Numerical Study of Cross-Laminated Timber Under Fire

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ABSTRACT

This paper presents the fire performance of unprotected Cross-laminated timber (CLT) floor panel by comparing available experimental results against numerical and analytical analysis. A numerical model of multi-layered CLT panel has been developed using Finite Element (FE) Method. Temperature distribution within the cross-section of CLT panels was investigated. The charring rates for CLT panels obtained from the numerical model were compared with experimental results and those provided by Eurocode simplified approach. The falling off of the charred layer of the CLT panel has also been investigated using the FE modelling. The results show that assuming the immediate falling off of charred layer would happen when the interface between the layers has reached 300°C could lead to consevative prediction.

KEYWORDS: Timber structure, cross laminated timber, charring rate, fire resistance, numerical analysis.

INTRODUCTION

The fire behaviour of structural timber elements is an important research topic to ensure the attainment of the required safety level in timber buildings. Cross-laminated timber (CLT) is increasingly being used in the construction of high-rise buildings due to its simple manufacturing system. In terms of fire resistance, CLT 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.

The investigation of the performance of timber product exposed to fire has increased over the past decades. Several experimental investigations have been carried out on different wood products, such as laminated veneer lumber [1, 2], glued laminated timber [3] and cross-laminated timber (CLT) [2, 4, 5]. Small- and large-scale tests were performed on loaded and unloaded specimens subjected to one- or two-dimensional heat fluxes in furnaces of different sizes. Design of timber structures has been outlined in Eurocode 5 [6], notional charring rate for softwood and hardwood timber is given. For timber member subjected to one-dimensional charring, a constant value of charring rate 0.65 mm/min is recommended for softwood. For the performance of the CLT panels in fire, only little information on charring is available and whether the fire behaviour of CLT panels is similar to homogenous timber panels has not yet been systematically analysed.

The fire behaviour of cross-laminated solid timber panels has been experimentally and numerically investigated [2, 4, 7-10] in the past decades. Experimental investigations on small and large scale tests of unloaded and loaded cross-laminated timber specimens manufactured by various producers with different characteristics were carried out [2, 4, 7-8], the outcome of the tests revealed that the fire behaviour of cross-laminated timber elements was mostly linked to the thickness of the layers

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and the type of adhesive used to produce the timber panels [4]. A simplified charring model to determine the residual cross-section for CLT panel has been introduced [11, 12] based on the available fire tests. To develop a better understanding of CLT panels fire performance, applying analytical and numerical methods as a more effective way to study the mechanical and thermal performance of CLT elements exposed to fire. It can be done without performing experimental tests which are hazardous and expensive. At the same time, experimentation at different scales is required to provide the fundamental data for model development. The fire resistance of timber structures can be assessed by standardised fire tests, such as ISO 834 [13], and can be calculated by methods such as those suggested in the Eurocodes [6]. Design standards [6] allow the use of advanced calculation methods, which eliminate the cost of expensive fire testing by using validated numerical finite element (FE) computer models to determine the thermal and structural performance of timber members exposed to fire.

This paper presents the main results of the numerical analyses. Particular attention is given to the comparison of the fire behaviour of cross-laminated solid timber panels obtained from the numerical findings with the experimental results [2, 8].

NUMERICAL ANALYSIS

For the numerical analyses presented in this paper full versions of the programs SAFIR 2016 were used. SAFIR is a special purpose finite element program developed at the University of Liege, Belgium, for analysing the behaviour of building structures under ambient temperatures and subjected to fire. It consists of an integrated thermal and structural analysis program for carrying out two-dimensional (2D) and three-dimensional (3D) analyses of steel, concrete, timber and composite structures in fire conditions. The structure can be made of a 3D skeleton of linear elements such as beams and columns, in conjunction with planar elements such as slabs and walls. Complex model such as connections can be analyses using volumetric elements. The thermal and mechanical properties of steel, concrete and timber, following the Eurocodes, are incorporated into the program, but one can also use user-defined materials for the thermal or structural analysis [14-15]. The influence of temperature on the thermal properties is automatically implemented in the SAFIR finite element (FE) software. Alternatively, user-specified material thermal properties can also be defined through its thermo-physical parameters which govern the heat conduction process.

1D HEAT TRANSFER EXAMINATION

A simple solid timber member model has been set up using SAFIR to simulate an one-dimensional (1D) heating test on unprotected spruced timber members exposed to ISO-fire [13] on one side for 90 minutes, presented by König and Walleij [16]. The modelled section was discretized into 48 numbers of 2D SOLID elements to be representative of a 24mm by 96mm strip of solid timber specimen. The test specimen had an initial moisture content of 12% with a bulk density of 480 kg/m³. One side of the model was exposed to the ISO 834 fire curve. the emissivity of timber surface and convection factor assumed to be 0.8 and 25 W/m^{2}K, respectively, which the experimental data has not been made available the recommendations from the EN1995-1-2 [6] have been used. No heat and mass flux on the top side of cross section is considered, a convective coefficient of 9 W/m²K (which accounts for both radiative and convective losses) and an initial ambient temperature of 20°C were applied to the surface. The sides of the model were assumed adiabatic. Temperatures across the cross-sectional were measured in a depth of 6, 18, 30, 42 and 54 mm from the surface exposed to fire and compared to the experimental data [17]. Figure 1 illustrates the 2D SAFIR model and the temperature profile across the cross-sectional of the timber specimen at 3600 seconds. The charred material is represented by maroon red, whereas red colour corresponds to 300°C temperature, as is typical in the literature [6], where char depth was assumed as the location of the 300 °C isotherm.

The numerical variation of heat flux led to temperature increases close to the thermocouple records as displayed in Fig. 2. Note that the grey lines indicated were temperature measurements taken at various depths into the wood for a series of test [16], with the black line being the average of those measurements. The thermal analysis across the cross section of the timber strip has been predicted with good accuracy despite a coarse mesh was used in the FE model.

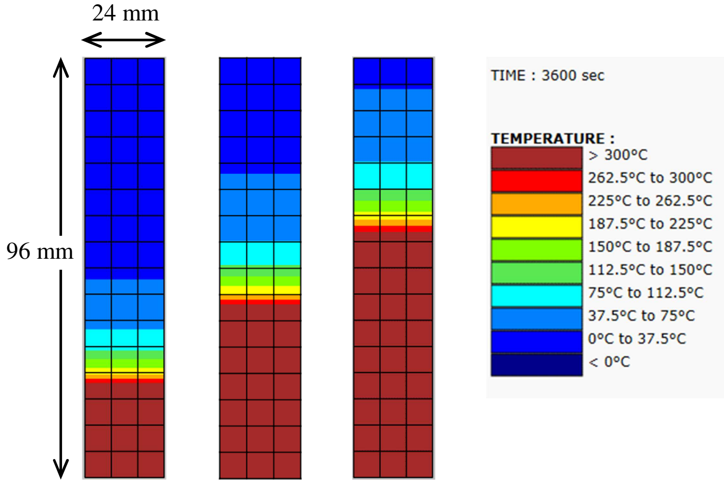

Fig. 1. Temperature distributions within the cross-section of solid timber after 60 minutes of fire exposure.

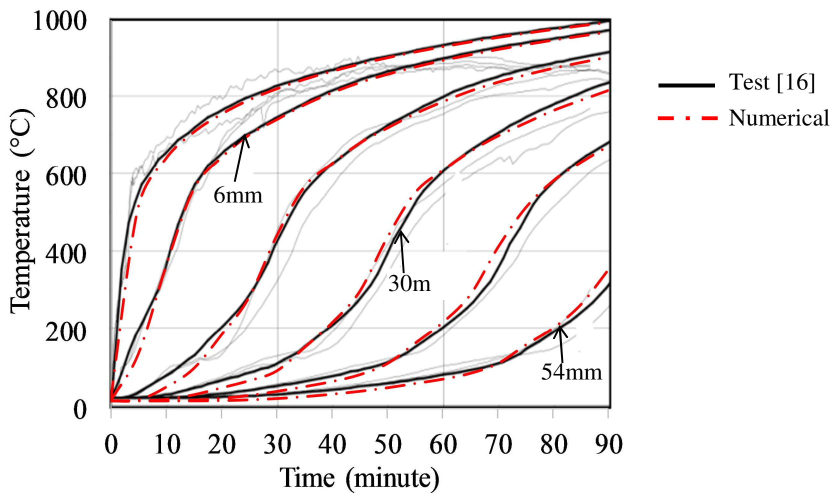

Fig. 2. Experimental [16] and numerical temperature distributions at various depth across the cross section of solid timber.

NUMERICAL-EXPERIMENTAL COMPARISONS FOR CROSS-LAMINATED TIMBER PANEL

Fire tests were conducted on CLT panel specimen as reported in [2]. The geometrical characteristics of the CLT panel are 600 mm thick, 150 mm width and 5600 mm long. The specimen was built using five bonded layers of 42, 19, 28, 19 and 42 mm. Polyurethane (PU) adhesive was used to manufacture the tested panels. The bottom side of the specimen was exposed to heat in the furnace, exposed to the standard ISO 834 fire [13].

A 2D finite element model has been built using 36 SOLID elements in SAFIR, was used to simulate the temperature distributions in the panel. The thermocouples considered in the numerical simulations were placed at coincident nodes corresponding to depths of 21 mm and 52 mm from the exposed surfaces (Fig. 3). In the finite element modelling, the moisture content of the CLT sample was assumed as 12%, and the corresponding initial density was 460 kg/m^3. From the collected experimental data [2], there was no evidence to suggest that any quick temperature increases indicating the falling-off of charred layers. Thus, the CLT cross section was modelled as solid wood, the delamination behaviour of the charred layer has not be considered in the numerical modelling. The adhesive layer between the CLT layers is relatively small (less than 0.2 mm) and it was neglected in the conduction process during the FE analysis of the CLT element. Nonetheless investigation [8, 17] on shear behavior of different adhesives at high temperatures has revealed that the fire behavior of CLT panels is strongly influenced by the behavior of the adhesive that used for the CLT panels bonding system. Degradation of adhesive between individual CLT layers can lead to charred layer fall-off which in turn leads to exposure of the directly underlying layer.

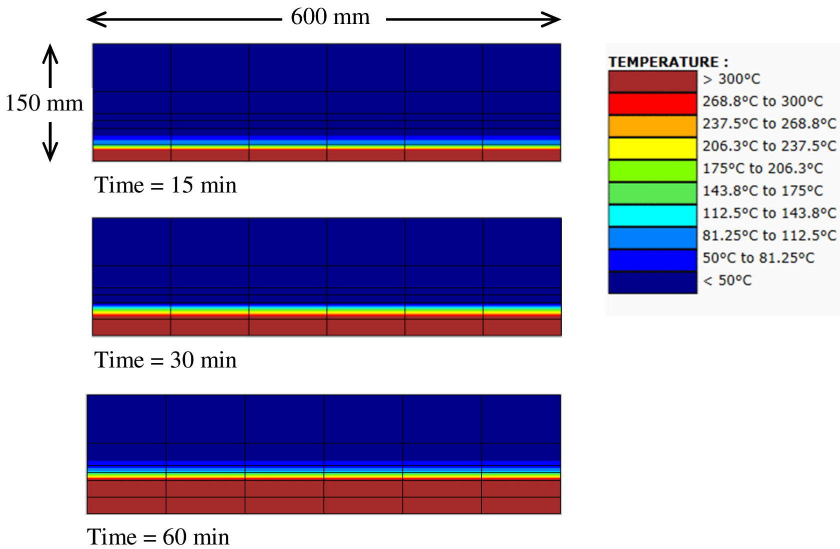

Fig. 3. Numerical temperature profiles across the cross section of CLT and the formation of charring layer at different fire-exposure times.

Figure 3 illustrates the predicted temperature profiles of the CLT sample as a function of fire-exposure time, and shows the formation of char layer increases as fire exposure time increases. Figure 4 compares the temperature distribution recorded during the fire test [2] at depth 21 and 52 mm from the bottom surface that exposed to fire, with the numerical thermal prediction. It can be seen that, the temperature-time curve for the depth at 21 mm obtained from the numerical and experimental data were almost corresponding, the slight differences could be due to the mesh size and time steps used in the model. The curves recorded at 52 mm depth indicate an acceptable approximation. The numerical and experimental data were in good agreement from the beginning till after 60 minutes fire exposure, the numerical prediction has the temperatures gradually increasing while the experiment data showed more rapid increase of temperature after 87 minutes at which time the recorded temperature was 300°C.

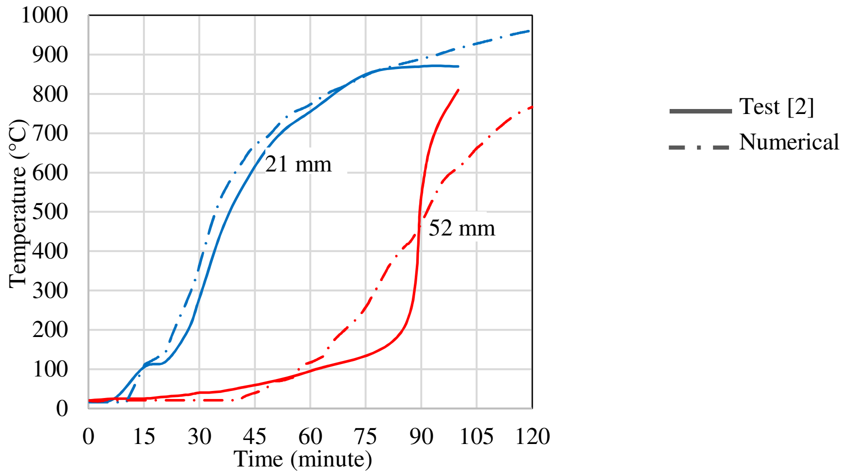

Fig. 4. Comparison between predicted and measured temperatures for CLT panel in fire.

NUMERICAL- EXPERIMENTAL COMPARISONS FOR THE DELAMINATION OF CLT PANEL

One of the main concern when comes to the fire resistance properties of CLT is the delamination of CLT layers due to fire exposure. The investigation on the influence of the temperature-dependent material properties of the adhesive on the resistance of CLT beams exposed to fire have been carried out [7], it was demonstrated that the fire behavior of cross-laminated timber panels is strongly influenced by the behavior of the adhesive that used for the CLT panels bonding system. CLT 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 [13] on one side.

In this section, the numerical simulation aims to model the delamination of CLT and the rapid increase in temperature of the layer direct above the charred layer. Test specimens [8] consisted of cross-laminated timber panels made of spruce boards with the dimensions of 1.15 m by 0.95 m had the thickness of 60 mm. The specimens were exposed on one side to the standard fire curve according to ISO 834 [13]. It was observed during the fire tests [8], falling off of the charred layers was occurred for all specimens manufactured with the polyurethane (PU) adhesives, where temperatures measured between the layers starting at about 300°C increased very rapidly and reached the furnace temperature. It was suggested that the thermocouples placed between the CLT layers exposed directly to fire as the charred layers fell off during the fire tests.

In the numerical modelling, the finite element mesh consisted of 30 SOLID elements. The moisture content of the specimens was assumed to be 12%. The thermocouples considered in the numerical simulations were placed at coincident nodes corresponding to depths of 10, 20, 30 and 40mm from the exposed surface. To simulate the delamination behaviour of the CLT panel, two assumptions have been considered on the falling off of the charred timber layer, first when the interface between the layers has reached 300°C, the immediate falling off of charred layer is occurred, this has been based on the experimental observation [8] as mentioned above. The simulations result is shown in Fig. 5. The second assumption made is that the falling off of the charred layer occurs when the temperature of the subsequent layer at depth 10mm from the exposed surface has reached 300°C. Figure 6 illustrates the numerical prediction adopted the second assumption.

Figures 5 and 6 illustrate the result corresponding to the two assumptions made. The experimental test data are shown in black and red curves correspond to numerical predictions. It can be seen that the first assumption gives conservative predictions, the falling off of each timber layer formed the CLT panel occurs earlier than experimental observation [8]. The numerical simulation and experimental data were shown to be in good agreement with the second assumption (see Fig. 6).

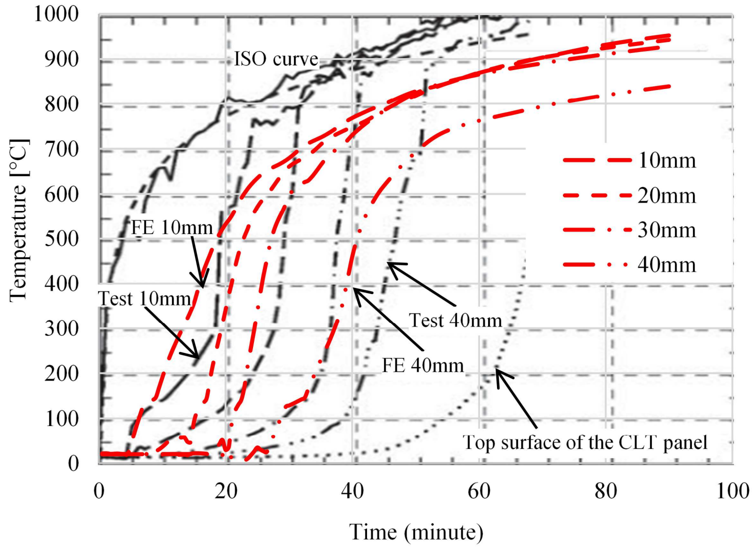

Fig. 5. Comparison between measured temperatures for the fire tests V2 [8] and numerical simulation with the assumption that charred layers immediately fall off after charring.

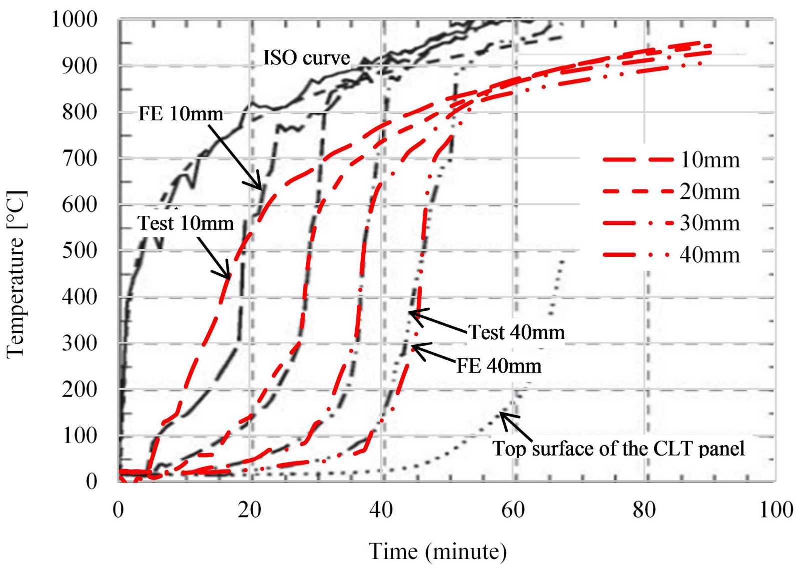

Fig.6. Temperature distributions across the cross-section of cross-laminated timber panels - experimental and numerical.

The delamination behaviour of the CLT panel where significant increase in temperature has been observed after the layer is completely charred, the time when the protective charcoal has fallen off have been well predicted by the numerical simulation, suggested that the polyurethane adhesives between individual layers was still holding the fire exposed charred panel and the subsequent layer, until which the formation of a new 10mm thick char layer on the subsequent layer, the adhesive bonding function lost, fire exposed charred layer is then fall-off. As mentioned above, the thermocouples has exposed to fire as the charred layers fell off, therefore the temperature profile after the falling off of the charred layer could be neglected.

Table 1. Charring depth (d_{char}) and charring rates calculated for cross-laminated timber panel under fire test [8] and numerical analysis of the 2nd assumption made

d_{char} (mm)	Time reached 300°C (min)		Charring rates (layer) (mm/min)		Charring rates (panel) (mm/min)	
	Test	FE	Test	FE	Test	FE
10	18	13	0.56	0.77	0.56	0.77
20	27	27.5	1.11	0.69	0.74	0.73
30	36	36	1.11	1.18	0.83	0.83
40	43	45	1.43	1.11	0.93	0.89

Simplified approach suggested by current codes of practice [6], the charring rate of timber is defined as the rate of movement of the 300ºC. The 300°C isotherm is assumed as the border between charred and heated wood as suggested by Eurocode 5, Part 1-2 [6]. Table 1 reports the time when the 300°C was measured at the interface between layers, for both obtained from experiments [8] and numerical modelling. The calculated charring rates for the single layers and for the whole cross-sections of the CLT panel are also shown in Table 1. For the calculation of the charring rate of the single layers it was assumed that a layer started charring when the temperature measured at its exposed bottom side reached 300°C and then it was completely charred when the temperature of 300°C was measured on the unexposed top side of that layer. The predicted charring rate of the first layer is 0.77 mm/min which showed a higher charring rate in comparison to the one-dimensional charring of 0.65 mm/min [6] as well as the test result 0.56 mm/min (see Table 1). The resulting average charring rate of the 5-layered timber panels was 0.76 mm/min (fire test [8]) and 0.80 mm/min (numerical model).

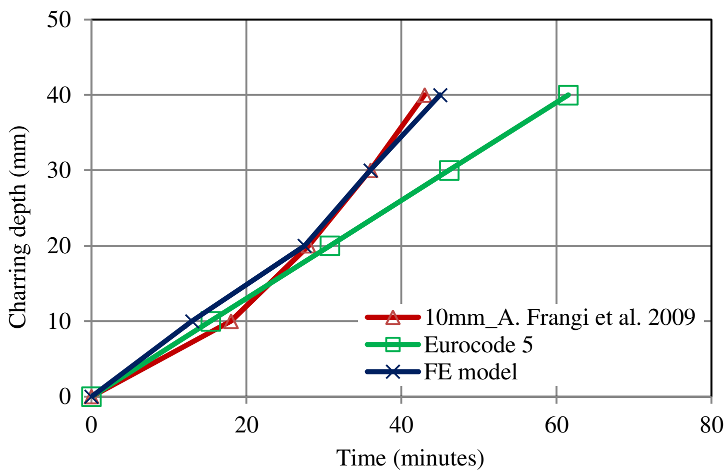

Fig.7. Charring depth for CLT panel measured from test [8] and compared with EN 1995-1-2 [6] and numerical model.

Figure 7 compares the charring depth as a function of time for the test result [8] and the numerical model. The charring depth corresponds to the Eurocode [6] recommended 0.65 mm/min one-dimensional charring rate for homogeneous timber was also shown for comparison. The measured charring depth agrees well with the numerical prediction. The effect of the increase of the charring rate can be seen from the test and numerical model, the differences between predicted and measured charring depth are very small. The measured [8] and predicted charring depth of the CLT panel is higher than for the solid homogeneous timber according to Eurocodes [6].

CONCLUSION

The paper presents a 2D finite element modelling with 1D heating implemented in SAFIR software package to simulate the thermal behaviour of unprotected cross-laminated timber panel with and without falling off of the charred layers subjected to the exposure to standard fire on the bottom side.

The numerical model validated by experimental results was compared with analytical approach by means of simplified design methods, proposed by EN 1995-1-2. Good agreement between numerical simulations and experimental data was found despite a coarse mesh was used in the FE model, it is however the presented model needs to be performed with mesh refinement analysis to investigate the influence of meshing in the simulation. The simplified approach was found given lower value charring rate among those.

When timber is exposed to elevated temperatures, the simulation of the pyrolysis is a key task for accurate prediction of the realistic temperature distributions, as the different chemical components in wood undergo thermal degradation that would affect the performance of timber in fire. The numerical investigation was found to agree well with the experimental approach if assuming that the falling off of the charred layer occurred when the temperature of the next layer at depth 10 mm from the exposed surface has reached 300°C. Although further numerical investigation is recommended to be performed on CLT panels that formed by various layer thicknesses to provide further verification on the assumptions made on the simulations of the phenomenon of delamination of a CLT-elements. The fire behaviour of timber panels subjected to a standard fire could be differ significantly to a real fire, which requires considerable additional research to be performed to investigate the heat transfer beneath the charred layer under a range of possible heating conditions cases.

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