the half-lapped joint configuration, all other panel-to-panel joints required the use of plywood splines to securely fasten the CLT panels together. All joint assemblies were sealed using a bead of intumescent firestop sealant to prevent smoke leakage.

Eight failure times were recorded and compared to predictions using analytical models such as the CLT Handbook and Eurocode 5:1-2. From the failures times, it can be shown that current models accurately predict the integrity failure. Based on engineering analysis and the stepped charring model of the CLT Handbook, joint coefficients for the single and double surface spline configurations have been developed.

Based on the test data, joint coefficients of 0.35 for a half-lapped joint located at mid-depth, 0.40 for a plywood internal spline at mid-depth and 0.60 for the single and double surface splines are recommended. It is noted that a more in-depth analysis could involve specifying a minimum thickness that would enable fasteners to continue developing withdrawal and/or lateral resistance. This would yield potentially lower joint coefficient values. Modeling the behaviour of these joints using a transient finite element thermal model could also be useful to support the engineering approach based on the stepped charring model. Further testing of CLT panel-to-panel joints is required.

Lastly, the effect of floor covering and/or topping has not been evaluated in this study. It is anticipated that using floor covering materials such as a concrete topping would limit the passage of flames and hot gases and the joint coefficient may be taken as unity, as suggested in Eurocode 5:1-2.

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