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FIRE RESISTANCE TESTS AND CHARRING RATES IN AUSTRALIAN PLANTATION *Eucalyptus Nitens* CROSS-LAMINATED TIMBER FLOORS

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ABSTRACT: Australia is home to extensive *Eucalyptus nitens* plantations. However, this timber species has yet to be widely utilised for structural purposes. Significant research has taken place in Australia to assess the potential of E. nitens in the production of Cross-Laminated Timber (CLT). While structural performance has been studied under ambient conditions, further research is needed on the fire resistance and charring rates of plantation E. nitens CLT floors. In this study, both small-scale and full-scale tests following AS 1530.4 were conducted to address the knowledge gap regarding E. nitens CLT floor panels. Additional instrumentation was installed in the specimens to determine charring rates, charring depths, and heated sections. The loaded CLT floors tested in the furnace achieved a fire resistance level (FRL) of 120 minutes (REI 120). The char development was described based on the analysis of in-depth thermocouples and residual cross-sections after the tests. The study presents the results of the fire tests and the accompanying numerical models that enable the prediction of the bending capacity of E. nitens CLT when applied to various geometries and loading conditions. By leveraging this knowledge, performance-based design solutions can be developed for various applications, such as for the first mass timber building erected in Tasmania, using E. nitens CLT floors.

KEYWORDS: CLT Floors, fire resistance, charring rates, Eucalyptus nitens, Tasmania.

1 – INTRODUCTION

Eucalyptus nitens (E. nitens) stands as a prominent plantation timber species in Australia, widely utilised for pulp and woodchip export. Its exceptional strength and stiffness have captured the interest of the structural timber sector in applications such as glued-laminated timber (glulam) and cross-laminated timber (CLT) [1]. Some Australian companies have commenced the production of commercial glulam and CLT building components using Tasmanian plantation E. nitens to satisfy the increasing demand for structural timber products in the Australian building market [2]. Despite extensive research into the structural properties, prefabrication methods, and connections, further exploration into the structural fire performance of plantation E. nitens requires consideration for the commercial application of this timber species in large timber structures, where fire safety relies on the structural integrity of the timber building.

Traditionally, CLT has been made from softwood timber species like spruce in Europe and pine in Australia. Numerous studies have been conducted on these species to understand their charring rates, thermal penetration, and structural integrity. The charring rate for solid and glued-laminated softwood timber species under one-dimensional standard fire exposure is usually assumed to be 0.65 mm/min, as described in Eurocode 5 [3]. Several authors have reported charging rates after exposing CLT glued with different types of adhesives (heat resistant vs. non-heat resistant) floors for 90 minutes to a standard furnace test. For example, Friquin et al. (2010) reported that the charring rates for spruce CLT exposed to standard and parametric fires vary between 0.55 – 0.67 mm/min. Klippel et al. (2014) reported that CLT made of Lodgepole pine presented a charring rate of 0.74 mm/min [5]. Klippel et al. (2018) also noted that the average charring rates for several European CLT panels glued with heat-resistant adhesives with different configurations tested up to 90 minutes were lower than 0.65 mm/min [6]. Van der Westhuyzen et al. (2019) conducted several fire resistance tests on South African pine and eucalyptus CLT. This study is one of the first to report charring rates for hardwood CLT. It demonstrated that the average charring rate for the South African pine CLT and eucalyptus CLT panels was 0.95 mm/min and 0.76 mm/min, respectively [7]. These findings indicate that while softwood CLT has been extensively researched in furnace tests, there is limited evidence regarding the charring rates and thermal penetration of

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CLT floors made from plantation hardwood timber species.

In Australia, fire resistance and charring rates shall be determined according to standard fire tests described in AS 1530.4:2014 [8], which establish building products to maintain structural adequacy, integrity, and insulation for the targeted Fire Resistance Level (FRL). Although FRL is a critical parameter for structural systems to comply with the National Construction Code of Australia [9], understanding charring rates and thermal penetration within timber is also critical for assessing fire performance and ensuring the fire safety of a structural timber element in a building. When these parameters are known, a performance-based assessment of timber structures can be developed to predict the fire resistance of timber elements in various scenarios that may differ from those tested according to the standard. These parameters are also essential for demonstrating adequate safety of timber structures beyond the relatively limited Deem to Satisfy (DtS) solutions.

A series of fire tests and modelling at different scales was performed to understand the fire performance of E. nitens CLT. This series of tests included studying the charring rates, thermal penetration, and bending capacity of small CLT specimens exposed to different constant heat fluxes, which could represent a fire exposure similar to that of standard furnace tests. These tests provided the details required to model full-scale samples' performance before being tested at a larger scale. Using the data collected in the small-scale testing and the results of the models, full-scale testing following AS 1530.4 was carried out to calculate charring rates, fire resistance level (FRL), and span tables for different panel configurations and load cases.

Another critical aspect of large-scale tests was understanding the fire performance of E. nitens CLT joints. Two types of lap joints were included in the large-scale tests. One joint was tight with no gaps between the timber panels, while the other was a tolerance joint, where gaps were intentionally left between the panels. An intumescent fire-rated tape was placed in the joint to fill the gaps left in the construction. This type of joint aims to accommodate the expected occurrence of these gaps in the construction of CLT floors.

The data obtained from the standard fire test is critical for engineers, designers, and building certifiers in predicting and validating the structural fire performance of CLT panels. This data provides the tools for further modelling these panels' structural fire behaviours in different scenarios. It will give a good understating of the performance of the joints in a full-scale test and provide evidence to building designers and certifiers of the system's behaviour. It will also pave the way for incorporating plantation eucalyptus species in future mass timber buildings in Australia. Notably, this knowledge was instrumental in constructing the first mass timber building in Tasmania, Australia, which utilised approximately 500 m^2 of E. nitens CLT.

2 – MATERIALS AND TEST METHODS

2.1 SMALL-SCALE HEAT PANEL TESTS

Six CLT panels made from Australian E. nitens hardwood and a non heat-resistant one-component polyurethane (1C-PUR) adhesive, each measuring 1200 mm by 300 mm by 125 mm and comprising five layers (with each layer having a thickness of 25 mm), were tested under a constant radiative heat flux from below. The average density of the panels was 600 kg/m^3, with an average moisture content of 10.3%. The panels were subjected to constant heat fluxes of 50 and 90 kW/m^2 for 90 minutes (three specimens for each heat flux level) over a 400 mm by 300 mm area, as shown in Figure 1. Twelve thermocouples, positioned at various depths from the exposed side (5, 12.5, 20, 25, 30, 40, 45, 50, 55, 65, 75, and 100 mm) along the cross sections, were installed in each panel to gauge temperature profiles at differing depths. The thermocouples had a stepped hole diameter of 2 mm, which was reduced to 1.5 mm for the final 8 mm of the length of the hole and was arranged in a circular pattern with minimal spacing between adjacent thermocouples to minimise measurement interference and the impact of spatial variability of the timber.

Figure 1. Small-scale fire tests on E.nitens CLT (Wiesner, 2020).

2.2 FULL-SCALE FURNACE TESTS

2.2.1 Standard fire tests of CLT

Two E. nitens CLT panels, measuring 2950 mm by 4325 mm, underwent testing following the standard furnace test specified in AS 1530.4:2014 [8]. The panels were 175 mm and 225 mm thick (equivalent to 7 and 9 layers of 25 mm each) and were subjected to uniformly distributed loads of 4 and 8 kPa, respectively, as illustrated in Figure 2.

Figure 2. Experimental set-up for the standard fire tests as per AS 1530.4:2014 in E. nitens CLT panels.

The two outermost layers of the panels were oriented in the same direction to increase their capacity in the longitudinal (main load-bearing) direction. The average density of the panels was 607 and 590 kg/m^3, with an average moisture content of 7.3 and 7.4%, respectively. In addition to the standard instrumentation required per AS 1530.4:2014, the panels were fitted with extra in-depth thermocouples to measure temperature profiles and determine charring rates. Internal temperatures were determined using Type K thermocouples of 1.5 mm diameter, installed by drilling 2.0 mm holes for each depth. Cotton pads and gap gauges were available to assess integrity criteria during the tests. Figures 3 and 4 display the panel measurements and test setups before the commencement of the test.

2.2.2 Joint characteristics

Two different types of half-lap joints were tested in each system and scenario. One joint was a tight fit where timber panels touched each other, with a weathertight sealing tape applied to the unexposed surface of the joint. The other joint allowed a small gap between the panels to accommodate dimensional tolerances during construction. This type of joint featured a 3-4 mm gap in the top and bottom steps of the lap joint, and an intumescent fire tape was placed in the horizontal section of the joint. A flexible intumescent fire stripe of 10 mm x 2 mm (FIRESTRIPE10 from Rothoblaas) was installed in the 175 mm panel, while a fire intumescent seal of 20 mm x 2.5 mm (PROMASEAL PL-SK 2.5 from Promat) was used in the 225 mm panel. Fire-rated sealant was also used at the end of the joint to prevent air entrainment to the furnace at the location of the joints. A weathertight sealing tape was also fitted on the unexposed surface to cover the joint and limit oxygen entrainment. The joint had a lap length of 55 mm for both panels, positioned 112 mm from the exposed face. Consequently, for the 225 mm panels, the lap was situated precisely at half the thickness of the panel. However, for the 175 mm panel, the lap was not located at half the thickness, as there was a necessity to protect the joint from the char progression. Figures 3 and 4 illustrate the details of the joints for both tests.

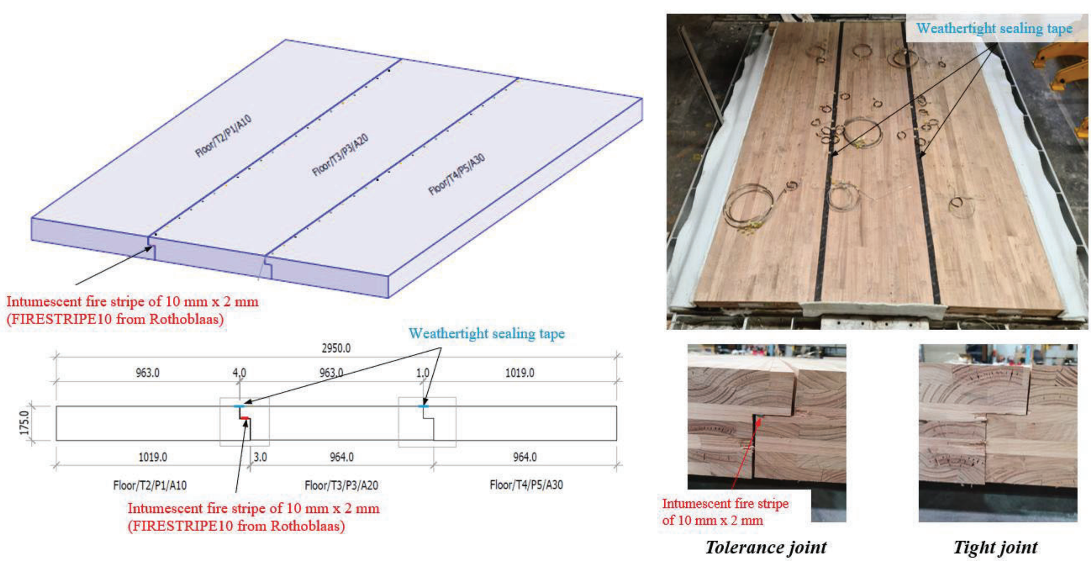

Figure 3. CLT measurements and cross-sections for the 175 mm panel (7-layer) before the standard test.

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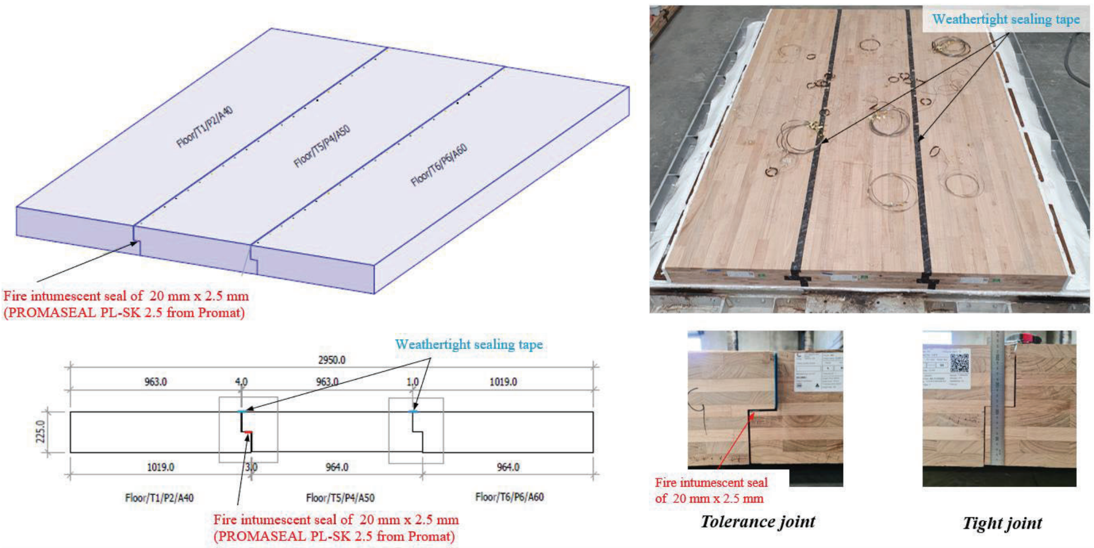

Figure 4. CLT measurements and cross-sections for the 225 mm (9-layer) panel before the standard test.

3 – RESULTS AND ANALYSIS

3.1 SMALL SCALE HEAT PANEL TESTS

3.1.1 Temperature Profiles

The test results presented in the paper focus on the results of 90 kW/m^2 of heat exposure, as this exposure provides energy similar to those received by surfaces after 90 minutes of exposure in a furnace test [10]. However, this approach merely compares the total incident energy input between the two test methods. In reality, the heat transfer processes within the furnace and due to the radiant exposure are considerably more complex. Temperatures were recorded over a duration of 90 minutes, which corresponds to the test length.

Figure 5 presents the temperature measurements for all specimens exposed to a constant heat flux of 90 kW/m^2. These temperature measurements were used to calculate the charring rate from the position of the 300 ºC isotherm, which was used to determine char depth and average charring rate.

Figure 6 illustrates the temperature profiles in the CLT cross-section after 90 minutes of exposure with a constant heat flux of 90 kW/m^2. All panels experienced char fall-off throughout the testing, which caused localised flaming in freshly exposed timber. The start of char fall-off was observed between 20 and 41 minutes of exposure. However, large pieces of char fell between 40 and 45 minutes of exposure, coinciding with the char and heat front reaching the first bondline.

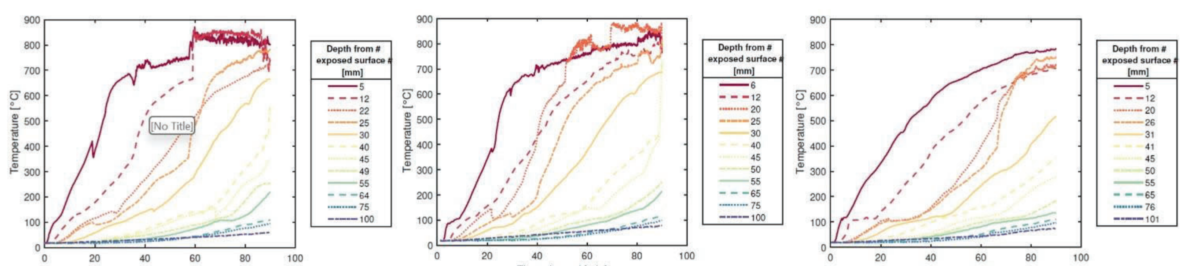

Figure 5. Temperature measurements for small-scale specimens subjected to a constant heat flux of 90 kW/m^2 (Wiesner,2020).

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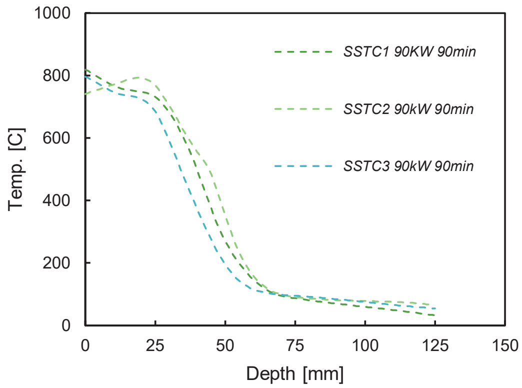

Figure 6. Temperature profile for samples tested to a constant heat flux of 90 kW/m^2 after 90 minutes of exposure.

3.1.2 Charring rate

Figure 7 illustrates the char depths recorded throughout the test duration for heat flux levels of 50 and 90 kW/m². The average charring rates for specimens exposed to 90 kW/m² after 90 minutes of exposure were measured at 0.53, 0.53, and 0.47 mm/min [11]. The plots in Figure 7 indicate that some of the slope changes may be related to charring layer fall-off during the tests. These preliminary results suggest that the charring rates are significantly lower than those observed for other CLT products from plantation softwood species [3-7]. This finding indicates that even when using a non-heat-resistant adhesive, the charring rates remain considerably lower than those of other softwood CLT products, potentially enhancing the fire resistance of the panels over the same fire duration.

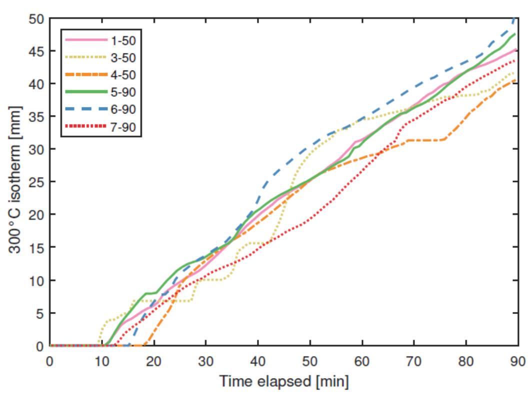

Figure 7. Temperature profile for samples tested to a constant heat flux of 90 kW/m^2 after 90 minutes of exposure (Wiesner,2020).

3.1.3 Prediction of bending capacity

Due to limited knowledge about the fire properties (charring rates and thermal gradients) of the panels, an accurate prediction of the bending capacity was essential to ensure that the panels could withstand the loads imposed during the standard fire tests. Australian codes specify that structural CLT floors must have a minimum Fire Resistance Level (FRL) of 90 minutes for typical use in office and residential buildings. Therefore, understanding the fire performance of the panels was vital to achieving the required FRL and preventing structural failure before the tests concluded.

The findings from the charring rates and temperature profiles gathered in the small-scale tests were crucial for predicting the panels' bending capacity and determining the loads and test duration for the large-scale tests.
Two distinct methods were employed to assess the panels' capacity: the reduced cross-section method suggested in the Eurocode and an alternative model that utilises the reduction in the mechanical properties proposed by Gutierrez et al [12,13].

The reduced cross-section method employed the stepped charring rate model outlined in Eurocode 5 [3,14] using non-heat-resistant adhesives. This model indicates that for CLT floors where charring layer fall-off occurs, the charring rate for the first 25 mm of each board should be doubled, except for the first layer of the CLT. As the results from the small-scale tests were quite similar to those published in Eurocode 5 for glue laminated members with hardwood species that have a characteristic density exceeding 450 kg/m^3, a notional charring rate of 0.50 mm/min was applied in the model to estimate the panel's capacity. Assuming a double charring rate of 1 mm/min and the zero strength layer of 7 mm used in the Eurocode (although knowing that his value is changed in prEN1995-1-2:2024), the effective cross-sections for the panels after 90 minutes of exposure were 102.5 mm and 52.5 mm for the 175 mm and 225 mm panel thickness. This method used the mechanical properties of CLT presented in Table 1.

The alternative model proposed by Gutierrez [12,13] utilised the reduction factors for mechanical properties outlined in Annex B of Eurocode 5 [3]. With this method, the capacity of the CLT was determined, assuming a perfect elastoplastic model for its compressive strength based on the properties published for E. nitens CLT at normal ambient temperatures [15], as presented in Table 1. Table 2 illustrates the reduction in CLT capacity calculated for both methods.

Table 1: E. nitens CLT Properties at ambient temperature.

Mechanical Property	
Bending strength, σ_c [MPa]	24.0
Compressive strength, σ_c [MPa]	25.0
Tensile strength, σ_t [MPa]	24.0
Modulus of elasticity, E [MPa]	13000

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Table 2: Bending capacity reduction of CLT after 90 min of exposure.

	Method 1 – Reduced cross-section Model	Method 2 - Reduction of Mech. Prop.
Panel thickness [mm]	175	
Bending capacity at ambient temperature [kN.m]	113.5	
Residual Bending capacity after 90 min of exposure [kN.m]	15.9	9.9
% Reduction	86.0%	91.3%
Panel thickness [mm]	225	
Bending capacity at ambient temperature [kN.m]	175.9	
Residual bending capacity after 90 min of exposure [kN.m]	18.7	25.4
% Reduction	89.4%	85.6%

According to the CLT bending capacity predictions presented in Table 2, the maximum distributed loads that the 175 mm and 225 mm panels can endure during a 90-minute fire are 4.9 kPa and 9.3 kPa, respectively. This prediction confirms that the panels could support uniformly distributed loads of 4.0 kPa and 8.0 kPa for a 90-minute fire without undergoing structural failure. This information was key in determining the load and minimum duration selected to conduct the standard large-scale tests to assess the FRL of the CLT panels.

3.2 LARGE SCALE FURNACE TESTS AS PER AS 1530.4

3.2.1 Temperature profiles

Three stations were equipped with in-depth thermocouples to measure the thermal penetration during each test. Figures 8 and 9 present the temperature measurements for the 175 mm and 225 mm panels throughout the tests. These temperature readings were utilised to calculate the average charring rate from the position of the 300 °C isotherm [16,17].

All panels experienced significant charring layer fall-off during the testing, leading to localised flaming in newly exposed timber. The initial charring layer fall-off in the 175 mm test was noted between 40 and 45 minutes of exposure, correlating with the findings from the small-scale tests. Char fall-off in the 225 mm panel can also be observed in the discontinuities of the temperature profile and the increase in internal temperatures following these observations.

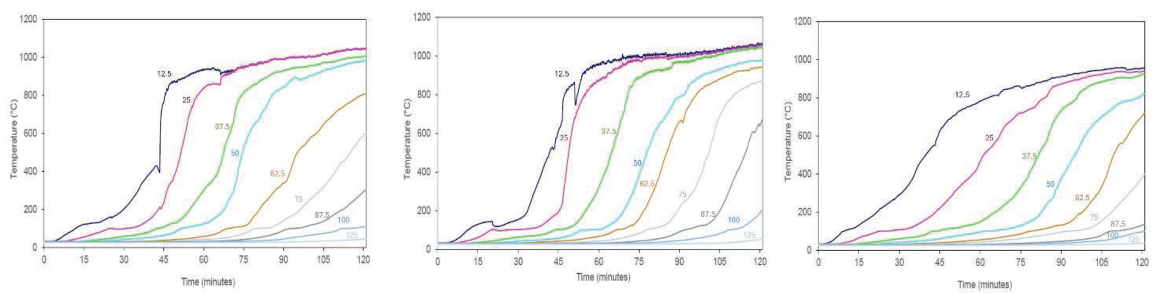

Figure 8. Temperature measurements for the 175 mm panels measured at three locations across the panels. The legend shows the distance in mm from the exposed surface (Warrington Fire, 2022).

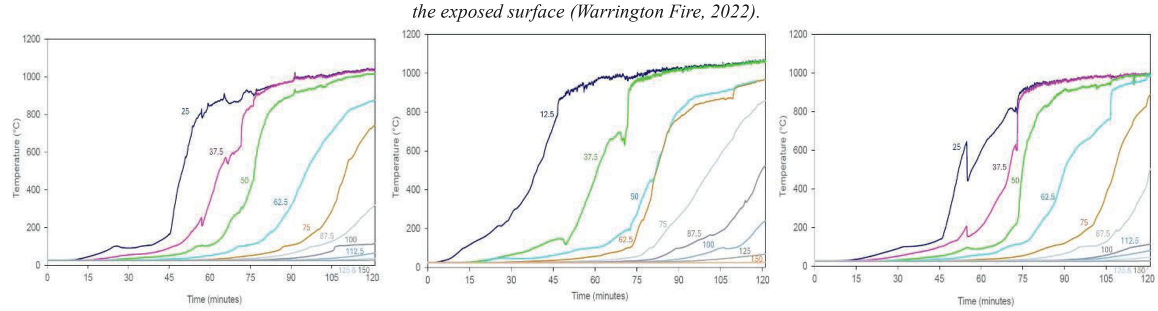

Figure 9. Temperature measurements for the 225 mm panels measured at three locations across the panels. The legend shows the distance in mm from the exposed surface (Warrington Fire, 2022).

3.2.2 Charring Model

The charring rates were determined based on the time required for the in-depth thermocouples to reach 300 °C, which reflects the progression of the charring front. Similar to the small-scale tests, a stepped charring model was used to describe the charring rate in the panels, aligning well with the temperature profiles obtained through the tests. The estimated charring rate for the first layer of the panel was 0.54 mm/min. According to the stepped model, the accelerated charring rate is 1.08 mm/min for the first 25 mm of each layer. Given that each layer of the nitens CLT is 25 mm thick, the charring rate for the remainder of the cross-section consistently follows the accelerated charring rate of the stepped model. When comparing the char depths derived from the 300 °C isotherm based on temperature readings with the estimated charring depth calculated from the stepped model, the difference between the two measurements ranges from 0.1 to 2.6%. This minor variation highlights the accuracy of the model.

3.2.3 Bending Capacity

Both panels exhibited no evidence of failing to meet the three criteria outlined in AS 1530.4 (structural adequacy, integrity, and insulation). Both panels achieved a fire resistance level (FRL) of 120 minutes (REI 120) for the specific loading applied and the tested spans, and the stringent predictions of bending capacity based on the models and the results from the small-scale tests were appropriate for estimating the panels' structural adequacy. The proposed charring rate model based on the position of the 300 °C isotherm obtained from the large-scale furnace test was not significantly different from the estimated charring model obtained from the small-scale tests used to predict the panels' bending strength.

3.2.4 Residual cross-sections

Once the tests were completed, the panels were removed from the furnace, and the fire was put out by spraying water onto the exposed surface. Five residual sections of the panels from each test were cleaned and measured to estimate the charring depth following the tests. The residual cross-section was measured following the methodology proposed by Schmid et al. (2020) [18]. Figure 10 illustrates the residual cross-sections of the panels. The white dots mark the points where the residual section was manually measured. The results of these measurements are shown in Figure 11.

Figure 10. Cleaned residual cross sections of 175 and 225 mm CLT after 121 min of fire exposure

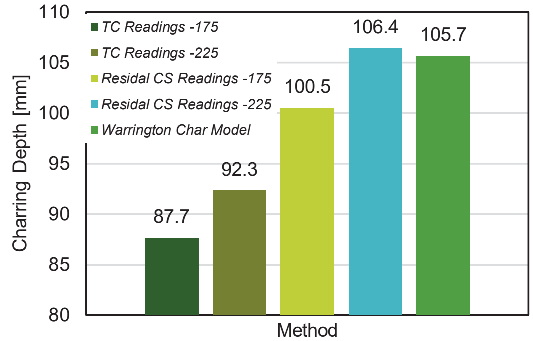

Figure 11. CLT char depth after furnace test estimated from different methods after 121 min of fire exposure.

Figure 11 illustrates the charring depth obtained through three methods: the in-depth temperature readings, the proposed stepped charring model and measurements from the residual cross-sections collected after the tests. The results indicate that the temperature readings reflect a lower charring depth than the other two methods. These results coincide with the findings of Fahrni et al. (2018) [19] and Pope et al. (2020) [20], who demonstrated that there is a significant under-prediction of temperatures for ‘back-inserted’ thermocouples and that the temperature readings for the 300 °C isotherm are considerably lower than the actual temperature in the specimen. Although the authors were aware of this situation, it was not possible to install the thermocouples from the side during the standard fire tests.

While the residual cross-section measurements for the 225 mm panel show a slightly higher char depth than those from the charring model, this discrepancy may be attributed to a longer fire duration, as the panels are not necessarily extinguished immediately after completing the tests. These findings provide confidence that the proposed charring model offers a conservative scenario for predicting the residual cross-section of the panels and estimating the structural adequacy of CLT, providing a sufficient level of safety for designing fire-safe structures using E.nitens CLT. This statement shall be confirmed in the future with additional fire tests.

4- CONCLUSIONS

E. nitens CLT panels underwent several tests to predict charring rates and propose a charring rate model for safely designing Plantation E. nitens CLT floors under fire conditions. Leveraging the test results and data analysis from small-scale tests using a radiant heat panel, the CLT panels were successfully tested in a standard furnace test, achieving an FRL of 120 min (REI 120). The charring rate models were compared against experimental data, and the bending capacity of the panels was validated against the tests.

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A charring model has been developed and validated for designing E. nitens CLT floors. This represents the first published models specifically for plantation E. nitens CLT, allowing engineers to predict fire bending capacity and fire resistance accurately. With the findings presented in this paper, engineers and designers can use the proposed models to design E. nitens CLT floors for fire conditions, accommodating various geometries and spans beyond those tested.

These results were crucial for utilising this product in the first-ever mass timber building built in Tasmania, Australia, which featured approximately 500 m² of E.nitens CLT in one of the floors.

5 – ACKNOWLEDGEMENTS

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