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EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF IRISH SITKA SPRUCE CLT WALL PANELS UNDER EXPOSURE TO STANDARD FIRE CONDITIONS

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ABSTRACT: Cross-laminated timber (CLT) is a sustainable engineered timber product. The fire behaviour of cross-laminated timber (CLT) is a significant concern due to its combustible nature. Currently, there is limited data available on the performance of charring of CLT panels made from C16 grade timber under fire. In this research, an experimental and numerical investigation of CLT floor panels exposed to a standard fire i.e., ISO 834 was performed. The CLT floor panels were manufactured from C16 grade Sitka spruce grown in Ireland. Overall, four CLT floor specimens were tested using standard heating conditions. The charring rate and temperature distribution at different depths from the fire-exposed face of the CLT panel were studied. The test panels were also protected with different protective claddings and the delay in charring of the CLT panel provided by these claddings is presented. Furthermore, a 2D finite element (FE) model was developed and the results from the FE model were compared with experimental results that show a good correlation in terms of the charring rates and temperature distributions.

KEYWORDS: Charring rate, Cross-laminated timber, Finite element analysis, Fire testing, Sitka spruce.

1 INTRODUCTION

Cross-laminated Timber (CLT) consists of at least three layers of timber boards that are glue bonded orthogonally. CLT is gaining popularity due to its enhanced structural capabilities compared to traditional timber construction methods and its simple erection process. The fire behaviour of CLT is an important research aspect and therefore the investigation of fire analysis of timber products has increased in the past few years. For the fire design of timber structures exposed to ISO 834 [1], two simplified methods i.e., the reduced cross-section method and the reduced properties method are presented in Eurocode 5 [2]. The former method measures the charred depth of timber by considering that the char will occur at a uniform charring rate of 0.65 mm/min for solid timber with a density greater than 290 kg/m^3. Furthermore, a section of 7 mm, called the zero-strength layer adjacent to the charred area that is considered to have zero load-bearing capacity, will be added to the char depth.

Timber undergoes thermal degradation upon heating which passes through different stages to reach the decay phase [3]. During the thermal degradation of timber, combustible gases evolve in addition to a mass loss which results in the formation of a char layer. The lower thermal conductivity of the char layer protects the inner section of the timber from heating up rapidly until cracks appear in the char layer causing heat penetration to the unburnt timber [4]. The degradation of timber on heating and fire behaviour can be analysed in terms of charring rate. Various factors that affect the charring rate include the type of wood, density, heat flux and ventilation conditions [4]. Eurocode 5 (EC-5) [2] uses the simplified one-dimensional charring rate β_0 for solid and glue-laminated timber panels with a density of more than 290 kg/m^3 when exposed to standard fire conditions i.e., ISO 834 [1]. A notional charring rate β_n is used to consider the effect of corner rounding in beams and columns which leads to an increase in the charring at the corner of the cross-section. The one-dimensional and notational charring rates for different wood products from EN 1995-1-2 are shown in Table 1.

Both experimental [3, 4] and numerical investigations [5]–[8] have been performed on the fire behaviour of CLT panels. The studies performed by Friquin et al. [3] show that the fire behaviour and charring rates of CLT panels largely depend on the fire curves. High temperatures and fast temperature growth of a fire curve led to a higher charring rate compared to fire curves with slower temperature growth and low peak temperatures. The magnitude and duration of the charring peak of CLT depend on the rate of heating, the test setup, as well as the size of the test sample and its orientation [5]. A series of 5-layer CLT floor panels were tested when exposed to Standard temperature conditions by Fragiacomo et al. [11]. The authors found that the CLT panels which were directly exposed to fire exhibited similar charring rates as given in the Eurocode 5. Furthermore, the finite element

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(FE) model showed a good correlation in predicting the charring rates with that of the experimental results [11].

Table 1: *Charring rate as per the EN 1995-1-2 [2]*

Material	β_0 (mm/ min)	β_n (mm/ min)
Softwood and beech	0.65	0.70
Glued laminated timber with a characteristic density of 290 kg/m^3		
Solid timber with a characteristic density of 290 kg/m^3	0.65	0.8
Hardwood		
Solid or glued laminated hardwood with a characteristic density of 450 kg/m^3	0.50	0.55
Panels*		
Wood paneling	0.9	
Plywood	1.0	
* The one-dimensional charring for the panels is applied to a panel thickness of 20 mm or more with a characteristic density of 450 kg/m^3.		

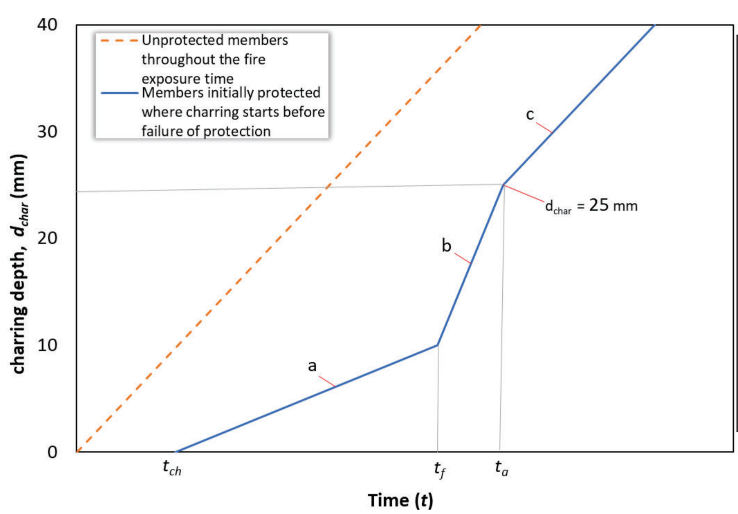
The behaviour of CLT can be different from solid timber in a fire. Experimental tests have been performed to study different factors that affect the fire performance of CLT including the behaviour of the adhesive [12], layer thickness and the number of layers [12]–[14], the effect of protective cladding [11, 15], and calculation of a zero-strength layer [7].

Numerical models are often developed to extend the experimental results and to avoid expensive fire tests [10], [15]–[18]. Validated numerical models can be useful tools to examine the behaviour of CLT in a multitude of different fire-loading situations, ensuring compliance with design standards and can significantly increase the safety associated with CLT in construction. Wong, B.V.Y [10] developed a 2D FE modelling to simulate the thermal behaviour of CLT when exposed to a standard fire and found good agreement with the experimental results.

Similarly, Wang et al. [19] developed a FE model which was validated with experimental fire test results and it was shown to accurately simulate the thermomechanical behaviour of the CLT panel under elevated temperatures. While CLT has been used as an exposed surface in many structures, there are also alternative finishes that are commonly used to protect the CLT from direct exposure to fire which include gypsum plasterboard. Gypsum plasterboard is a protective cladding that is widely used as a fire protection system due to its easy installation, ready availability, and high specific heat capacity [20]. Gypsum plasterboards are non-combustible and are commonly available in two thicknesses i.e., 12.5mm and 15mm. At a temperature of up to 100°C during a fire, the gypsum plasterboard absorbs a significant amount of heat to remove water causing delays in the development of high temperatures until the whole board is dehydrated. Furthermore, the low thermal conductivity of the gypsum plasterboard keeps the unexposed surface of the plasterboard at lower temperatures [21].

For the CLT panels which are initially protected, the following will need to be considered:

- The charring behind the protective cladding is delayed until time t_{ch}, where t_{ch} is the time at which the charring behind the protective layer starts.
- The charring behind the cladding can start before the failure of the protective layer with a lower charring rate until the failure time t_f of the fire protection as shown in Figure 1. After the failure of protective cladding (t_f), the charring rate increases in line with the values shown in Table 1, from the EN 1995-1-2, until time t_a, where t_a is the time at which a char depth of 25 mm has been made.
- The charring rate returns to the value given in Table 1 of EN 1995-1-2 at a time t_a when the charring depth is either 25 mm or equal to the charring depth of the same member without fire protection.



Key:

a. Charring starts at t_{ch} at a reduced rate until the protection has fallen-off
b. Charring starts at a higher rate, when the protection has fallen-off
c. Charring rate reduced to the rate given in EN 1995-12-2, when the char depth exceeds 25 mm.

Figure 1*: Variation of the charring depth when for $t_{ch} < t_f$ [2]*

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In recent years, considerable efforts have been made to focus on the fire analysis of CLT panels. However, the fire behaviour of CLT can vary for different timber species. Limited research studies have been conducted on the fire analysis of CLT floor panels made of Irish spruce which is characterised as a low-density timber due to the rapid growth conditions in Ireland and typically achieves a C16 structural grade. In this study, Irish spruce CLT floor panels were tested under exposure to standard temperature conditions. Furthermore, an FE analysis was carried out and validated against the experimental results creating an FE tool for CLT elements manufactured from Irish-grown Sitka spruce to be modelled in more significant and severe conditions.

2 EXPERIMENTAL TESTING

2.1 Materials

Boards of C16 grade Irish Sitka spruce were used to produce CLT floor panels that were 970 mm long and 500 mm wide. Boards used in the production of CLT floor panels were conditioned at a relative humidity of 65% ± 5% and a temperature of 20 °C ± 2°C. For the preparation of CLT panels, one-component polyurethane (PUR) adhesive was applied on the surface of the lamellae at a spread rate of 0.0160 microns/cm^2. The pressing of the panels was performed using steel plates to apply a pressure of 60 N/cm^2 for 120 mins. The panels were placed again in the conditioning chamber before the experimental tests to ensure and limit the moisture content of the specimens.

2.2 Test Specimens

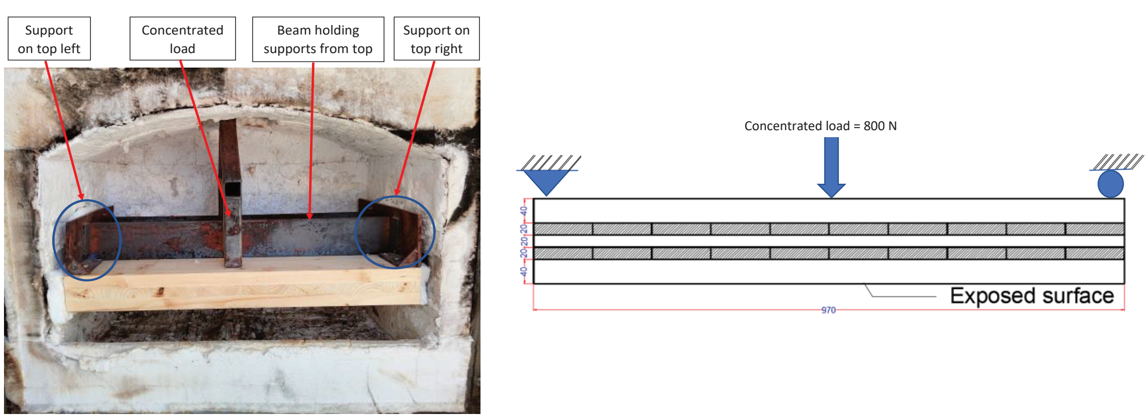
The experimental work was carried out at the Structural Engineering laboratory of the Munster Technological University (MTU). A total of four CLT floor panels were tested in the fire-testing kiln under ISO standard heating conditions [1]. Three and five lamellae CLT lay-up configurations were studied having an overall thickness of 110 mm and 140 mm, respectively. All the CLT panels were simply supported and a constant concentrated load of 0.8 kN was applied at the mid-span throughout the fire testing. A deflection gauge was installed to measure and record the deflection at the mid-span during the testing. Specimen details and test setup for both the 3-layer and the 5-layer CLT panels are shown in Figure 2. The tested CLT panels were manufactured from Irish Spruce timber having a measured average density of 381 kg/m^3 at a 12% moisture content (MC). The measured average moisture content was 11.5-12.5% prior to the testing. The details of specimens and test configurations are provided in Table 2. Specimens A-1 and B-1, which comprised 3 layers and 5 layers, respectively received no protective cladding. The exposed surfaces of the remaining 3-layer and 5-layer CLT panels were protected with different protective claddings. The 3-layer CLT panel was protected with two different protective cladding configurations i.e., a combination of 12.5 mm Fireline gypsum plasterboard (FP) and 12.5 mm plywood (PW). The exposed face of the 5-layer CLT panel was protected with a 12.5 mm Fireline gypsum plasterboard.

2.3 Placement of thermocouples

The temperature of the kiln was monitored throughout the test and each CLT panel was instrumented with thermocouples (TC). A plate thermometer was used to record the temperature in the kiln during the test. Type K TCs were inserted in a drilled hole from the side of the CLT panels at different depths, to record the internal temperature distribution and the progression of the char line during fire testing. The thermocouples were strategically placed at the interfaces between different layers of the CLT panels as well as between the fire-protective cladding and the CLT panel. The details of the thermocouple tip location and its depth from the exposed surface are shown in Table 3.

3 RESULTS

Different researchers defined the charred front at different temperatures in timber due to the high-temperature gradient. In this study, the charred front which is a transition between charred wood and pyrolysis layer is considered to be at the 300˚C isotherm as defined in EN



a. b.

Figure 2: *a. 3-layer CLT floor panel in the kiln b. Drawing and layout of 5-layer CLT panel*

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Table 2: *Test specimen details*

Specimen	layers	Layers layout (mm)	Panel thickness (mm)	Protection on the exposed side
A-1	3	40-30-40	110	No
A-12.5FP12.5PW	3	40-30-40	110	12.5 mm Fireline gypsum plasterboard and 12.5 mm Plywood
B-1	5	40-20-20-20-40	140	No
B-12.5FP	5	40-20-20-20-40	140	12.5mm Fireline gypsum plasterboard

1991-1-2. The charring rate of CLT panels and their individual layers were measured by considering the temperature measured at various TCs from the exposed surface. For CLT panels which were protected with different protective claddings, the charring rate of the outermost layer is taken when the temperature at the interface between the protective claddings and the CLT panel reaches 300˚C.

3.1 Temperature distribution

The temperatures recorded at different depths of the CLT panels using K-type TCs for all fire tests are shown in Figure 3. Moreover, the kiln temperature was recorded using a plate thermometer, ensuring the experimental fire curve is comparable with the ISO-834 curve heating conditions.

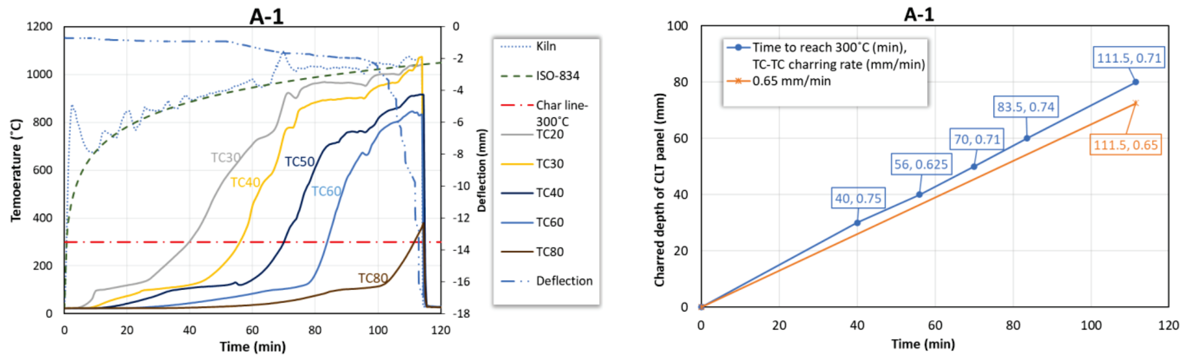
It can be seen from Figure 3 (a-d), the temperature of the kiln closely followed the standard fire curve in all tests. It can also be observed from the temperature-time curves, that the temperature at different depths of the CLT panels plateaus at around 100°C which was then followed by a rapid rise in temperature. This can be attributed to the loss of water at around 100 ˚C to 120˚C which also results in a decrease in the density as well as a decrease in specific heat capacity. In panels which were initially protected with different claddings, the temperature distribution at the interface between the CLT panel and cladding demonstrates the same trend. In all protected panels, the temperature behind the cladding reached the kiln temperature when the interface temperature between the CLT panels and the cladding was around 700°C and 800°C. This quick rise in temperature behind the claddings indicates that the fall-off of the protective cladding occurs when the temperature of the inner face of the cladding reached approximately 700°C and above.

3.2 Charring rate

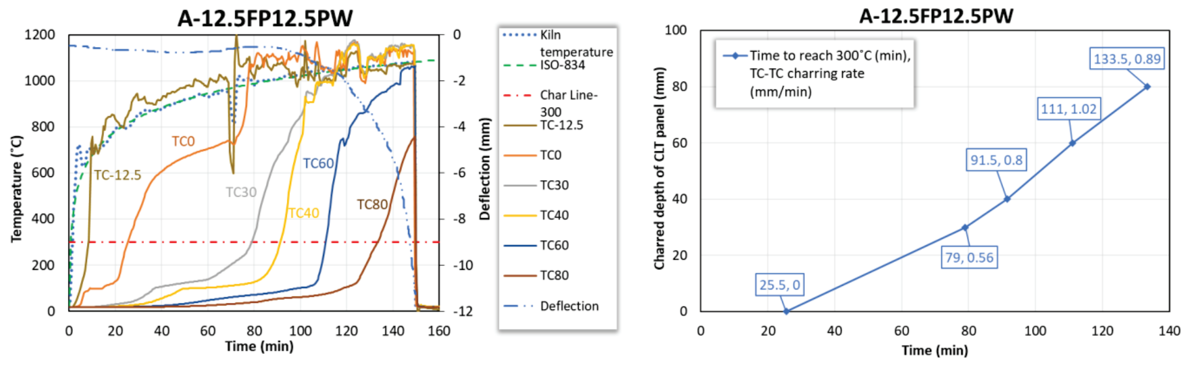
The charring rate of the CLT panels and their individual layers were measured by considering the temperature measured at various TCs and their respective depths from the exposed surface. The char line which is a transition between charred wood and the pyrolysis layer is taken at the 300°C isotherm as given in the EC-5 (EN 1995-1-2). The temperature recorded by TCs installed at various depths of the CLT panels was used for measurement of the charred depth with time which in turn gives the charring rate. The charring rate calculated from TCs data at different depths of the CLT panels is illustrated for each specimen in the right column of Figure 3. It can be observed that in an unprotected CLT floor panel (Figure 3a (A-1), and Figure 3c (B-1)), the charring rate calculated throughout the cross-section of the CLT panels was close to the one-dimensional charring rate of 0.65 mm/min as defined in the EC-5. The CLT panels which were initially protected with different claddings showed a delay in the charring of the CLT panels as expected. The charring of the CLT panels was then started with a lower rate as shown in the right column of Figure 3 (c) and (d). The lower charring rate was followed by a sudden higher charring rate which is due to the fall-off of the protective cladding on the exposed face of the CLT. The fall-off of the cladding exposes the CLT panel directly to fire and thus the char rate increases. The fall-off of the claddings happens in all tests at around 70 min to 80 min from the start of the fire which can be observed from the sudden increase in temperature between the CLT panel and the exterior cladding. The temperature recorded by the thermocouple placed between the CLT panel and protective cladding is shown by TC0 in Figure 3. (b), and (d).

Table 3: *Location of thermocouples from the exposed face of the CLT panel to fire*

Specimen	Between two claddings	Between cladding & CLT panel	Thermocouples depth from the exposed surface of CLT panels (mm)						
			20	30	40	50	60	80	100
A-1	-	-	-	TC30	TC40	TC50	TC60	TC80	-
A-12.5FP12.5PW	TC-12.5	TC0	TC20	-	TC40	-	TC60	TC80	-
B-1	-	-	-	TC30	TC40	-	TC60	TC80	TC100
B-12.5FP	-	TC0	TC20		TC40	-	TC60	TC80	-



a.



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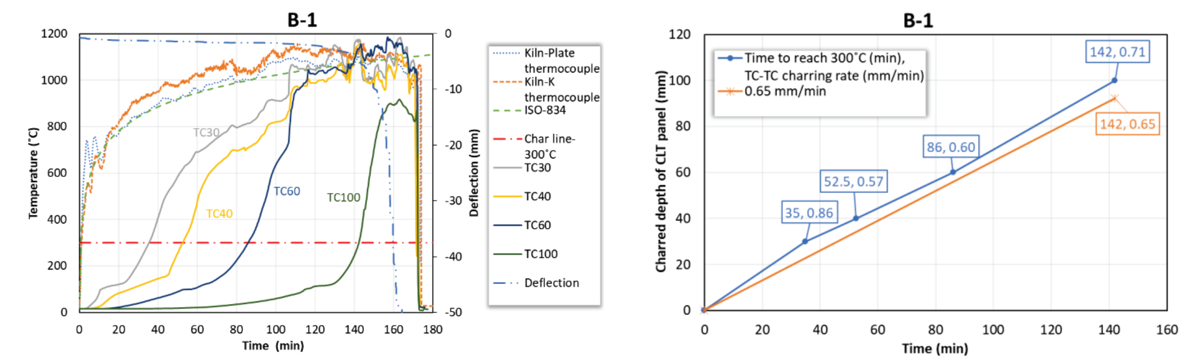

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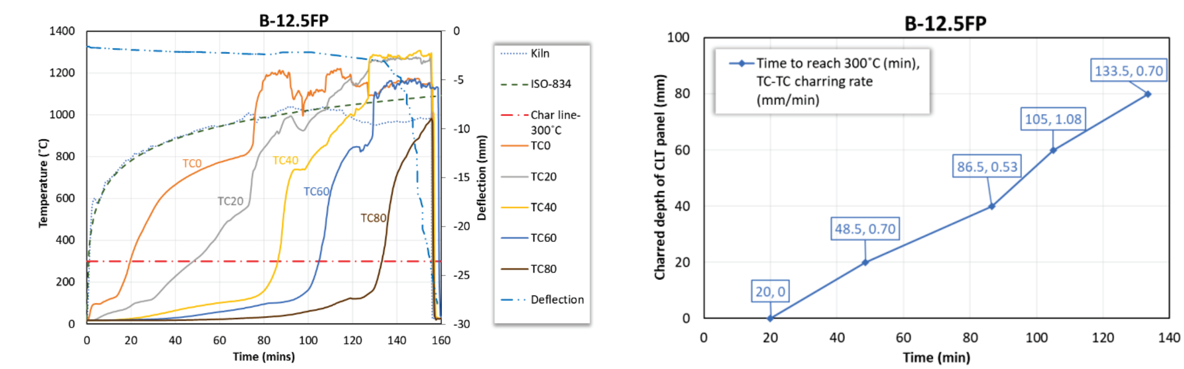

d.

Figure 3: *Left column: Temperature-time curves of test panels, Right column: Charring rate from TC-TC, (a) A-1, (b) A-12.5FP12.5PW, (c) B-1, (d) B-12.5FP*

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The charring rate of plywood from EN 1995-1-2 with a thickness of less than 20 mm is given in Equation (1).

$$B_{0,\rho,t} = \beta_0 * k_\rho * k_h \quad (1)$$

Where, $k\rho = \left(\frac{450}{\rho k}\right)^{0.5}$, $kh = \left(\frac{20}{hp}\right)^{0.5}$

h_p is the thickness of the panel in millimetres and ρ_k is the characteristic density in kg/m^3.

The charring rate from Equation (1) for a 12.5 mm plywood layer is 1.10 mm/min while the experimental testing gave a higher charring rate of 1.47 mm/min.

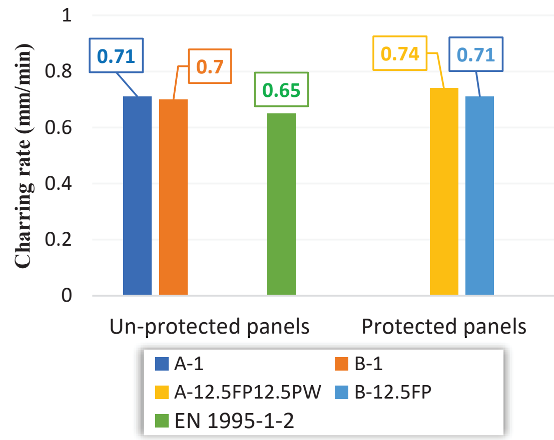
It can be observed from the charred depth-time curves of protected panels as shown in the right column of Figure 3 (b), and (d), that the charring behind the protective cladding is delayed until time t_{ch}. It can also be observed that the charring behind the cladding started at a reduced rate, while the protective layer is still up against the CLT panel. However, an increase in the charring rate was observed after the failure of the protective claddings in all protected test panels. The overall charring rate at the end of the fire tests for all panels is shown in Figure 4 (a). The overall charring rate of both unprotected 3-layer and 5-layer CLT panels were 0.71 mm/min and 0.70 mm/min, respectively, which is slightly higher than the one-dimensional charring rate of 0.65 mm/min as defined in EC-5 for glue laminated or solid timber with densities greater than 290 kg/m^3. The charring rate calculated for initially protected panels after the charring begins was at a similar rate to unprotected panels. This shows that the protective cladding initially delays the charring of the CLT panel. However, after the CLT panel starts charring, the char rate remains similar to the unprotected panel, if it's exposed to fire for a longer duration. This shows that the protective cladding only delays the charring of the CLT panels, and it still chars at a similar rate if it's exposed to fire for a longer duration.

3.3 Effect of protective cladding on the delay of charring

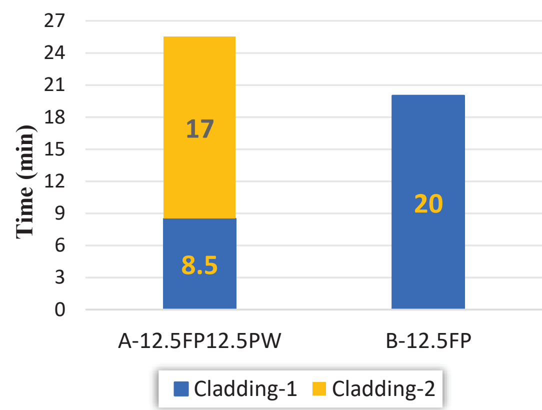
Protective claddings provided at the exposed face of the CLT panel delayed the charring of the test specimens. The delay in charring of the CLT panels provided by different claddings on the exposed face of the CLT panel to fire in terms of time (mins) is given in Figure 4 (b). The 12.5 mm FP gives a protection time of 20 mins when used on the exposed face of a 5-layer CLT floor panel. A combination of 12.5 mm FP and 12.5 mm PW delayed the charring of the CLT panel by 25.5 mins. It was observed that the temperature at the interface between the exterior 12.5 mm PW layer and the inner 12.5 mm FP reached 300˚C in 8.5 mins. EN 1995-1-2 [2] provides the relation as given in Equation 2 to measure the start of charring of the CLT panel behind the gypsum type A or F plasterboards at internal locations or the perimeter adjacent to filled joints. The delay in charring of the CLT panels calculated using Equation 2. for type A and type F plasterboards are 21 mins, which is very close to the experimental values of 20 mins as calculated in this research for 12.5 mm FP.

$$t_{ch} = 2.8h_p - 14 \quad (2)$$

Where h_p is the thickness of the protective cladding.



a.



b.

Figure 4: *a) Charring rate for tested CLT panels, b) Fire protection provided by different cladding configurations.*

4 NUMERICAL ANALYSIS

The numerical FE analysis was carried out in Abaqus FE software. The 2D model of the CLT panel was developed in full length with the load and supporting conditions, material properties, and exposure to fire applied. The element type considered for this analysis was CPE4T which is a 4-node plane strain thermally coupled quadrilateral, bilinear displacement and temperature. Thermomechanical analysis which is a sequential thermal stress analysis was performed for all CLT panels. The analysis was performed in 2 steps. In step one, the load was applied to the CLT panel followed by the fire exposure of the CLT panel in the second step.

4.1 Material properties

The mechanical properties of the C16 timber both in parallel and orthogonal orientation were applied to the model. In this research, the EC-5 temperature-dependent modulus of elasticity model was used. The material properties were taken from the research performed on similar wood by O'Ceallaigh et al. [22]. The temperature-dependent thermal properties of the timber including the conductivity, specific heat and density relationships were used as defined in the EN 1995-1-2 [2]. As recommended

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by EN 1991 and EN 1995-1-2, the convection coefficient and emissivity were taken as 25 W/(m^2.K) and 0.8, respectively. In addition to the thermal properties provided by EC-5, the FE analysis was also performed using modified values of conductivity at higher temperatures as shown in Table 4. In order to make the analysis simpler, the conductivity values of timber given by EC 5 were adopted to consider the effect of faster charring and quick temperature raise after the layer's fall off.

A mesh sensitivity study was carried out and an element size of 10 mm was used in all CLT panels to ensure adequate accuracy in the results as well as to obtain temperature data for the nodes in a similar location to the location of thermocouples in the experimental testing. For the CLT panel which was initially fire-protected with plywood and plasterboard, the plywood has not been modelled due to the unavailability of its thermal properties at higher temperatures as well as its negligible mechanical resistance.

Table 4: *Temperature-dependent thermal conductivity used in FE analysis*

New Proposal	EC-5	Temperature
W. m^{-1}. K^{-1}		(°C)
0.12	0.12	20
0.15	0.15	200
0.07	0.07	350
0.09	0.09	500
0.35	0.35	800
0.5	-	850
1	-	900
2	-	950
10	1.5	1200

4.2 FE results and comparisons with experimental tests

In all of the experimental tests, the temperature of the kiln closely followed the Standard fire curve [1]. Therefore, the standard heating conditions were applied on the exposed face to fire in the FE analysis of initially unprotected panels. The comparison of experimental and FE results in terms of the overall charring rate from the fire-exposed side of the CLT panels was made and is shown in Table 5. It can be observed from Table 5 that the charring rate predicated using the model proposed in this research gives a closely matching charring rate to that of experimental fire testing. The charring rate predicated using EC-5 thermal properties gives a lower charring rate than the experimental results. This is partially due to the fact that thermal properties in EC-5 are presented for solid or glue-laminated timber which doesn't consider the effect of delamination, which usually happens in horizontal CLT panels. Furthermore, the char layer provides extra protection to timber from direct exposure to fire and thus reduces its overall charring rate. Thus the effect of an increase in the charring rate due to the fall off of sections of charred timber is needed to be considered in the thermal analysis. A simplified procedure to consider a higher charring rate after the layers charred has been included in the FE model which is validated with the experimental results. This is performed by using higher thermal conductivity values for a temperature of more than 800°C to avoid considering the complexity of modelling the char fall-off in the numerical simulation. In Figure 5, the charred depth at 60 mins from the start of the fire test from the FE analysis is shown for B-1 and B-12.5FP panels using the EC-5 thermal properties with the conductivity values taken from the new proposal as shown in Table 4. The charred depth of the CLT panels in Figure 5 is represented by a grey colour while the pyrolysis layer is shown in red.

Furthermore, the temperature distribution at different depths from the exposure of a panel to fire from experimental tests is compared with the FE analysis and is shown in Figure 6. It can be observed that the temperature-time curves for both experimental tests and FE results using the new proposal follow a similar trend to reach the char line temperature (i.e., 300˚C). Overall the temperature distribution from the numerical analysis, which is predicated using thermal properties given in EC-5 gives lower temperature distribution than the experimental results. The temperature-time curves from the FE analysis using EC-5 thermal properties follow a similar trend to that of the experimental results for the first hour of the FE analysis. The difference in the time to reach the char line temperature from FE analysis using EC-5 was higher than the experimental results for a longer duration of tests. On the other hand, the proposed model not only gives a good approximation of the char depth but also closely predicts the time to reach the char line temperature and the charring rate well.

Table 5: *Comparison of experimental and FE results*

Specimen	Overall charring rate (mm/min)		
	Exp	FEM	
		New Proposal	EC-5
A-1	0.72	0.71	0.58
A-12.5FP12.5PW	0.70	0.76	0.68
B-1	0.70	0.71	0.61
B-12.5FP	0.71	0.73	0.71

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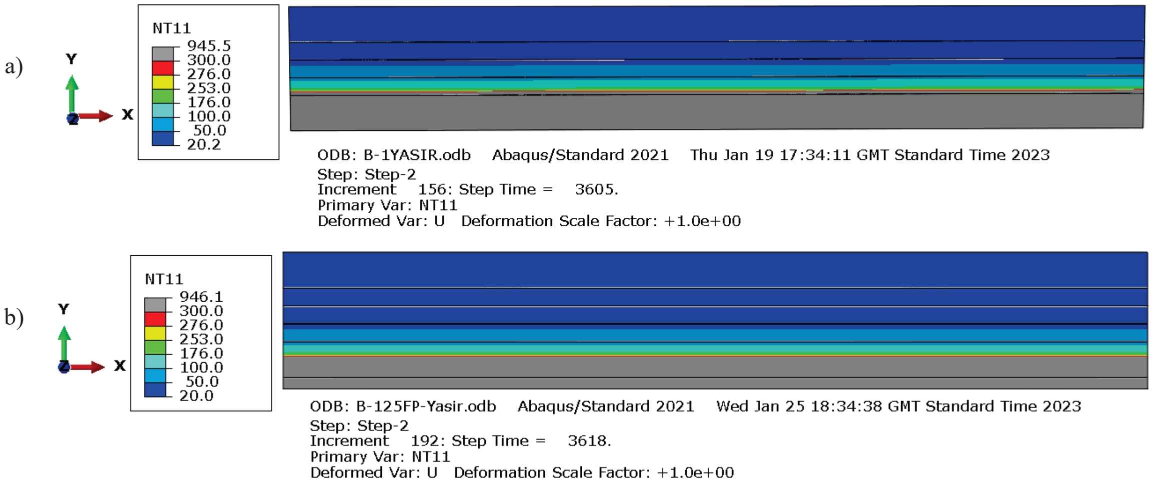

Figure 5: *Visualization of charred depth at 60 mins from FE analysis, a) B-1, b) B-15FP*

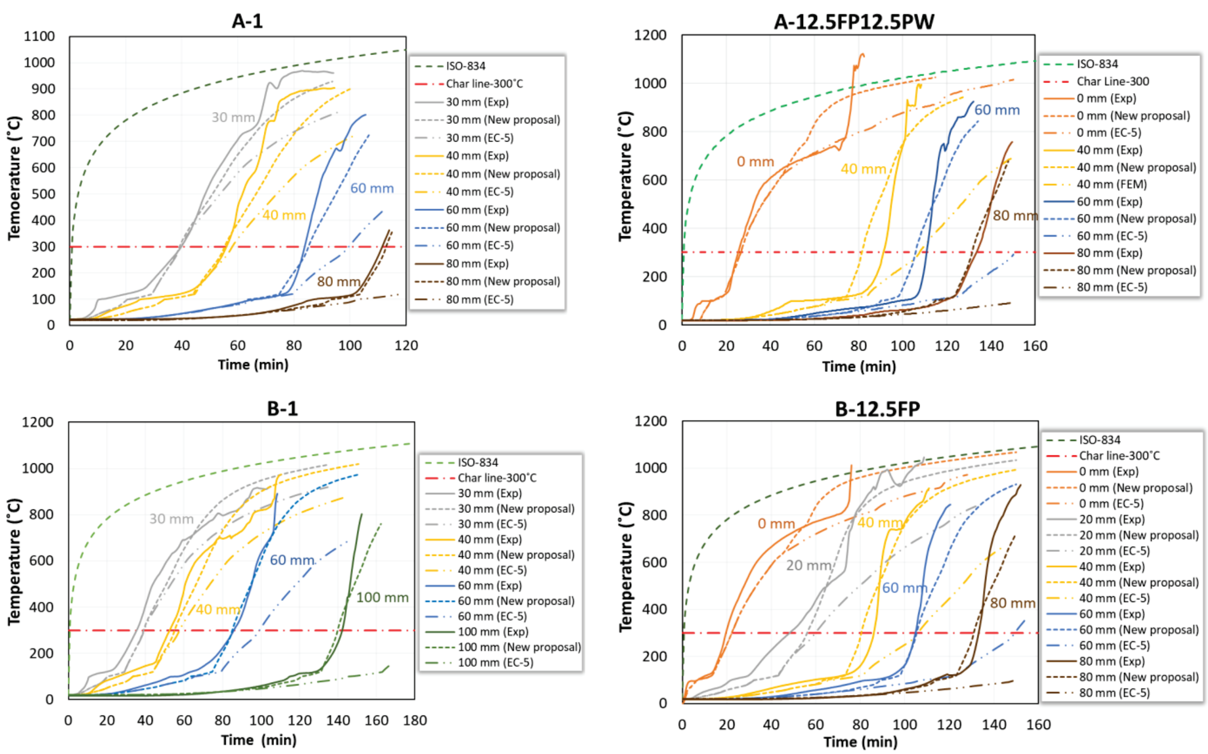

Figure 6: *Comparison of temperature distribution at the interfaces of layers of experimental tests and FE analysis*

5 CONCLUSIONS

The experimental testing of CLT floor panels made from C16 Grade Irish Sitka spruce was performed to measure the charring rate under ISO-834 standard heating conditions. Different protective claddings were used on the fire-exposed side of the CLT panels to determine their effectiveness in delaying the charring of the CLT panels. The main conclusions drawn from the experimental testing and FE analysis are as follows:

- The charring rate of both 3-layer and 5-layer unprotected CLT panels is 0.71 and 0.70 mm/min respectively, which is slightly higher than the one-dimensional charring rate given by the Eurocode 5 (EN 1995-1-2). No significant difference in the effect of the thickness of CLT layers was observed on the charring rate.
- The 12.5 mm Fireline gypsum plasterboard delayed the charring of the CLT panels by 20 minutes. A combination of a 12.5 mm Fireline gypsum

plasterboard with a 12.5 mm plywood protects the CLT panel from charring by 25.5 minutes.

- All CLT panels which were initially protected using different protective claddings give an overall charring rate of 0.70 mm/min to 0.71 mm/min. A higher charring rate was observed after failure and fall off of the fire protective cladding.
- In all of the panels with a protective layer, the charring of the CLT panels started while the protective cladding was still intact with the panels. In all of the panels, the protective claddings fall off around 70 mins to 80 mins from the start of the test.
- It was observed that the protective layer on the fire-exposed face of the CLT panels delayed the start of charring of the CLT panels. However, there is no significant difference in the overall charring rate of both unprotected and initially protected CLT panels at the end of the fire test.
- A 2D FE model was developed in Abaqus with a new proposal to consider higher values of conductivity than that defined in EC-5 for temperatures more than 800°C. The results from the FE analysis using the new proposal were shown to be in good agreement with the temperature distribution and charring rate of the experimental testing of the CLT panels. The FE analysis using the new proposal demonstrated good agreement with the experimental results in terms of charring rate and time to reach the charring temperature compared to the FE analysis performed using EC-5 thermal properties.
- The validated FE model may now be used to analyse a series of different fire loading conditions, panel lay-ups and protective measures for C16 Grade material and will serve as a useful tool to improve the safety and reliability of timber structures subject to fire loading.

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