# Fire Performance of Unprotected Cross Laminated Timber Panel

Kong Fah Tee
University of Greenwich, Kent, UK
Email: K.F.Tee@gre.ac.uk

Bernice V.Y. Wong
Hydrock, London, UK
Email: BerniceWong@hydrock.com

Joanna Woszczak
University of Greenwich, Kent, UK
Email: woszczak.joanna@gmail.com

***Abstract*— The main objective of this paper is to define the fire performance of unprotected Cross Laminated Timber (CLT) floor panel by comparing available experimental results with numerical and analytical analysis. A numerical model of multi-layered CLT panel is implemented in ABAQUS using Finite Element Method (FEM), while analytical analysis based on simplified design method known as the Reduced Cross-Section Method proposed by Eurocode 5, Part 1-2. Mechanical and thermal analysis of unprotected, 5-layer CLT panels is performed to simulate bending test at ambient temperature and during fire condition. Temperature distribution within the cross-section of the slab panel has been investigated and the fire resistance of the loaded timber elements has been evaluated. The overall results obtained from the numerical and analytical analysis show level of agreement is satisfactory as compared with the experimental data.**

***Index Terms*— cross laminated timber, fire resistance, thermal analysis, thermo-mechanical analysis, FEM.**

## I. Introduction

Fire resistance of timber structures raises many divergent opinions and emotions. Among the main materials used in building construction processes (timber, steel, concrete, ceramics, aluminum), timber is the only flammable material and in general this material is considered to have zero fire resistance [1]. A complex numerical model calibrated with data collected during laboratory experiments gives an opportunity to execute parametric studies with various material properties (geometrical, mechanical and thermal), as well as external loads or different boundary conditions [2]-[3].

This paper presents the evaluation of the fire resistance of multi-layered CLT panel; the proposed analysis will be undertaken in three main stages. At first, simple bending deflection analysis will be carried out in ABAQUS to examine the accuracy of the assumed material parameters, selected type of analysis and proposed simplified static scheme of the element. The main aim of this step is to reduce the potential errors that may be found in the FE model. The outcome of these exercises is compared with available test results [4]. The second part is to examine the CLT panel behaviour under fire conditions, both analytically and numerically. The final step is analytical-numerical comparison which will be performed to confirm the FE model accuracy. The overall aim of the proposed program and methodology is to set up the reliable FE model which can be introduced as a tool for predicting timber behaviour in fire without the need for expensive laboratory testing.

## II. Mechanical Analysis of CLT Panel at Ambient Temperature

### A. *Large Scale Fire Test*

Four-point bending test at ambient temperature was carried out at Ivalsa Trees and Timber Institution in San Michele all'Adige (CNR-IVALSA), Italy. Specimens tested in the laboratory have been divided into two series. First one (series "S") presents 5-layer CLT with different layers thickness: 42, 19, 28, 19, 42mm, produced using C24 strength class boards joined together with polyurethane (PU) adhesive. Another one (series "M") describes 5-layer CLT with the thickness equal 5x19mm, boards strength class C24 and glued with melamine urea formaldehyde (MUF) resin.

The simply supported 5000 mm span CLT specimens were loaded out-of-plane at the third points using two jacks distant 1700 mm from each other. Five linear voltage displacement transducers (LVDTs) were positioned on each specimen to record deflections close to the supports, at 100 mm from the supports, and at mid-span. The deflections other than at mid-span were found to be negligible. The results evaluated from experimental bending test shows the maximum failure load applied $P_u$, the bending resistance $f_{m,i}$ and the modulus of elasticity

Manuscript received August 8, 2019; revised March 29, 2020.


doi: 10.18178/ijscer.9.2.114-120

recorded for each specimen for panels series ‘S’ and ‘M’ (Table I).

TABLE I. EXPERIMENTAL RESULTS OF BENDING TEST ON CLT PANEL OF SERIES A) “S” AND B)”M” AT AMBIENT TEMPERATURE

(A)

| Specimen No. | $P_u$ [kN] | $f_{m,i}$ [N/mm$^2$] | $E_{m,g,i}$ [N/mm$^2$] |
|---|---|---|---|
| 1 | 116.62 | 46.41 | 12922 |
| 2 | 124.70 | 49.63 | 13746 |
| 3 | 91.44 | 36.39 | 12007 |
| 4 | 106.54 | 42.40 | 12657 |
| 5 | 86.60 | 34.54 | 12358 |
| 6 | 112.26 | 44.68 | 13039 |
| 7 | 105.66 | 42.05 | 11731 |
| 8 | 96.10 | 38.25 | 12055 |
| Mean Value | 105.02 | 41.79 | 12564 |
| Stand. Deviat. | 12.95 | 5.15 | 662 |

(B)

| Specimen No. | $P_u$ [kN] | $f_{m,i}$ [N/mm$^2$] | $E_{m,g,i}$ [N/mm$^2$] |
|---|---|---|---|
| 1 | 33.04 | 38.13 | 10745 |
| 2 | 26.80 | 30.93 | 10449 |
| 3 | 30.28 | 34.95 | 10468 |
| Mean Value | 30.04 | 34.67 | 10554 |
| Stand. Deviat. | 3.13 | 3.61 | 166 |

## B. *Bending Analysis – FE Modelling*

Both building and solving of a Finite Element model requires prior preparation of detailed information on the material properties, boundary conditions, geometry configuration, loadings cases (if applicable) and even indicative failure modes. Collection of these information helps to select type of analysis, mesh arrangement, and constitutive models along with proper numerical controls for stability. Two numerical models have been implemented in ABAQUS software. First model simulates experimental bending analysis of CLT samples from series “S”, while second model evaluates numerical results from experiments carried out on samples from series “M”. The assumed static schemes consider half of longitudinal sections of specimens (based on symmetry assumption). Both static schemes are in the form of beam with roller support on left end and constraint allowing only for vertical displacement on right end.

The cross-section of the CLT panel in the FEM modelling has been divided into 5 separate layers (3 parallel layers and 2 perpendicular layers) and each layer has been assigned with corresponding material type (parallel and perpendicular respectively). Each material type has been specified as linear elastic with isotropic behaviour. Young’s Modulus parallel to the grain has been assumed based on mean value obtained from experimental tests – E0=12564 N/mm$^2$ for CLT series “S” and E0=10554 N/mm$^2$ for CLT series “M”. Young’s Modulus perpendicular to grain has been assumed E90=E0/30 [5] and are equal to E90=418 N/mm$^2$for CLT series “S” and E90=352 N/mm$^2$. Poisson’s ratios are equal to 0.3 and 0.5 for parallel and perpendicular layers, respectively. Maximum load applied in model has been assumed based on average failure load readings from experimental tests, and so equal to $P_u$=105kN (series “S”) and $P_u$=35kN (series “M”). An important factor influencing the accuracy of the analysis is the density of the mesh assigned to the elements. In general, it can be stated that the denser the grid, the more accurate the results of the analysis. The mesh size chosen for CLT series “S” divides the model into 600 elements (with varied widths and 50mm length) and for series “M”, 750 elements have been used (6.3mm wide and 50mm long).

## C. *Experimental-Numerical Comparison*

Comparison in terms of mid-span deflection has been made between that was obtained from the experimental and FE analysis as shown in Fig. 1. It has been demonstrated that the numerical and experimental results have shown good agreement; the CLT panel bending behaviour at ambient temperature has been accurately predicted.

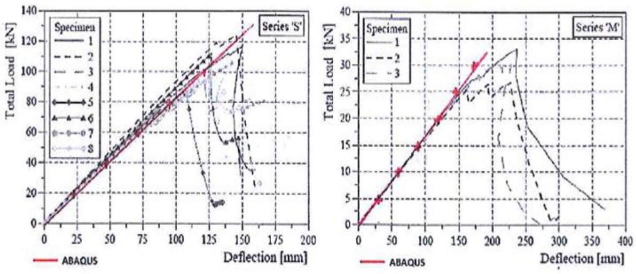



Figure 1. Experimental-numerical comparison of bending mid-span deflection at ambient temperature.

## III. THERMAL ANALYSIS OF CLT PANEL IN FIRE SCENARIO

## A. *Experimental Fire Test at CNR-IVALSA*

Three large-scale fire tests have been performed at Ivalsa Trees and Timber Institute [4]. However, in this paper only one of them will be discussed. The tested CLT panel (specimen S1) was formed by 5-layers of Cross Laminated Timber panel and have been subjected to the large-scale fire test carried out at CNR-IVALSA. The size of the tested specimen is 150x600x5600mm with measured density of approximate 450kg/m$^3$and moisture content of 12%. The panel has been subjected to standard fire exposure as ISO from the bottom of the panel. The horizontal furnace has the 3mx5m opening. Temperature inside the furnace has been controlled by eight thermocouples and two temperature regulators. Specimen S1 was loaded out-of-plane with uniformly distributed load of 10kN/m$^2$ which is equivalent to 26% of the ultimate mean strength of panel at ambient conditions.

All the panels tested at the CNR-IVALSA were instrumented with thermocouples to record the temperature distribution within the cross-section during the fire test. The values of the charring depth have not been recorded directly during the test, as the tested specimen S1 has failed and fell inside the furnace. As suggested in Eurocode 5, Part 1-2 [6], the isotherm of 300 ° was assumed as a border line between the charred and heated wood. Based on the recorded temperatures at different location across the depths of the specimen, the charring rate $\beta_0$ has been calculated as a displacement rate of 300 ° isotherm within the CLT panel cross-section. At approximately one minute before the panel failed, the 300 ° isotherm reached one of the three thermocouples within the specimen which was 75mm from the exposed surface. After reaching 75mm, the temperature within the cross-section started to increase more rapidly due to a crack at the mid-span of the element. Based on these observations it could be revealed that the residual cross-section, about 75mm was no longer be capable to carry the applied load. The fire resistance of the CLT panel obtained from the fire test is 99 minutes.

### B. *Analytical Analysis of CLT in Fire Conditions*

In this section the charring rate and overall fire resistance of the CLT panel has been evaluated based on Eurocode 5 [6] and the result has been compared with the experimental data obtained from the fire tests performed at CNR-IVALSA. The experimental data is taken from specimens S3-I, S3-II and S3-V, in which charring rate is measured based on the residual cross-section of the unprotected specimens. The average value of charring rate is $\beta_0$=0.613mm/min, which is slightly lower than that suggested by the Eurocode, $\beta_0$=0.65mm/min. The small margin between the fire test and Eurocode approach may be influenced by following tests conditions [7]:

a) heating rate in the furnace was noticed to be slightly slower when compared to standard fire curve
b) the position of the specimen in the furnace
c) time needed to extinguish the specimens after the end of the fire test may increase the charring depth of the specimen

To evaluate fire resistance of the CLT panel, one-dimensional charring rate and Reduced Cross-Section Method (RCSM) that proposed in Eurocode 5, Part 1-2 has been adopted [8]-[9]. For slab panel, the corner rounding of timber element will not be considered in this analysis. To simplify, the charring rate calculations degrades down into single formula including 'zero-strength' layer for element subjected to high temperatures, as shown in Eq. (1) below:

$$d_{char,0}= \beta_0 t + k_0 d_0 \qquad (1)$$

where $d_{char,0}$ is the design charring depth for one-dimensional charring (mm);

$\beta_0$ is the one-dimensional design charring rate under standard fire exposure (mm/min);

t is the time of fire exposure (min);

$k_0$ is 'zero-strength' layer modification factor;

$d_0$ is 'zero-strength' layer (mm)

As previously mentioned, Eurocode 5 does not specify the charring rate for CLT panel. In this paper a charring rate $\beta_0$=0.65 mm/min is assumed. The 'zero-strength' layer is taken as $d_0$=7mm, and the 'zero strength' layer modification factor are defined as follows:

$$k_0 = 1/t \text{ for } t < 20 \text{ min and } k_0 = 1 \text{ for } t > 20 \text{ min} \qquad (2)$$

Based on the bending test for Series 'S' (Table 1a), the bending resistance of the CLT panel is taken as $f_{m,i}$=41.79kN/mm². The panel is subjected to UDL of 10kN/m². The dead load of the CLT panel is determined by assuming the density of panel equals to 450kg/m³. The cross- sectional dimension of the element is 600mm in width, 150mm in depth and the total length is 5000mm. The fire resistance period of the CLT panel is 97.8 minutes according to the fire test whereas the calculated fire resistance of the CLT panel based on RCSM (Eurocode 5, Part 1-2) is calculated to be 103 minutes, which is slightly overestimated compared to the experimental result. In terms of charred depth, the measured charred depth from the fire test is 75mm and the estimated charred depth from the analytical method is calculated to be 74mm, which has shown a very good agreement.

### C. *FE Modelling*

In the FE modelling, only the unprotected specimen in series 'S' (S1) has been analysed and load case is ignored in the analysis. The 2D FE model was subjected to one-dimensional (1D) fire exposure to standard fire temperature curve - ISO 834 [6]; an uncoupled heat transfer analysis within the depth of the CLT panels is carried out by using ABAQUS. Restraint conditions of the model is roller supported on left end and the constraint allowing only for vertical displacement on right end (Figure 2). In the FE modelling, the temperature of the CLT panels was set to be 0 ℃ at initial thermal conditions. The interaction between tested samples and the environmental temperature has been considered using different boundary conditions of radiation and convection for exposed (bottom) surface and unexposed (top) surface. The convection coefficient and emissivity of exposed surface have been assumed equal to 25W/m$^2$K and 0.8 respectively, as suggested in Eurocode 5, Part 1-2 [10] for emissivity, and Eurocode 1 [11] for convection. For unexposed surface, Eurocodes suggest the same value for emissivity and convection coefficient which are equals to 4W/m$^2$K.

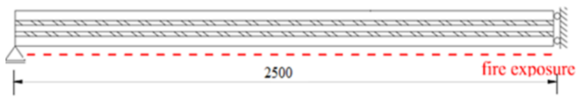



Figure 2. Static scheme of CLT panel implemented in ABAQUS

To conduct the heat transfer analysis, it is also necessary to provide the thermal properties of the materials, such as thermal conductivity, specific heat and density. In the case of wood, it is important that the values of these parameters depend on the temperature. In ABAQUS, it is possible to declare the above parameters as a function of temperature. For this study, the thermal properties of wood were assumed based on compilation of Eurocode 5 and Frangi's proposals as summarised in Table II. The mesh chosen for thermal analysis differs slightly to the one determined in bending analysis. In this model, the CLT panel has been divided into 200 equal rectangles with 250mm long and 7.5mm high as shown in Fig. 3. The reason of using such mesh composition is the need of better accuracy along the depth of the elements rather than the length (the same mesh will be used in thermo-mechanical analysis where the key factor is thickness of charred depth in bottom and middle part of element).

TABLE II. WOOD PROPERTIES WITH TEMPERATURE ASSUMED IN THERMAL NUMERICAL MODEL (Ω- MOISTURE CONTENT EQUALS 12%)

| Temperature [°C] | Specific Heat [$kJkg^{-1}K^{-1}$] | Density Ratio | Conductivity [$Wm^{-1}K^{-1}$] |
|---|---|---|---|
| 20 | 1.53 | 1+*w* | 0.132 |
| 99 | 1.77 | 1+*w* | 0.203 |
| 99 | 13.60 | 1+*w* | 0.203 |
| 120 | 13.50 | 1.00 | 0.223 |
| 120 | 2.12 | 1.00 | 0.223 |
| 200 | 2.0 | 1.00 | 0.295 |
| 250 | 1.62 | 0.93 | 0.228 |
| 300 | 0.71 | 0.76 | 0.162 |
| 350 | 0.85 | 0.52 | 0.096 |
| 400 | 1.00 | 0.38 | 0.104 |
| 500 | 1.20 | 0.33 | 0.119 |
| 550 | 1.30 | 0.31 | 0.127 |
| 600 | 1.40 | 0.28 | 0.180 |
| 800 | 1.65 | 0.26 | 0.450 |
| 1200 | 1.65 | 0.00 | 1.500 |

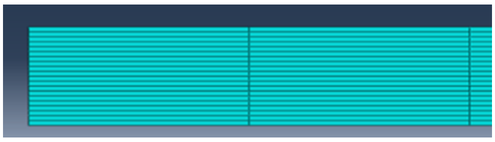


Figure 3. Mesh size in the FE model

### D. *Experimental-Numerical-Analytical Comparison*

Comparison has been made between numerical results and test results obtained from CNR-IVALSA. The temperatures within the cross-section of the CLT panel were recorded along the centreline of the specimen at depths 21, 52 and 75 mm away from the fire-exposed surface, which refers to thermocouple Ta, Tb and Tc, respectively as shown in Fig. 4. It can be seen that the temperatures-time plot predicted by the numerical analysis has shown reasonable approximation to the data of the real fire test.

Fig. 5 shows the comparison of charred depth obtained from experimental, numerical model, and that suggested by the Eurocode 5 based on constant charring rate $\beta_0$=0.65mm/min for solid and glue laminated timber. The comparison again shows good agreement between these results. Graphical visualization of temperature distribution through CLT panel cross-section at different times has been presented in Fig. 6. The grey colour refers to charred layer whereas red colour corresponds to temperature at 300℃. It represents the thermal state of CLT panel exposed to 1D fire from bottom at the beginning of the process (at time 0 min), after 30, 60, 90 min respectively, and finally just before failure at 110 minutes. It can be noticed that about half of the depth of the CLT panels still remain at ambient temperature (blue colour) after the panel failed at 110 minutes.

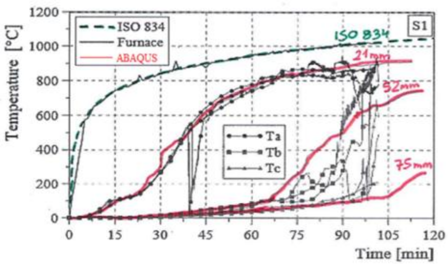



Figure 4. Experimental-numerical-analytical comparison of temperature distribution within unprotected CLT panel model

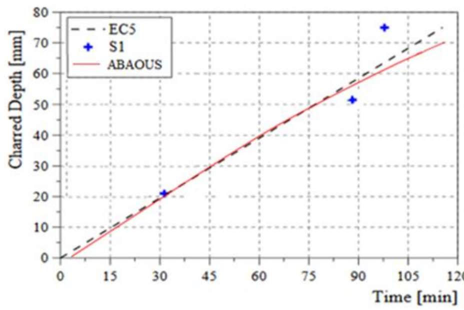



Figure 5. Comparison between charred depths

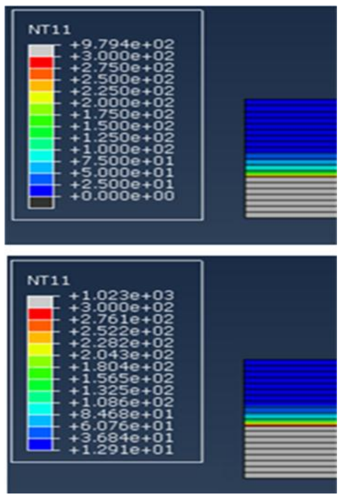



Figure 6. Temperature distributions through CLT panel cross section

## IV. Thermal-Mechanical Analysis of CLT In Fire Conditions

### A. FE Modelling

To predict the fire resistance period of the unprotected CLT panel tested at CNR-IVALSA, the sequential coupled heat transfer analysis was carried out by using ABAQUS. Thermal analysis has been conducted before determining the pattern of temperature distribution through the structural element in fire. The output from the thermal analysis has been used as an input for the thermo-mechanical analysis. This procedure is the most appropriate because stresses generate in the element are dependent on the actual thermal state in the cross-section, while the inverse dependence does not hold. In order to perform mechanical simulation based on the results obtained from the thermal analysis, the two models must be identical in terms of geometry and mesh selection. This procedure could provide the perfect correspondence of node and element labels during conversion process from thermal state into mechanical simulation. The CLT panel was subjected to uniformly distributed load (UDL) $q=10kN/m^2$; the UDL has been modelled as a uniform pressure applied on top unexposed surface In the FE model. The restraint conditions in the FE model is similar to that adopted for ambient temperature i.e. roller support at left end and free vertical movement on right.

The mesh consists of 200 rectangular elements of size 7.5x200mm which is similar as the previous model. A four-node quadrilateral, linear reduced-integration elements type 'CPS4R' has been used, due to its influence on structural behaviour. Mechanical properties of wood at elevated temperature, where the degradation in the stiffness and strength due to the increasing temperature has been assumed based on Eurocode 5, Part1-2 [6] as shown in Fig. 7.

Since in ABAQUS allows only for implementing one degradation law, reduction of Young's Modulus in tension under temperature has been assumed. This choice was dictated by the results from experimental analysis, during which all the failures of samples occurred due to fracture in tension. The more conservative approach suggested that implementing the reduction factors in compression as the values are shown larger impact to the structural element than that in tension. However, the main aim of this paper is to propose a numerical model which has a very close fit to the experimental results, and that is why the first approach has been assumed. To determine the strength properties of CLT panel, different stress-strain relationship in compression and tension has been suggested. Their dependency upon temperature has been presented in [4]. The 'Concrete Damage Plasticity' (CDP) model available in ABAQUS library has been used to define the elasto-plastic and elasto-brittle stress-strain relationship for different temperatures in compression and tension, respectively.

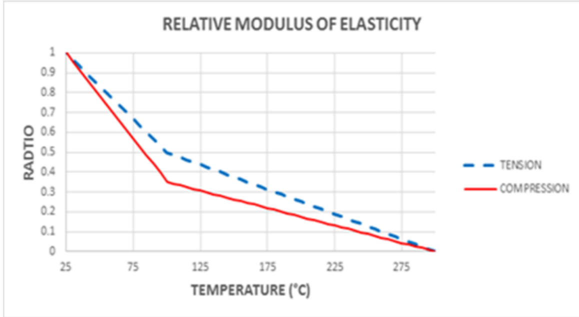


Figure 7. Effect of temperature on modulus of elasticity parallel to grain of softwood

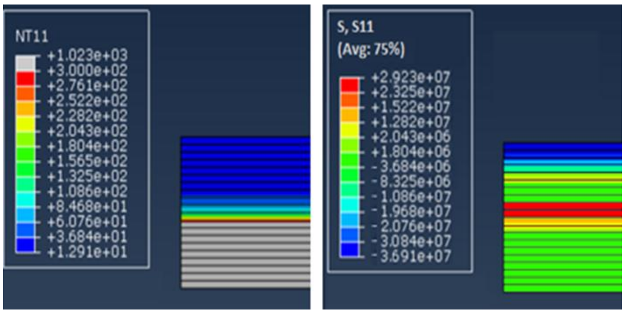
This model represents well the timber structures mechanisms, as well as the plastic behaviour of the CLT element, the brittle behaviour that occurred during a tensile failure of CLT element. Under uniaxial compression the element gives a linear elastic response until a yield stress limit, at which point stress hardening occurs and strain softening follows, after the ultimate stress is reached [12]. The failure of the CLT panel is assumed when the analysis is failed to converge. At the same time, stresses occur in some integration points has reached the maximum strength of the material at the corresponding thermal state. Consequently, the time at which the last increment of analysis has occurred is considered to be the fire resistance period of the tested sample [13].

### B. Results

The process of the stress distribution through the depth of element can be explained in the following way: the layers that closer to the fire has the load-bearing capacity which reduces due to thermal heating and charring process – this results in significant increase in stresses on the upper layers as the load is constantly apply to the element while the residual cross section is reducing. The graphical visualization of the temperature (Figure 8a) and the stress distribution through the element cross-section (Figure 8b) clearly presents the dependency between these two. The green colour represents the material with zero load-bearing capacity which in this case refers to the charred layer of panel and also to the perpendicular-to-grains layers. The red colour symbolizes the tensile stress, while blue represents compression stress in the residual cross-section.

In order to present the complete view of numerical analysis, the maximum mid-span deflection has been taken into consideration. Figure 9 represents the comparison between the experimental and numerical results. The numerical curve shows slightly higher deflection values but in general follows the experimental displacement pattern. After 80 minutes of fire exposure, finite element analysis shows that the deflection values are underestimated quite significantly as compared to the fire test, the reason being that the numerical model is based on one-dimensional heat flux analysis, which has overestimated the fire resistance of the CLT panel, whereas the analytical analysis was adopted a two-dimensional heat flux analysis as in a real fire test. Table

III shows that the estimated failure time using finite element model is around 11% and 6% higher than the experimental and analytical results, respectively.




(a) (b)

Figure 8. Graphical visualization of residual section after 110 minutes of fire exposure, when the failure occurred a) temperature distribution, b) stress distribution

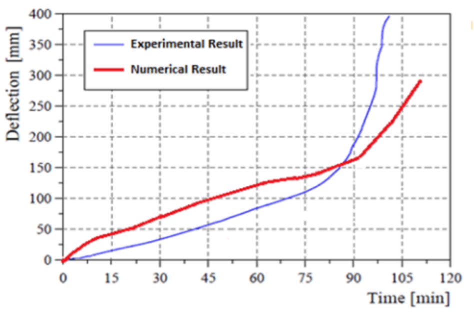



Figure 9. Numerical and experimental mid-span deflection of CLT panel series 'S1'

TABLE III. NUMERICAL-ANALYTICAL-EXPERIMENTAL COMPARISON OF FAILURE TIME OF CLT PANEL SERIES 'S1' IN FIRE SCENARIO

| Method | Time (min) |
|---|---|
| Numerical Analysis - ABAQUS | 110 |
| Analytical Analysis – RCSM | 103 |
| Experimental Results | 99 |

## V. CONCLUSION

The main focus of this paper is to evaluate the thermal and structural performance of cross-laminated timber floor panel subjected to the fire using both numerical and analytical analysis. The large-scale fire test performed at Ivalsa Trees and timber Institute has been considered as the scientific foundation for experimental analysis and additional source of reference. Finite element models have been implemented in ABAQUS software, and the results obtained have been compared with analytical predictions based on simplified design methods. Uncertainties of design process, approximations required at different stages of investigation, as well as the accuracy of the results obtained from all three methods have been analysed carefully.

### A. Thermal Modelling

Numerical modelling was implemented to analyse the thermal impact of fire on unprotected CLT panel. The anisotropic nature of wood was simplified and described in model by defining different material properties for layers parallel and perpendicular to the main floor direction. The CLT panel assembly, which has been subjected to experimental test, was thermally modelled to validate the accuracy of the thermal parameters used later on in structural modelling of element behaviour in fire conditions.

The observations can be summarised as follows:

a) When compared to thermocouple readings from laboratory tests, the analytical model gives acceptable approximation of the temperature distribution within the cross-section of unprotected CLT panel subjected to 1D heat flux;

b) The charring rate and charred depth, predicted by the FE model at the beginning of the fire until around 90 minutes, has good agreement with the CLT behaviour in real fire scenario; after exceeding that time the numerical model underestimates slightly the results;

c) Eurocode 5 has no specific guidelines to evaluate charred depth for cross-laminated timber, however the charring rate of $\beta_0$=0.65mm/min gives an acceptable approximation of charring progress when compared to CLT fire test results.

### B. Thermo-Mechanical Modelling

In ABAQUS, 'Concrete Damage Plasticity' model has been used to simulate CLT behaviour in tension and compression. In order to determine different material behaviours in tension and compression, the elasto-brittle and elasto-plastic stress and strain relationship depending upon temperature have been implemented, respectively. The numerical model has been initially validated based on the bending test at ambient temperature (undertaken in laboratory) in terms of parameters and based on the bending analysis (performed in ABAQUS) in terms of accuracy of FE method. The temperature distribution obtained from previous model has been adopted as an input for thermo-mechanical model. The numerical predictions of CLT fire resistance and the maximum mid-span deflection have been compared with both experimental and analytical results.

The observations can be summarized as follows:

a) The stress redistribution within CLT panel cross-section due to charring is clearly noticeable.

b) The prediction of fire resistance obtained from numerical analysis are slightly overestimated as compared to experimental data however these can be easily explained by the occurrence of crack in the panel and 2D heat flux which has been recorded in furnace;

c) The failure time estimated using finite element model is around 11% and 6% higher than experimental and analytical results, respectively.

d) Some of the discrepancies resulted from experimental and numerical analysis can be influenced by dependency of thermal and mechanical properties of wood on temperature which has been implemented in FE software.

### C. Analytical Analysis - RCSM

The analytical design calculation of fire resistance of CLT was based on Reduced Cross-Section Method, proposed by Eurocode 5, Part 1-2. The selected calculation method has been simplified in order to provide simple, quick hand calculation technique.

The observations can be summarized as follows:

a) RCSM provides a very good prediction in terms of depth of the reduced cross-section panel just before failure when compared with test result. A depth of 74mm of residual cross-section that obtained from the analytical method gives very good approximation with the experimental result i.e. a slight 1.3% margin.

b) RCSM provides slightly under conservative result of 103 min fire resistance of CLT panel, which is 5% higher than experimental result.

To summarise, the discrepancies between different computational methods (numerical and analytical) and the reality cannot be avoided. The sources of possible errors are numerous, and these can be limited only by comprehensive research, reasonable assumptions and a great number of repetition and changes. In this paper, the FE model of multilayer cross laminated timber floor panel has been presented, calculated and evaluated.

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

Joanna Woszczak conducted the finite element modelling, analyzed the data and draft the paper; Kong Fah Tee and Bernice Wong analyzed the data and revised the paper.

## References

[1] BS EN 13501-1:2007+A1:2009, Fire classification of construction products and building elements. Classification using test data from reaction to fire tests. BSI, 2007.

[2] A. Nadjai, N. Goodfellow, K. F. Tee, F. Ali, S. K. Choi, "Analysis of composite floor cellular steel beams in fire," *Journal of Structural Fire Engineering*, vol. 1, no. 3, pp. 161-175, 2010.

[3] N. Goodfellow, A. Nadjai, K. F. Tee, F. Ali, S. K. Choi, "Fire composite floor cellular steel beams for buildings," in *Proc. of the International Conference on Applications of Structural Fire Engineering*, Prague, Czech Republic, February 19-20, pp. 496-501, 2009.

[4] A. Menis, Fire resistance of Laminated Veneer Lumber (LVL) and Cross-Laminated Timber (XLAM) Elements. Universita Degli Studi Di Cagliari, Italy, 2012.

[5] P. Fellmoser, H. J. Blab, "Influence of rolling shear modulus on strength and stiffness of structural bonded timber elements," University of Karlsruhe, Germany, 2004.

[6] BS EN 1995-1-2:2004, Eurocode 5: Design of timber structures — Part 1-2: General — Structural fire design. BSI, 2004.

[7] A. Frangi, M. Fontana, E. Hugi, R. Jobstl, "Experimental analysis of cross-laminated timber panels in fire," *Fire Safety Journal*, vol. 44, pp. 1078-1087, 2009.

[8] B. V. Y. Wong, K. F. Tee, "Charring rate for fire exposed X-Lam," in *Proc. of IOP Conference Series: Materials Science and Engineering*, 216, 012061, 2017.

[9] B. V. Y. Wong, K. F. Tee, T. M. Yau, "Numerical study of cross laminated timber under fire," in *Proc. of the* $9^{th}$ *International Seminar on Fire and Explosion Hazards*, Saint-Petersburg, Russia, April 21-26, pp. 1088-1096, 2019.

[10] BS EN 1995-1-1:2004+A1:2008, Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings. BSI, 2008.

[11] BS EN 1991-1-1:2002, Eurocode 1: Actions on structures- Part 1-1: General actions- Densities, self- weight, imposed loads for buildings. BSI, 2012.

[12] J. W. O'Neill, "The fire performance of timber floors in multi-storey buildings," University of Canterbury, New Zealand, 2013.

[13] B. V. Y. Wong, K. F. Tee, "The fire performance of exposed timber panels," *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, vol. 8, no. 10, pp. 1045-1051, 2014.



**Dr Kong Fah Tee,** BEng(Hons) PhD PGCert(HE) MBA DIC FHEA, is a Reader in Infrastructure Engineering at the University of Greenwich. His research effort has been focused on structural system identification and health monitoring, structural reliability and failure analysis, experimental stress analysis, fatigue, fracture mechanics and structural dynamics. He has published a book and over 170 refereed international journal and conference papers. He has been awarded research grants with the total amount of over £1M. He has successfully supervised 7 PhD students. He is currently serving as an Editor-in-Chief of the International Journal of Forensic Engineering (Inderscience), editorial board members for over 20 international journals and organizing committee/international scientific committee for over 35 international conferences. He was awarded an International Research Collaboration Award from the University of Sydney and invited as a foreign expert to the Nanjing University of Aeronautics and Astronautics. He has been invited as an expert witness and a forensic engineering consultant to industry. He is a regular reviewer of papers, books, research proposals as well as an external examiner of research degrees. He has given a short course, two keynote speeches and over 30 seminars and conference presentations.

**Dr Bernice Wong**, BEng(Hons) MSc PhD CEng MIET, is an associate fire engineering consultant with Hydrock in London. She has an expertise in the field of fire safety engineering and structural fire engineering. She has worked on a variety of projects nationally and internationally such as high-rise buildings, commercial, retail, residential, office, healthcare, railway stations and tunnels. She has also been involved in third party reviews on behalf of building control authorities. She has a PhD in structural fire engineering from the University of Sheffield. Her PhD research considered the structural fire behaviour beam with web-openings. She published a number of journal papers in structural fire engineering and regularly present in related conferences. She is a regular reviewer of papers and contributed to the development of best-practice guidance documents. She also interacts and collaborate with several other universities in the UK.

**Joanna Woszczak**, MSc Civil Engineering, University of Greenwich, Kent, UK.