

The Fire Performance of Exposed Timber Panels

Bernice V. Y. Wong, Kong Fah Tee

Abstract—Cross-laminated timber is increasingly being used in the construction of high-rise buildings due to its simple manufacturing system. In term of fire resistance, cross-laminated timber panels are promoted as having excellent fire resistance, comparable to that of non-combustible materials and to heavy timber construction, due to the ability of thick wood assemblies to char slowly at a predictable rate while maintaining most of their strength during the fire exposure. This paper presents an overview of fire performance of cross-laminated timber and evaluation of its resistance to elevated temperature in comparison to homogeneous timber panels. Charring rates for cross-laminated timber panels of those obtained experimentally were compared with those provided by Eurocode simplified calculation methods.

Keywords—Timber structure, cross-laminated timber, charring rate, timber fire resistance.

I. INTRODUCTION

TIMBER frame is one of the fastest growing modern method of construction in the United Kingdom (UK), as wood is effectively carbon neutral, with timber frame benefiting from being the only organic, non-toxic and naturally renewable building material, whilst minimizing energy consumption. In recent years many developments have been made in relation to timber technology and construction products. For heavy timber construction, cross-laminated timber (CLT) panel load bearing wall and floor assemblies system is becoming increasingly common. Cross-laminated timber, commonly referred to as CLT was originally developed in Switzerland in the 1970s as an extension of plywood technology. The potential of CLT construction is beginning to be recognized in the UK with the construction of a number of CLT buildings in the residential and educational sectors. CLT is commonly produced in Austria where planks of timber, typically spruce or pine, are stacked and glued together under high pressure bonding system in perpendicular layers. These solid timber panels, with thickness varies from 50mm to 300mm in 3 to 8 layers, are cut to size in the factory according to the structural drawings taking into account openings such as doors, windows and stairwells, using layers of softwood planks glued together with each layer arranged at right angles to one another (Fig. 1), and are delivered to site ready for immediate erection of walls, floors and roofs.

The benefits of this huge building system are the good structural performance, thermal and acoustic insulation characteristics, the great prefabrication, and the rapidity of erection [1]. The use of large solid timber panels is also

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favorable case of fire, as the risk of fire spread through void cavities is reduced in comparison to light timber frame constructions. Although, large solid timber panels increase the fire load in the room.

In recent years advanced and simplified calculation methods have been recommended for analyzing how timber behaves when exposed to elevated temperatures [2]. Experimental investigations on small and large scale tests of unloaded and loaded cross-laminated timber specimens manufactured by various producers with different characteristics have been carried out [3]-[5]. The outcome of the tests revealed that the fire behavior of cross-laminated timber elements were mostly linked to the thickness of the layers and the type of adhesive used to produce the cross-laminated timber panels [1]. Analytical and numerical methods are effective ways to study the mechanical and thermal performance of cross-laminated timber elements exposed to fire without performing experimental tests which are hazardous and expensive [1].

This paper gives an overview of fire performance of CLT; the charring rates for CLT panels obtained from available experimental results were compared with those calculated by using the European design standard part 5, EN 1995-1-2 [2] simplified calculation methods. The fire behavior of CLT panel is being studied by using finite-element numerical approach, the studies however at the preliminary stage are still under investigation.

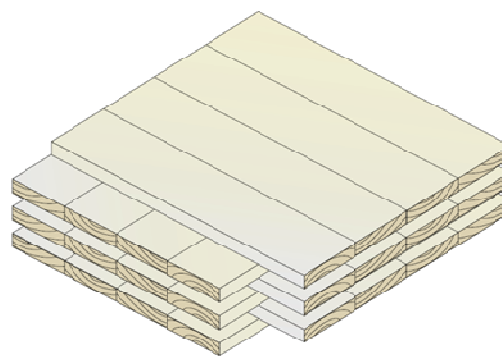


Fig. 1 Individual timber panels used to make a typical CLT [6]

II. FIRE BEHAVIOR OF TIMBER

All buildings must be constructed to meet national building regulations, which requirements for fire resistance. The fire resistance rating of a building assembly has traditionally been assessed by subjecting a replicate of the assembly to ISO 834 standard fire-resistance test [7]. In term of fire resistance, a structural element should not collapse or deflect beyond the permitted levels when subjected to the applied load throughout the fire test. Combustible building materials like timber burn

on their surface, release energy and thus contribute to fire propagation and the development of smoke in case of fire. It is often perceived that timber will perform unsatisfactorily during a fire situation; this is not necessarily the case as timber burns slowly and resists heat penetration by the formation of a self-insulating char (at 300°C), for panel that made from European Whitewood, its chars at a slow and known rate of 0.67 mm/min (40 mm per hour). When large timber members are subjected to fire, the uncharred inner portion maintains its strength, giving the structure a higher survival factor and more importantly, it retains its structural integrity being one of the reasons why large timber sections can often be used in unprotected situations where non-combustible materials such as steel would require special fire protection.

III. CHARRING RATE OF TIMBER

When exposed to heat of a fire, timber undergoes a thermal breakdown (pyrolysis) into combustible gases. Pyrolysis takes place in the timber when they are exposed to elevated temperatures between 150°C to 200°C. A layer of charcoal forms on the burning surface, the char layer grows in thickness as the fire grows, reducing the cross-sectional dimensions of the wood element. The char layer is a poor thermal conductor and protects the un-charred remaining residual cross-section from fire.

For unprotected wood surfaces throughout the duration of fire exposure, the charring rate β_0 for one-dimensional charring is assumed to be constant with time. EN 1995-1-2 [2] gives a value of $\beta_0 = 0.65$ mm/min for softwood, this has been confirmed by number of experimental studies [8], [9]. For beam and column section, in order to take into account the effects of corner roundings, to simplify the calculation of cross-sectional properties such as area, section modulus and second moment of area by assuming an equivalent rectangular residual cross-section, notional charring rates β_n are used. The charring rules are reasonably adequate for rectangular cross-sections that are exposed on three or four sides, or slabs exposed on one side, although this only applies when the timber is being exposed to ISO standard fire [7] and are to be adopted for determining of fire resistance criterion R. The effect of increased charring rate when the residual cross-section becomes very-small has not been taking into consideration, the reason is that mechanical resistance will be exhausted during that stage.

For protected timber surfaces, EN 1995-1-2 [2] suggested a simplified model taken into consideration the fact that different charring rates should be applied during different phases of the fire exposure. For timber surfaces with fire protection, the following have been taking into account;

- the time when the protection material starts charring (t_{ch})
- Charring of timber panel at reduced rate when protection material still in place
- the time when the protection material failed (fall off) (t_f)



Fig. 2 Charring of timber – one dimensional

- the increased charring of timber panel after the protection material have fallen off, as EN 1995-1-2 recommends $2\beta_0$, double the rate of initially unprotected surfaces, until the charring depth d_{char} (Fig. 2) has reached 25mm at time t_a
- the time when charring depth, $d_{char} = 25$ mm (t_a)
- Charring of timber panel back to normal rate after charred depth exceeds 25mm

When the timber is fire protected i.e. by gypsum boards, in the event of fire, the start of charring of the protected timber member is delayed by a calculated time (t_{ch}), which depends on the thickness of the fire boards. Unless otherwise specified, the time at which the fire protection fails (t_f) is assumed as the same time at which charring begins (i.e. $t_{ch} = t_f$) [2]. If charring is assumed to begin before fire protection fails (i.e. $t_{ch} < t_f$), it is calculated at a lower rate than the chosen charring rate (i.e. charring rate $< \beta_0$) until the calculated failure time of the fire protection. This reduced rate is based on the thickness of the protection layers. After the fire protection has failed, the charring rate is double ($2\beta_0$) the originally chosen value until the formation of a 25mm thick char layer. At this point the charring rate then reverts back to the originally chosen rate (i.e. β_0). Figs. 3 and 4 describe the charring depth vs. time relationship for initially protected timber surfaces according to EN 1995-1-2 [2].

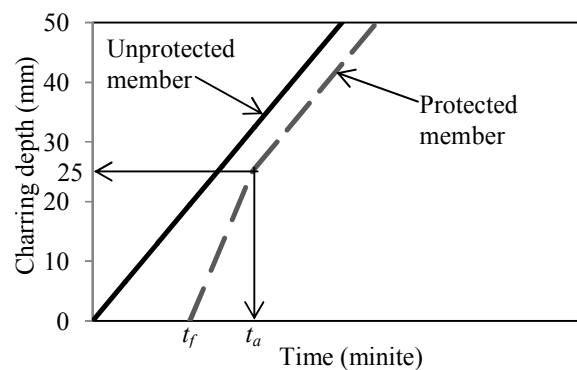


Fig. 3 Charring for initially protected timber surfaces according to EN 1995-1-2 [2] – Early failure of protection

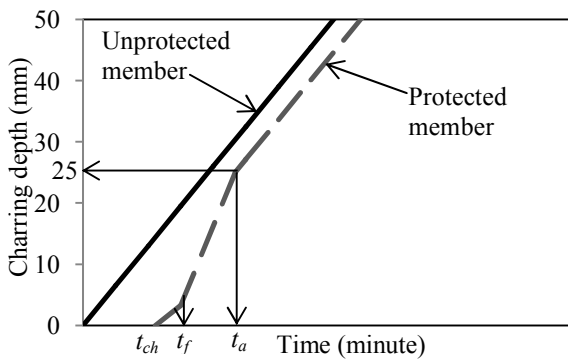


Fig. 4 Charring for initially protected timber surfaces according to EN 1995-1-2 [2] – delay failure of protection

IV. MECHANICAL RESISTANCE OF TIMBER IN FIRE

The European design standard part 5 [2] outlines design guide for timber structures. The Fire Part (Part 1.2) of the design standard was available in November 2004. Simplified method of calculating the mechanical resistance of timber members exposed to fire has been introduced, the residual load-bearing capacity of the charred timber structure can be calculated using one of two methods; the reduced cross-section charred timber member and reduced properties method.

A. Reduced Cross-Section Method

When timber is heated, a heat-affected zone of about 35mm to 40mm develops below the char layer. Strength and stiffness properties in the heated zone reduce as temperature rises. A zero strength layer (d_0) of depth 7mm immediately below the charred layer has been taken into account in charred section of the timber member, while the properties of the remaining cross-section are unchanged. The thickness of the zero-strength layer is defined such that the mechanical strength of the member, based on its total cross-section, minus the zero-strength and char layer, will theoretically possess an equivalent strength to that of an actual identical member subjected to the standard fire with the same char depth. The definition of residual cross-section and effective cross-section of charred timber is illustrated in Fig. 5.

The effective charring depth (d_{eff}) is therefore defined as;

$$d_{eff} = d_{char} + d_0 \quad (1)$$

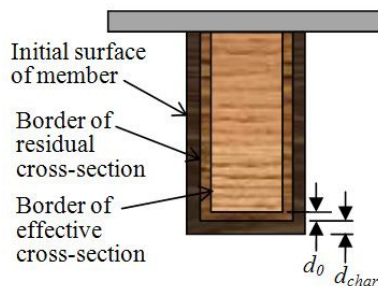


Fig. 5 Definition of residual cross-section and effective cross-section

B. Reduced Properties Method

The residual cross-section is determined by reducing the cross-section with the calculated total charring depth and only applies to rectangular cross-sections of softwood exposed to fire on three or four sides i.e. does not apply to timber panels used as walls or floor exposed to fire on one side only. In the case of fire, it is assumed that the residual cross-section has reduced properties which defined by multiplying the strength and stiffness properties for fresh wood with a modification factor ($k_{mod,fi}$). The residual load-bearing capacity of the residual cross-section is calculated based on the reduced properties of the wood at elevated temperatures.

Because the panels are cross-laminated, loads can be transferred in one direction i.e. for supports or girders, or on all sides, creating unique design opportunities.

V. FIRE BEHAVIOR OF CLT

The interest for CLT as a buildings system is increasing whilst for cross-laminated timber panels in fire only little information on charring is available. A few experimental investigations are available [3]-[5] on the fire behavior of cross-laminated timber panels. It has been revealed that, the fire behavior of cross-laminated solid timber panels is characterized by the behavior of the single layers. In the case of fire, if the charred layers of CLT panel remain in place, the charcoal protects the remaining uncharred layers of the cross-laminated timber solid panels against heat. In this case fire behavior similar to homogenous timber panels can be expected [3].

An increased charring is expected if the charred layers fell off after the panel system. This appearance is similar to the increased charring observed for protected timber surfaces after failure of the protection materials explained in Fig. 3.

The thickness of the CLT layers as well as the behavior of the bonding adhesive at elevated temperature can influence the falling of the charred layers [3], where CLT with thick layers behave better in fire than that of thin layers, due to the fact that CLT panels with thick layers should behave similar to homogenous timber panels and therefore the one-dimensional charring rate of 0.65 mm/min according to EN 1995-1-2 can be assumed, while CLT panels with thin layers should behave more like plywood and charring rate of 1.0 mm/min is assumed for plywood according to EN 1995-1-2 [2]. On the other hand, the fire resistance of a structural CLT element subjected to mechanical action however is not linearly related to the charring. The direction and the numbers of layers of CLT assembly play an important role in their structural behavior [10].

Observation from fire tests on CLT panels under ISO-fire exposure [4], [5], has suggested that at elevated temperatures falling off of the charred layers leading to increased charring rates in comparison to homogeneous timber panels. Similar effect to protected timber members after the fire protection has fallen off whereas for panels where no falling off of the charred layers the fire behavior was similar to that of homogeneous timber panels.

VI. PROPERTIES AND EFFECTS OF ADHESIVE IN FIRE

The adhesives are utilized to form bonds or joints between adhered materials such as metal, wood or plastic. In general only adhesive systems which are permitted to use in load-bearing timber structures according to EN 301 [11] and EN 15425 [12] or technical approvals, are allowed. For cross-laminated timber panel bonding system, Melamine-urea-formaldehyde (MUF) and one-component polyurethane adhesives (1K-PUR) are frequently used.

In general, the producers of CLT aim on reducing the width of gaps, at high temperature the performance of the assembled timber member depends highly on the resistance of laminating adhesives to elevated temperatures. Upon the bonding of the timber panel elements, adhesive film is placed between the pieces of two materials, which are commonly less flammable, and the film is not subjected to direct fire. Therefore, the effect of the adhesive joint on the fire hazard safety of an adhesive bonded panel is indirect. The investigation on the influence of the temperature-dependent material properties of the adhesive on the resistance of glued laminated timber beams exposed to fire have been carried out [13], and it was demonstrated that in fire, the behavior of adhesive that used in the bond-line between the lamellas has little influence on the resistance of the glued laminated timber beam and anticipated that the fire resistance will be governed by the bending resistance rather than shear resistance.

A series of tests were conducted to study the shear behavior of different adhesives at high temperatures, has demonstrated that the fire behavior of cross-laminated timber panels is strongly influenced by the behavior of the adhesive that used for the cross-laminated timber panels bonding system [5] and [14]. Cross-laminated timber panels manufactured with a less temperature-sensitive adhesive the charred layers almost remained in place throughout the fire tests and the panels behave just similar to homogenous timber panels exposed to ISO 834 [7] on one side. The tests result has demonstrated that the measured charring rate of these timber panels has lower rate than the one-dimensional charring rate of 0.65 mm/min that assumed for solid timber according to EN 1995-1-2 [2].

Moreover, the thermal behavior of one component polyurethane systems can be greatly varied by modifying their chemical structure. Test results based on 1K-PUR are therefore not valid for other polyurethane adhesives [5].

VII. CHARRING RATE OF CLT

A. Experimental Finding

In recent years, a series of fire tests on cross-laminated timber panels have been conducted [3]-[5] and [15], to analyze the fire behavior of timber panels when exposed to ISO 834 [7]. In the experiments, test specimens were made up of two to four layers of CLT panel, with layer thicknesses ranged from 9mm to 30mm.

Fig. 6 shows measured charring depth for the six tested CLT panels $6 \times 9\text{mm}$, $4 \times 10\text{mm}$, $5 \times 17\text{mm}$, $3 \times 20\text{mm}$, $3 \times 28\text{mm}$ and $2 \times 30\text{mm}$, compares with the charring depth calculated by using simplified linear model suggested by EN 1995-1-2 [2] for unprotected homogenous timber panel, with a value of 0.65 mm/min was used for the one-dimensional charring of the panel.

It can be seen that at the beginning of the charring process, cross-laminated timber with 2 layers of 30mm panels showed good agreement with the simplified model, until the charred layer reached 30mm, an increase of charring rate has been observed from the test; this fact explains the increase of charring rate to the second layer as the first charred layer fall off. The same effect for initially protected timber members after the fire protection has fall off.

Fig. 6 also illustrates that cross-laminated timber with thick panel layer show a better fire performance in comparison to CLT with thin panel layer. Comparisons were made in between CLT made from five layers of 17mm panels (85mm) and three layers of 28mm panels (84mm). For CLT with thin layers, the first layer fall off at around 24 minutes, whereas CLT with thick layers has the first charred layer fall off after 41 minutes. At 60 minutes, the CLT charred depth was 76mm and 52mm, for thin layers panel and thick layers panel respectively.

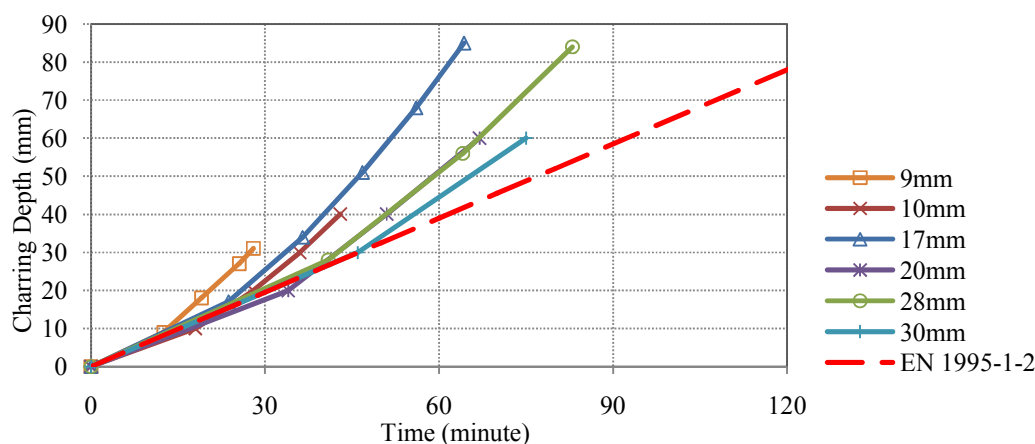


Fig. 6 Measured charring depth for CLT panels with layer thicknesses of 9, 10, 17, 20, 28 and 30mm [3]-[5] and [15] compared with charring depth according to EN 1995-1-2 [2] for unprotected homogenous timber panel

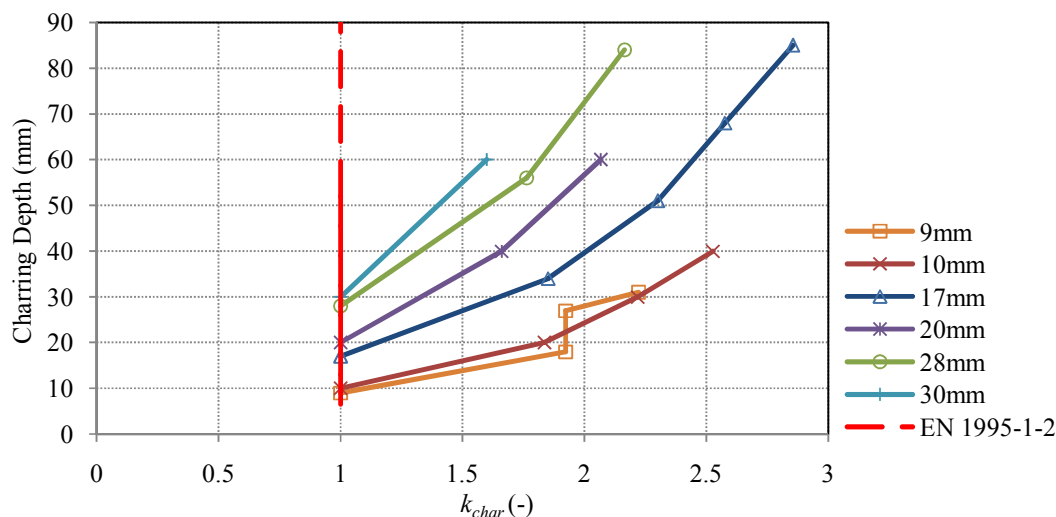


Fig. 7 Charring rate factor k_{char} for CLT panels with layer thicknesses of 9, 10, 17, 20, 28 and 30mm [3]-[5] and [15] compared with charring rate factor according to EN 1995-1-2 [2]

Fig. 7 shows charring depth as a function of char rate factor k_{char} for the six tests, CLT panels with 9, 10, 17, 20, 28 and 30mm of layer thickness. Charring rate factor is taken as the ratio of the charring rate of the CLT outer layer that exposed to fire ($\beta_{layer(1)}$) to the charring rate of the inner layer of the panel ($\beta_{layer(1+i)}$), and is expressed as the following:

$$k_{char} = \frac{\beta_{layer(1)}}{\beta_{layer(1+i)}} \quad (2)$$

It can be seen from Fig. 7 one-dimensional charring of the panel according to EN 1995-1-2 [2] for unprotected homogenous timber panel, a value of 0.65 mm/min is assumed to be constant throughout the fire, whereas results obtained from the six fire tests had shown that the fire behavior of CLT depends strongly on the number and thickness of the single layer, the effect of falling off of each layer after completed charred needs to be taken into account. Furthermore, the time when the completed charred layer falls off will also affect the increases of charring rate of the next layer; this is due to the fact that the increasing of fire temperature as the fire progress.

Comparisons were made in between CLT made from five layers of 17mm panels (85mm) and three layers of 28mm panels (84mm). Table I summaries the calculated charring rate factors for the 5×17 mm and 3×28 mm CLT panels. For CLT with 5×17 mm panels, charring rate of the second layer increase by 85% as compared to its first layer. After the second charred layer fall off, the third and fourth layers of the CLT panel charred at even higher rate, which is up more than double the initial rate. The fifth layer of the panel charred at 2.048 mm/min; almost triple the initial charring rate of 0.717 mm/min of its first layer, as shown in Table I and Fig. 7.

For CLT with 3×28 mm panels, after the first layer of the panel falls off, the second layer charred at 1.207 mm/min, almost 1.8 times the charring rate of the first layer. The k_{char} value of the last layer of the panel calculated to be 2.164, shown that the layer charred more than double the first layer of the CLT panel. This indicates the effect of falling off of

each layer after completed charred and the effect of time when the completed charred layer falls off, as well as the number and thickness of the single layers.

TABLE I
CHARRING RATE FACTOR (k_{char}) CALCULATED AFTER EACH LAYER OF THE CROSS-LAMINATED TIMBER PANEL IS COMPLETED CHARRED

CLT made from five layers of 17mm panel (85mm)			
Time (min)	d_{char} (mm)	β_{layer} (mm/min)	k_{char}
0	0		
23.7	17	0.717	1
36.5	34	1.328	1.852
46.8	51	1.650	2.301
56	68	1.848	2.576
64.3	85	2.048	2.855
CLT made from three layers of 28mm panel (84mm)			
Time (min)	d_{char} (mm)	β_{layer} (mm/min)	k_{char}
0	0		
40.9	28	0.685	1
64.1	56	1.207	1.763
83	84	1.481	2.164

B. Simplified Calculation Analysis

To date, there have been limited tests on CLT in fire, and no published literature has been found regarding the charring rate of CLT timber panel. EN 1995-1-2 [2] provides a simplified calculation method for the determination of the charring rate for protected softwood exposed to ISO 834 [7]. The effect for initially protected timber members after the fire protection has fall off and the increase of charring rate to the second layer as the CLT panel first charred layer fall off have been found having the same principle [3]-[5].

Fig. 8 illustrates the char depth vs. time, determined based on the calculation of the fire resistance of constructions with different layer thicknesses according to EN 1995-1-2 [2], and compared with the experimental results [4], [5].

The charring depth presented by the EN 1995-1-2(a) line was determined based on the European code [2] as expressed in Fig. 3. For line EN 1995-1-2(b) the charring depth has been calculated taken into account the subsequent fire-exposed layers, it is necessary to mathematically estimate an increased charring rate until the formation of a new 25mm thick char layer, the charring rate is suggested as below;

- 0.65 mm/min if only one layer is affected by exposure to fire;
- 1.30 mm/min for any additional layers affected by exposure to fire until charring or the formation of a 25mm thick char layer;
- a charring rate of 0.65 mm/min may be applied up to the next bonded joint.

From Fig. 8 it can be seen that, the best agreement between calculated and measured charring depth is observed for fire test performed with the cross-laminated timber panel with two layers 30mm. The effect of the increase of the charring rate can be seen from the test, the differences between calculated

and measured charring depth are very small.

The specimens with three layers of 20mm panel showed reasonable good agreement with the calculated values for the first and second layer. It should be note that a slightly higher charring rate of the first layer has been measured from the fire test as compared to the value of 0.65 mm/min assumed for the calculation according to EN 1995-1-2 [2]. Result from the fire test has shown that after second charred layer has fall off, there was no significant change in term of the charring rate, although the calculated values for EN 1995-1-2(b) has conservatively assumed a charring rate of 1.30 mm/min to be used for any additional layers affected by exposure to fire until charring or the formation of a 25mm thick char layer. The calculated values for EN 1995-1-2(a) assumed a 0.65 mm/min to the third layer give non-conservative estimation.

The effect of the increase of the charring rate can be seen from the test specimen with four layers of 10mm panel. The comparison between fire test and calculated values (Fig. 8) showed that the simplified models lead to safe results.

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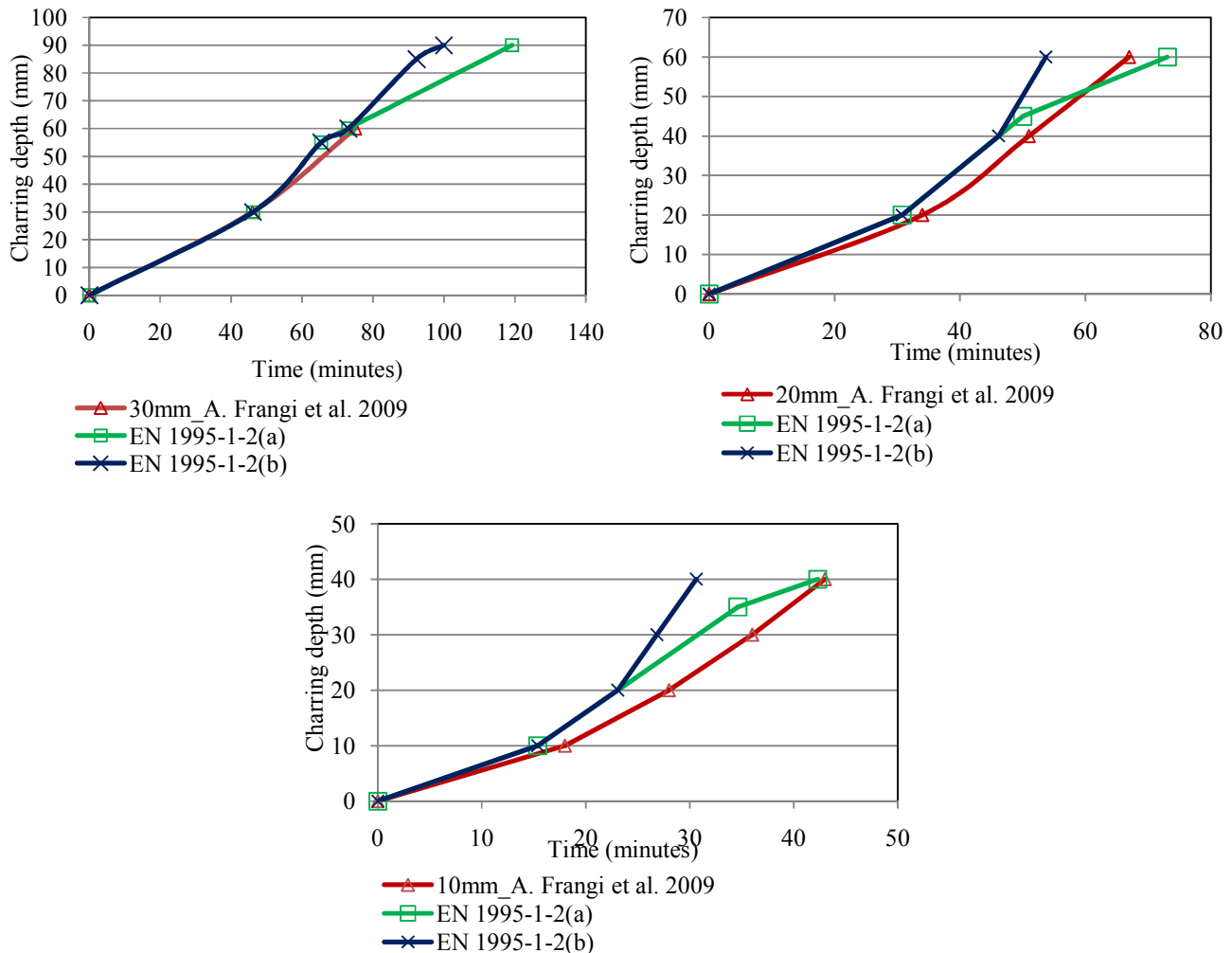


Fig. 8 Charring depth for CLT panels with layer thicknesses of 10, 20 and 30mm [5] compared with EN 1995-1-2 [2]

VIII. CONCLUSIONS

From the overview of available experimental results [3]-[5] and comparisons made between test results and simplified models [2] the following conclusions can be drawn:

- It was found that charring rate increased once a panel falls off, in which case, the fire resistance of CLT depends on the number and thickness of layers; whereas if individual layers do not fall off, charring behavior is similar to solid timber panels.
- Experimental results [5] showed that PU adhesives failed in fire, causing the charred layers to fall off, whereas the MUF adhesives held the charred layers.
- The calculations of the charring depth of cross-laminated timber panels should take into account the influence of the falling of charred layers, thickness of a single layer plays a significant role on the charring rate of CLT.
- EN 1995-1-2 [2] provides simplified model for homogenous timber but not overly conservative design methods for cross-laminated timber. Due to the limited number of fire tests on cross-laminated timber panel, it is not possible to conclude a suggestion of value for CLT panel charring rate.
- Fire behavior of CLT panel is being studied by using finite-element numerical approach, in order to extend and confirm the results of the experimental and simplified models performed. The studies however at the preliminary stage are still under investigation, the work will be presenting in the next stage.

REFERENCES

- [1] M. Fragiaco, A. Menis, I. Clemente, G. Boichichio, B. Tessadri, "Experimental and Numerical Behaviour of Cross Laminated Timber Floors in Fire Conditions," in *Proc. of World Conference on Timber Engineering*, Auckland, 2012.
- [2] CEN (European Committee for Standardization), "BS EN 1995-1-2 Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design," Brussels: BSI, 2004.
- [3] A. Frangi, G. Boichichio, & A. Ceccotti, "Natural full-scale fire test on a 3 storey xlam timber building," in *Proc. of 10th World Conference on Timber Engineering*, Japan, 2008.
- [4] A. Frangi, M. Fontana, M. Knobloch, & G. Boichichio, "Fire Behaviour of Cross-Laminated Solid Timber Panels". *Fire Safety Science*, vol. 9, pp. 1279-1290, 2009.
- [5] A. Frangi, M. Fontana, E. Hugi, & R. Jöbstl, "Experimental analysis of cross-laminated timber panels in fire", *Fire Safety Journal*, vol. 44 (8) pp. 1078-1087, 2009.
- [6] E. Karacabeyli, B. Douglas, *Cross Laminated Timber (CLT) Handbook: Introduction to cross-laminated timber*. FPInnovations, 2013.
- [7] ISO 834-1: Fire-resistance Tests—Elements of Building Construction—Part 1: General Requirements, International Organization for Standardization, 1999.
- [8] A. Frangi, & M. Fontana, "Charring rates and temperature profiles of wood sections," *Fire and Materials*, (27), pp.91-102, 2003.
- [9] E.L. Schaffer, "Charring rate of selected woods-transverse to grain," Research paper FPL-69. USDA Forest Product Laboratory, Madison, Wisconsin, USA, 1967.
- [10] J. K'onig & J. Schmid, "Bonded timber deck plates in fire," CIB W18, Meeting 40, Bled, Slovenia. Proceedings edited by Lehrstuhl für Ingenieurholzbau, University of Karlsruhe, Karlsruhe, Germany, 2007.
- [11] EN 301:2006-06, "Adhesives, phenolic and aminoplastic, for load-bearing timber structures – Classification and performance requirements."
- [12] EN 15425:2008-02, "Adhesives – One component polyurethane adhesives for load bearing timber structures – Classification and performance requirements."
- [13] M. Klippel, A. Frangi & M. Fontana, "Influence of the Adhesive on the Load Carrying Capacity of Glued Laminated Timber Members in Fire," in *Proc. of the 10th International Symposium of the International Association for Fire Safety Science*, Maryland, USA, pp. 1219-1232, June 2011.
- [14] A. Frangi, M. Fontana, A. Mischler, "Shear behaviour of bond lines in glued laminated timber beams at high temperatures," *Wood Science and Technology* 38, pp.119-126, 2004.
- [15] J. K'onig & L. Walleij, "Timber Frame Assemblies Exposed to Standard and Parametric Fires. Part 2: A Design Model for Standard Fire Exposure," Tra`tek – Swedish Institute for Wood Technology Research, Stockholm, Sweden, Report no 10001001, 2000.