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EXPLORING THE INFLUENCE OF HEATING CONDITIONS IN THE CHARRING PROFILE OF BARE TIMBER AND TIMBER PROTECTED WITH A THIN INTUMESCENT COATING

Stavros Spyridakis[1], Jeronimo Carrascal[2], Felix Wiesner[3], David Barber[4], Cristian Maluk[5]

ABSTRACT: This research examines the influence of a thin intumescent coating applied on mass timber, focusing on how changes in the in-depth charring rate may occur during a fire event. An experimental fire methodology was used whereby the transient in-depth heating conditions were carefully measured during testing. The heating conditions at the exposed surface of each sample were controlled by keeping a constant incident radiant heat flux at the exposed surface of the sample, considering the transient swelling of the intumescent coating – employing the H-TRIS method. Test samples of (200×200) mm^2 were prepared from Cross Laminated Timber (CLT) with a depth of 110 mm. The mean measured DFT amongst the coated samples was 1.19 ± 0.10 mm. Fire experiments were conducted for bare and coated timber samples, with the heated surface exposed at three different heat fluxes of: 25, 50, 75 kW/m^2. The outcomes of this experimental study demonstrated that timber protected with a thin intumescent coating shows a delayed onset of charring and reduced in-depth charring rate for all heating conditions examined. However, the coating underwent considerable thermal degradation and regression at higher heat fluxes. Additionally, the mean measured charring rate was directly proportional to the incident radiant heat flux.

KEYWORDS: Mass timber, Thin intumescent coatings, Timber charring, Fire experiment, H-TRIS

1 INTRODUCTION

1.1 BACKGROUND

Mass timber structures are becoming prominent across the globe as an avenue to a greener and more sustainable building industry, among other benefits such as speed of construction. Advances in the manufacturing of mass timber have led to the mainstream use of Engineered Wood Products (EWPs) – e.g., Cross Laminated Timber (CLT) and Glue Laminated Timber (Glulam) for varied applications (Figure 1) – with more reliable mechanical properties over sawn timber.

The increased aspiration for EWPs to be used in the built environment, especially in applications where fire safety considerations are vitally important (e.g., mid-, and high-rise buildings), has highlighted the need for understanding the fire behaviour of mass timber structures. One key challenge is the flaming combustion (i.e., burning) of exposed mass timber surfaces during a fire, including circumstances where flaming or smouldering (i.e., flameless combustion) of timber continues even after the moveable fuel load in the compartment has burnt out.

Figure 1: *Interior views of exposed mass timber framing (Ascent building, Milwaukee, Wisconsin – USA). Photo © David Barber.*

Consequently, burning of exposed mass timber elements can increase the severity and duration of a fire event [1-4], with potentially detrimental fire safety and structural implications. To date, a common fire engineering solution to mitigate the challenges with mass timber structures burning in a fire event has been the partial or complete

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encapsulation of timber using fire rated plasterboards. In its most basic definition, the purpose of encapsulating mass timber elements is to prevent timber from becoming part of the fuel load during a fire [5], and for load-bearing purposes to prevent or delay timber charring. Charring is usually assumed to occur when timber has reached a temperature of approximately 300 °C [6], with the charred section assumed to have negligible mechanical properties. However, the use of plasterboard does not allow for the expression of mass timber elements and can result in additional construction costs, as plasterboards need to be fitted after EWPs have been erected and installed on-site.

1.2 THIN INTUMESCENT COATINGS

Thin intumescent coatings are extensively used for steel construction in lieu of traditional passive fire protection, due to their proven architectural aesthetics, versatility (on-site or off-site application), and speed of application [7]. They are thermally reactive materials, applied to a coating thickness of a few millimetres – referred to as Dry Film Thickness (DFT). Intumescent coatings can swell multiple times their original thickness when heated [8], forming a thermal barrier that insulates the substrate material during fire, keeping its temperature below critical values, thus preserving its mechanical properties.

Despite the proven fire performance of thin intumescent coatings on steel structures, there is sparse published research available on their effectiveness for mass timber structures [9, 10]. However, exploratory testing to date on their application for mass timber has shown that they do swell during fire exposure, resulting in a delayed onset of charring and a reduced in-depth charring rate [11].

Additionally, recent developments in the production of intumescent paint products have led to the emergence of transparent intumescent coatings – which would make their commercial exploitation for mass timber buildings more likely. In the near future, the mainstream use of thin intumescent coatings on mass timber structures could result in (1) ease of application on-site or even off-site and (2) building aesthetic benefits.

1.3 RESEARCH MOTIVATION

This experimental study aims to demonstrate and provide confidence that thin intumescent coatings can be used for reducing the in-depth charring of mass timber during a fire, and to quantify how sensitive this may be to varied fire scenarios. Additionally, the work presented herein is the first stage of a larger experimental campaign of fire tests, to illuminate the effects of different intumescent paint types and thicknesses on the fire performance of mass timber.

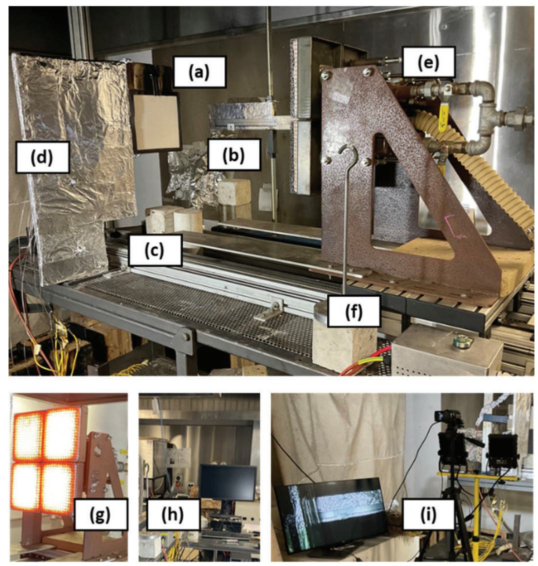
2 EXPERIMENTAL METHODOLOGY

2.1 TESTING APPARATUS

A bench-scale version (Figure 2) of the Heat-Transfer Rate Inducing System (H-TRIS) test method [12] was used to impose fire exposure conditions for this study.

This bench-scale version of H-TRIS is comprised of four radiant panels with a radiative surface of (300x400) mm^2, capable of controlling the incident radiant heat flux at the heated surface of test samples – in the range of 5 and 100 kW/m^2. For this study, H-TRIS was coupled with a sample holder with an integrated spark ignition system providing piloted ignition during testing.

The objective of this testing setup is to control the heating conditions at the target surface of the test sample protected with a intumescent coating or the bare timber sample. The position of the radiant panels is corrected to account for the swelling of the coating. The integrated spark ignition system was kept in a fixed position to the test sample.



(a) Sample holder with integrated spark igniter
(b) Stand with fixed ruler to track the coating's expansion
(c) Computer-controlled motion system for H-TRIS
(d) Thermocouples with shield protecting them from heat
(e) Gas and air supply for H-TRIS radiant panels
(f) Igniter box to turn on/off the spark igniter
(g) Radiant panels (300 x 400) mm^2 – H-TRIS system
(h) Computer system controlling H-TRIS with data logger
(i) Camera and monitor setup to record coating expansion

Figure 2: *Experimental setup with key components highlighted.*

2.2 TEST METHOD

The samples were tested at constant incident radiant heat fluxes of either 25, 50, or 75 kW/m^2 for 60 min. This time duration has no relation with the Fire Resistance Rating or Level used in Standard fire testing. Instead, it was selected for the purpose of obtaining sufficient data during testing based on the dimensions of the selected samples.

For the bare timber samples, the spark ignition was turned off when sustained flaming at the heated surface of the sample was observed – defined as continuous flaming greater than 30 sec. This is longer than the time required by standard reaction-to-fire tests [13].

For timber samples with intumescent coating, the spark ignition was kept on for the first 5 min of the experiments to capture the expansion of the coating under piloted conditions, also ensuring a consistent testing approach with the bare timber samples. This time was verified by

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preliminary testing. Further, the presence of the pilot is considered a more realistic testing approach, as in a real-life fire scenario pilot sources (e.g., flame, spark, embers) will usually be present.

The lowest heating condition (25 kW/m^2) was chosen to assess the burning behaviour of the samples above the critical heat flux for ignition of timber (13-14 kW/m^2) [14], but also near the threshold whereby most cellulosic materials are expected to auto ignite in a real fire (≥ 20 kW/m^2) [15]. The middle heating condition (50 kW/m^2) was selected such that to prevent self-extinction of bare timber [16], thus allowing for the timber's charring to continue. The purpose of the highest heating condition (75 kW/m^2) was to further examine the ability of the thin intumescent coating to reduce timber charring and char depth under more onerous heating conditions.

2.3 INSTRUMENTATION

The swelling of the tested thin intumescent coating was measured using a high-resolution video camera placed perpendicular to the direction of the expanding paint (i.e., on the side of the coated sample).

The internal temperature of timber was measured using thermocouples along the sample's depth and placed near the middle of the exposed surface. The 300 °C isotherm was tracked during post-processing of the experimental data, associated with the timber's char depth. The location of the 300 °C isotherm was calculated from a smoothing spline fit [17, 18] for every time instant.

Prior to testing, the thermocouples were inserted from the side of the sample (i.e., perpendicular to the principal direction of heat inside the sample) – minimising error of temperature readings as described by past researchers [19, 20]. Thermocouples were placed at the following depths from the heated surface: 5, 10, 20, 33, 50, 78, 110 mm.

The interior temperature evolution for both bare timber and timber protected with intumescent coating was recorded along the depth of each sample for the whole duration of heating (60 min) and cooling after the radiant panels were turned off (30 min).

2.4 TEST SAMPLE PREPARATION

Test samples of (200×200) mm^2 were prepared from CLT with a depth of 110 mm. The tested CLT comprised of three lamellas (32.5 mm, 45 mm, 32.5 mm) of Australian radiata pine softwood.

A commercially available solvent-based thin intumescent coating was used. Samples with intumescent coating were sprayed using an airless paint gun by a registered professional contractor, as per the product guidelines. The coating used has an opaque white finish and was originally formulated for structural steel applications, for either on-site or off-site use.

The bulk density of each sample was measured before each test by measuring its mass on a laboratory scale. The mean DFT of the coated timber samples was measured using an electronic gauge with an ultrasonic probe for timber substrates. The mean measured DFT for the six coated samples was 1.19 ± 0.10 mm – see Table 1.

The bulk moisture content of the tested timber was estimated using the oven dry method [21] from four sacrificial samples, which were stored in the same conditions as the test samples – at ambient temperature in a laboratory environment; the moisture content varied between 9.1 % and 9.8 %. Lastly, when placed inside the sample holder, each sample was wrapped on its sides using a ceramic wool and aluminium foil tape before being tested (Figure 3). This was done to minimise heat exchange between the sides of the sample and the metallic sample holder during testing, in order to enforce one dimensional heat transfer conditions akin to those in large, panelised mass timber.

Table 1: *Density and mean DFT for each test sample.*

Sample ID	Density [kg/m^3]	Mean DFT [mm]
BT-25-S1	509.6	-
BT-25-S2	476.9	-
BT-50-S1	501.1	-
BT-50-S2	472.9	-
BT-75-S1	523.6	-
BT-75-S2	495.8	-
IC-25-S1	494.9	1.18
IC-25-S2	519.0	1.20
IC-50-S1	510.6	1.12
IC-50-S2	496.5	1.11
IC-75-S1	509.1	1.26
IC-75-S2	556.2	1.29

Nomenclature:

- *Sample type:* *BT (Bare Timber), IC (Timber + Intumescent)*
- *Heating Condition:* *25, 50, 75 (25, 50, 75 kW/m^2)*
- *Sample repetition:* *S1, S2, (S1 – first, S2 – second)*

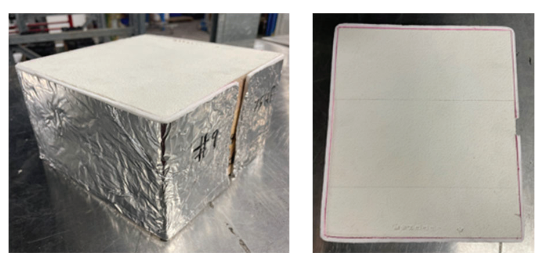


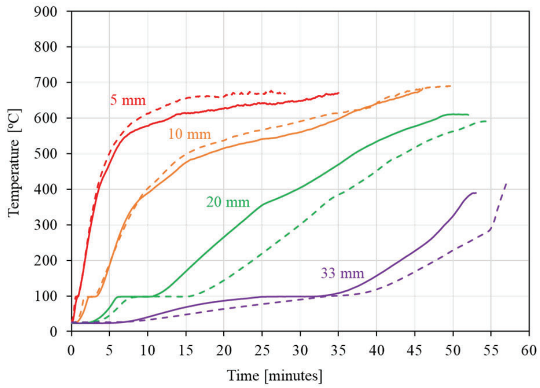
Figure 3: *Typical preparation of a sample prior to testing.*

3 TEST RESULTS

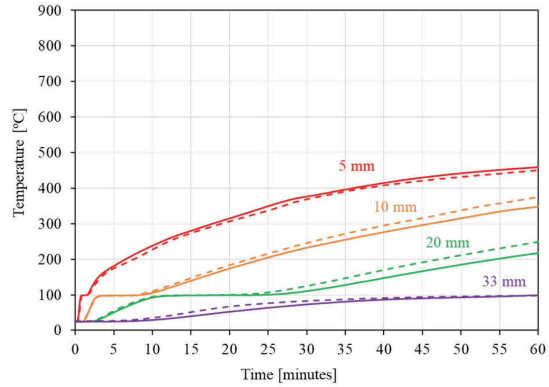
3.1 INTERIOR TIMBER TEMPERATURE

The temperature inside the timber was measured during heating (60 min) and cooling (30 min) of each test sample.

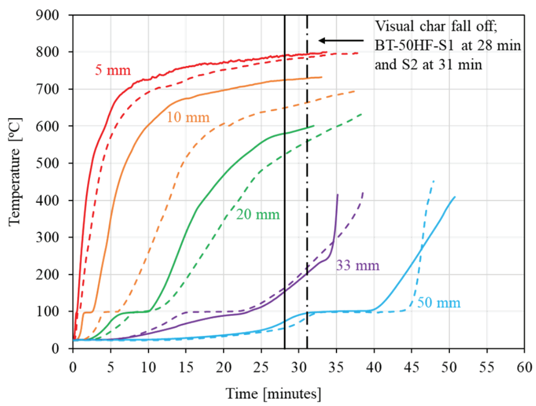
Figure 4 shows the in-depth temperature vs. time data carried for each repeat test – comparing plots without and with intumescent, side-by-side. Figure 5 shows the profile of temperature for each repeat test during heating – i.e., in-depth temperature vs. depth from the heated surface.



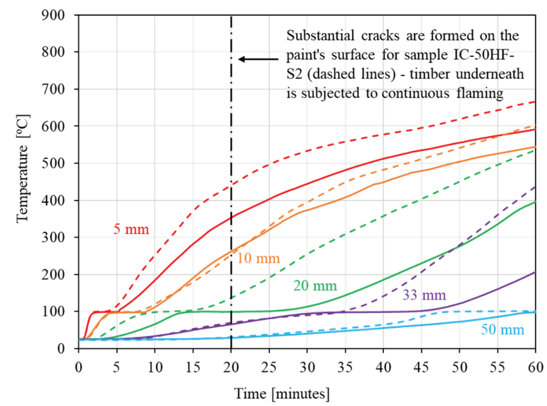
(I): Bare timber samples at 25 kW/m^2



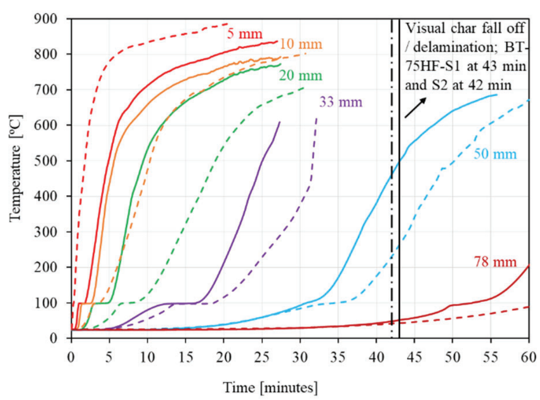
(II): Intumescent-coated timber samples at 25 kW/m^2



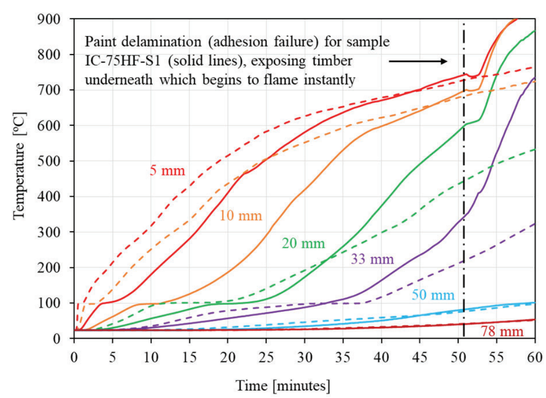
(III): Bare timber samples at 50 kW/m^2



(IV): Intumescent-coated timber samples at 50 kW/m^2



(V): Bare timber samples at 75 kW/m^2



(VI): Intumescent-coated timber samples at 75 kW/m^2

Figure 4: *In-depth temperature vs. time for varied depths from the heated surface. Plots are shown for samples without (left) or with intumescent (right) under different heating conditions. Note: Dashed lines show repeat samples.*

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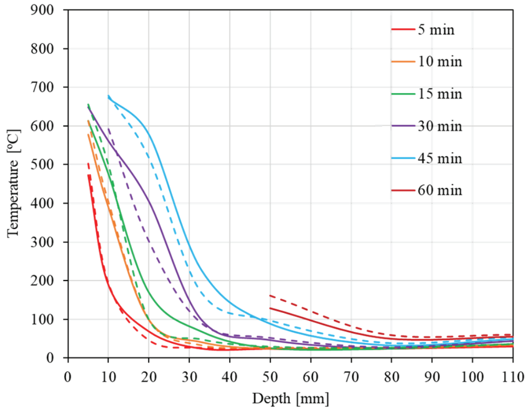
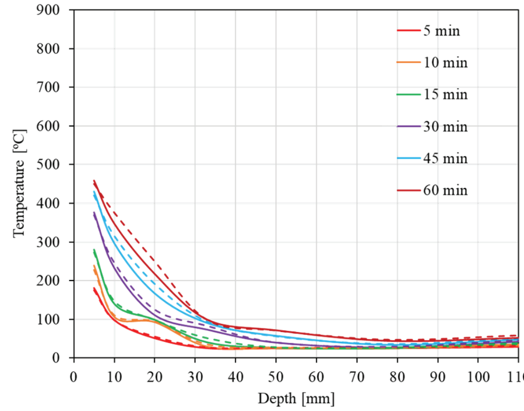
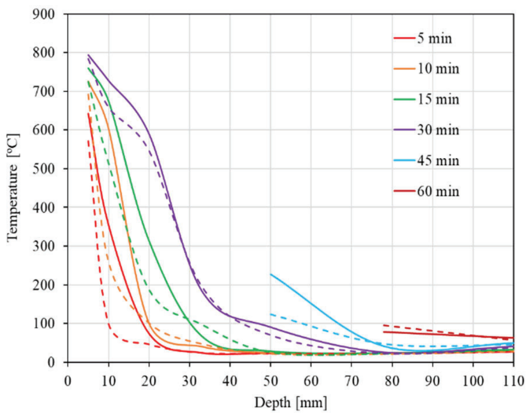


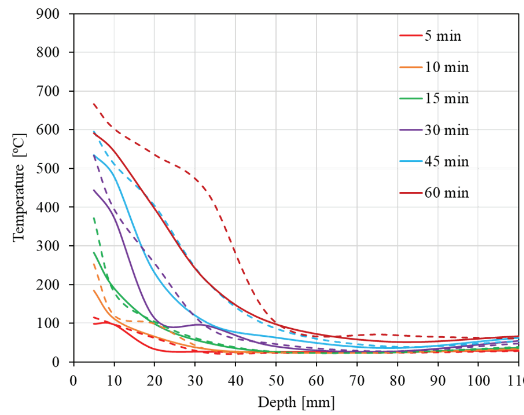
(I): Bare timber samples at 25 kW/m^2



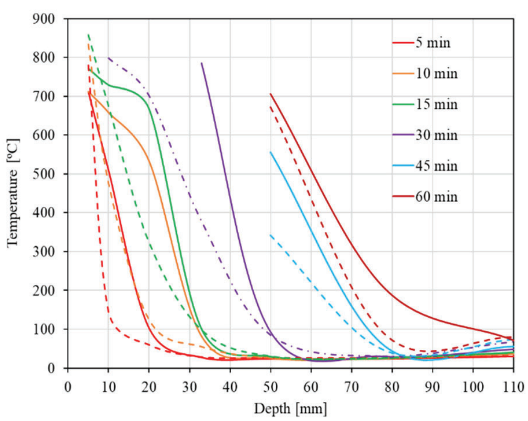
(II): Intumescent-coated timber samples at 25 kW/m^2



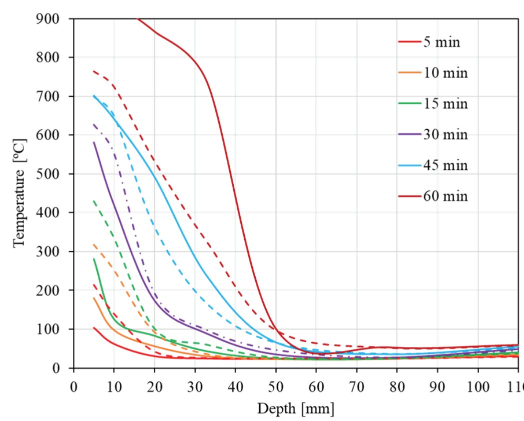
(III): Bare timber samples at 50 kW/m^2



(IV): Intumescent-coated timber samples at 50 kW/m^2



(V): Bare timber samples at 75 kW/m^2

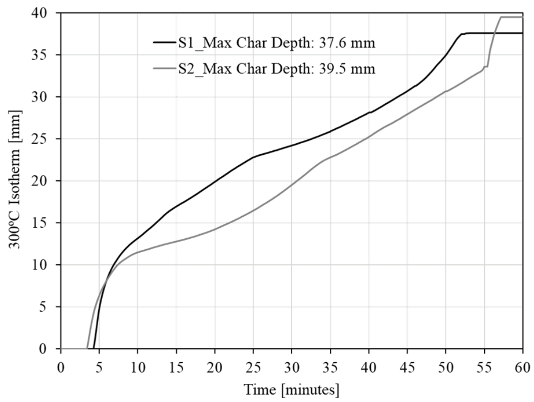


(VI): Intumescent-coated timber samples at 75 kW/m^2

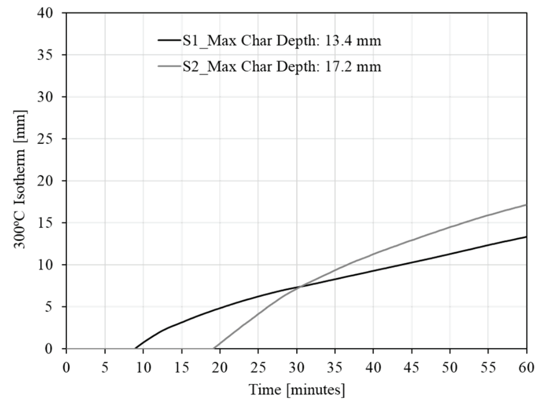
Figure 5: *In-depth temperature vs. depth from the heated surface at discrete times. Plots are shown for samples without (left) or with intumescent (right) under different heating conditions. Note: Dashed lines show repeat samples*

3.2 CHARRING OF TIMBER

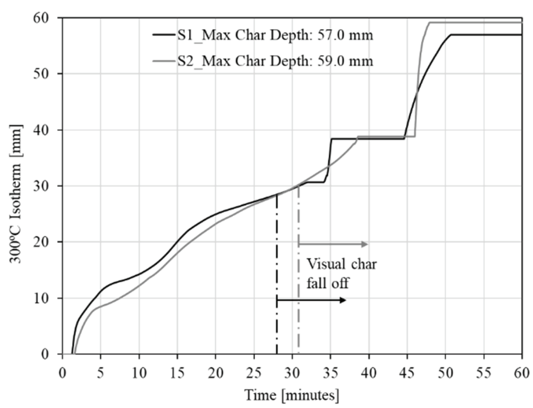
Figure 6 shows char depth from the heated surface against time. As noted before, the char front is assumed to be aligned with the 300 °C isotherm. In addition, the mean charring rate is calculated from the char depth data during heating; a summary of this data is provided in Table 2.



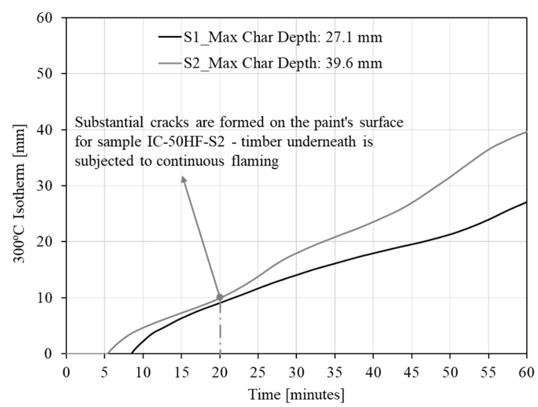
(I): Bare timber samples at 25 kW/m^2



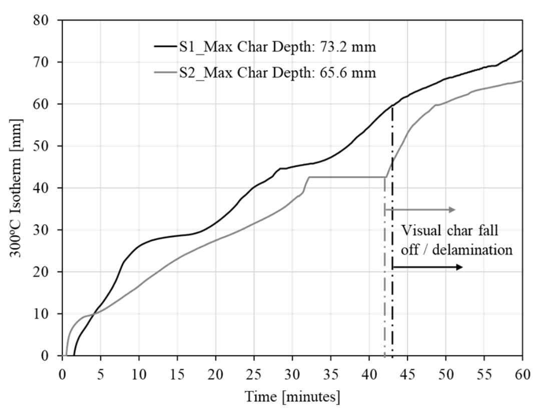
(II): Intumescent-coated timber samples at 25 kW/m^2



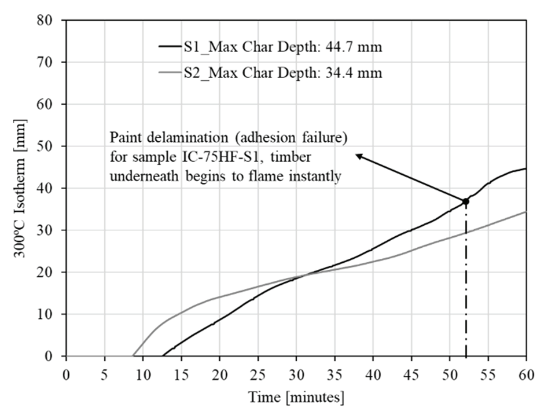
(III): Bare timber samples at 50 kW/m^2



(IV): Intumescent-coated timber samples at 50 kW/m^2



(V): Bare timber samples at 75 kW/m^2



(VI): Intumescent-coated timber samples at 75 kW/m^2

Figure 6: *Char depth from the heated surface vs. time – based on 300 °C isotherm. Plots are shown for samples without (left) or with intumescent (right) under different heating conditions. Note: Vertical axis scale varies per heating condition.*

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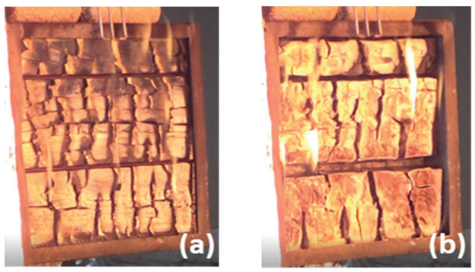
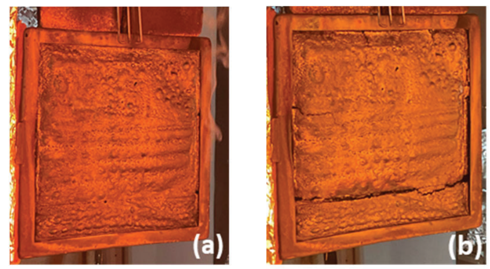
The condition of a typical test sample during fire testing is shown in Figure 7 for both coated and bare timber samples. Specifically, the exposed sample's surface at the beginning of the test (10 min) and near the end (45 min) under different heating conditions.



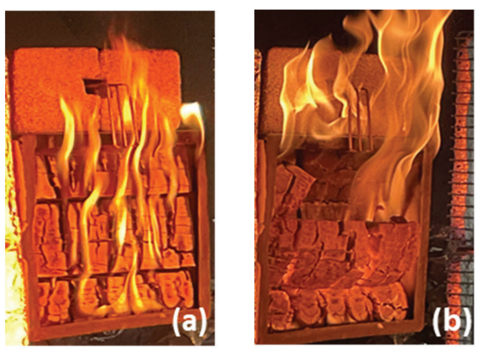
(I): Bare timber samples at <u>25 kW/m^2</u>

10 min (a); 45 min (b)



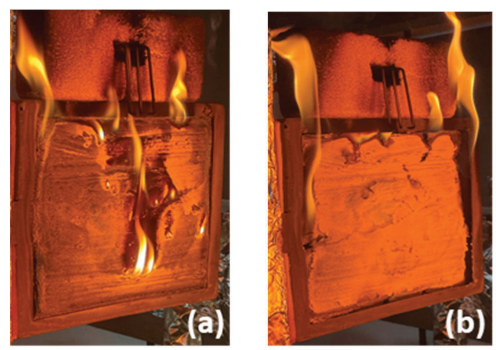
(II): Intumescent-coated timber samples at <u>25 kW/m^2</u>

10 min (a); 45 min (b)



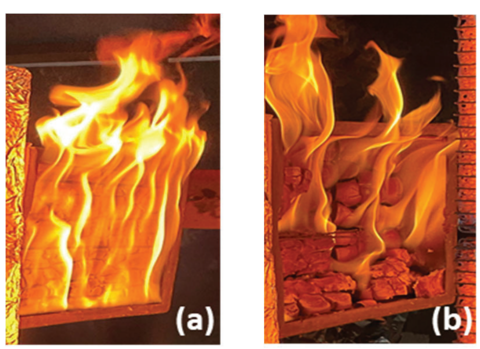
(III): Bare timber samples at <u>50 kW/m^2</u>

10 min (a); 45 min (b)



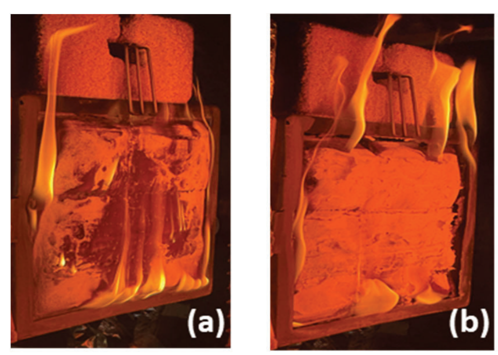
(IV): Intumescent-coated timber samples at <u>50 kW/m^2</u>

10 min (a); 45 min (b)



(V): Bare timber samples at <u>75 kW/m^2</u>

10 min (a); 45 min (b)



(VI): Intumescent-coated timber samples at <u>75 kW/m^2</u>

10 min (a); 45 min (b)

Figure 7: *Photographs showing the condition of a typical test sample during fire testing; early in the test (10 min) and towards the end (45 min). These are shown for samples without (left) or with intumescent (right) during varied heating conditions.*

4 ANALYSIS OF RESULTS

4.1 INFLUENCE OF INTUMESCENT COATING

The thin intumescent coating influence in the charring rate of the tested timber samples is summarised as follows:

Onset of charring – As shown from plots in Figure 6, there is at least a 5-min-delay on the onset of charring for timber samples with intumescent coating when compared to bare timber samples, irrespective of the heating condition.

In-depth charring rate – For the lowest heating condition (25 kW/m^2), a ~60 % reduction in the mean measured charring rate was observed for coated timber samples when compared to bare timber, while for the higher incident radiant heat fluxes of 50 and 75 kW/m^2, the mean measured charring rate was reduced by ~40 %.

Further, where periods of plateaus are noticed for the measured char depths presented in Figure 6 (i.e., in-depth temperature at the given location < 300 °C, thus zero charring rate), this reflects periods during testing where the timber samples either didn't start charring (e.g., at the beginning of the experiment), or due to char fall off in bare timber samples exposing the thermocouples to gas phase. The latter results in a delay of the subsequent in-depth solid phase measurements, given the gas phase measurements were removed from the temperature data (see Figure 4 and Figure 5) at the point of thermocouple exposure, as these readings do not represent this study.

4.2 INFLUENCE OF HEATING CONDITION

As seen in Table 2 below, the charring rate is directly proportional to the incident radiant heat flux at the heated surface of timber (without or with intumescent coating). In addition, the coating application significantly delayed the timber's time-to-ignition for samples tested at the higher incident radiant heat fluxes (50 and 75 kW/m^2), and it prevented ignition altogether at 25 kW/m^2.

Table 2: *Mean measured charring rate and time-to-ignition.*

Sample ID	Time-to-ignition [sec]	Charring rate [mm/min]
BT-25	67 ± 5	0.65 ± 0.02
BT-50	14 ± 1	0.95 ± 0.02
BT-75	13 ± 1	1.11 ± 0.04
IC-25	no ignition	0.25 ± 0.04
IC-50	257 ± 62	0.56 ± 0.10
IC-75	229 ± 14	0.66 ± 0.09

Note: *Time-to-ignition and mean measured charring rate values in each row are from two tested samples (bare or with coating) at the specified heat flux condition. The charring rate is taken as the mean of the char depth's first derivative – based on the 300 °C isotherm derived from a smoothing spline fit [17, 18] for every time instant.*

4.3 OBSERVATIONS DURING TESTING

In addition to the above, the following relevant events were observed during testing:

- The intumescent coating generally began to crack first along the edges of the timber boards (85 mm wide). For samples tested at 50 and 75 kW/m^2, the swelled coating underwent considerable thermal degradation (i.e., oxidation) and regression during the fire tests.
- Although at the end (> 60 min) of the 25 kW/m^2 fire tests the coating remained in place and no flaming was observed at the heated surface, edge crack formation propagated causing the swelled coating to regress.
- Flaming combustion (during the 50, 75 kW/m^2 tests) of the coated timber samples was generally observed near the sides of the heated surface due to shrinkage and thermal degradation of the timber and coating, exposing the bare timber edges to direct radiant heat. There were also small pockets of poor paint formation near the centre of the samples – creating small gaps exposing timber to direct radiant heat, resulting to intermittent flaming of the timber underneath.
- Swelled intumescent coating fall off was observed during late stages of the fire tests (during heating or cooling) for samples tested at 50 and 75 kW/m^2 – e.g., IC-50-S2 (> 70 min) and IC-75-S1 (> 50 min). This resulted from adhesion failure of the oxidated coating or delamination of charred timber.

5 CONCLUSIONS

Based on the experimental outcomes described herein, the following can be concluded:

- The onset of timber charring was delayed for at least 5 min for the intumescent-coated samples, regardless of the heating condition.
- The mean measured in-depth charring rate of timber was greatly reduced when using intumescent coating – in the range of ~40 to 60 % depending on the severity of the heating condition.
- Timber ignition was either prevented at the lowest incident radiant heat flux (25 kW/m^2), or significantly delayed at more onerous heating conditions (50 and 75 kW/m^2) when using a thin intumescent coating – for the duration of the 60 min heating period.
- The integrity of the thin intumescent coating was challenged at high heating conditions, experiencing large crack formations, or fall off when tested at an incident radiant heat flux of 50 or 75 kW/m^2.

Future work, being part of this fire research, will include testing and analysis of the following campaigns – under the previously nominated heating conditions:

- Timber test samples with intumescent coating applied at a higher DFT of the same commercially available intumescent product presented herein; and
- Timber test samples with a transparent intumescent paint product, also at different coating thicknesses. This paint product is a water-based thin intumescent coating for timber substrates, generally applied at low DFTs (< 1 mm).

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