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Modelling of fire performance of Cross Laminated Timber (CLT) panels

Trong Tuan TRAN[1], Mourad KHELIFA[1], Ali NADJAI[2], Marc OUDJENE[1] and Yann ROGAUME[1]

[1]*University of Lorraine, LERMAB, EA 4370, 27 rue Philippe SÉGUIN - 88051 Épinal - FRANCE*
[2]*Fire Safety Engineering and Technology (FireSERT), Ulster University, United Kingdom*

E-mail addresses: trong-tuan.tran@univ-lorraine.fr (Presenting author),
mourad.khelifa@univ-lorraine.fr (Corresponding author)

ABSTRACT

A numerical method has been developed to incorporate the effects of heat transfer in a CLT panel exposed to fire. The procedure has been added into the software package Abaqus [1] as a user-defined subroutine (Umatht), and has been verified using both time-and spatially dependent heat fluxes in two- and three-dimensional problems. The aim is to contribute to the development of simulation tools needed to assist structural engineers and fire testing laboratories in technical assessment exercises. The accuracy of the used thermal properties and the finite element models was validated by comparing the predicted results with an available fire test in literature. It was found that the model calibrated to results from standard fire conditions provided reasonable predictions of temperatures within CLT panel exposed to fire.

KEYWORDS

Fire performance; Thermal properties; Fire test; Abaqus; CLT; Finite element models.

1. INTRODUCTION

A major hurdle to the development of the use of timber panels in construction is their perceived combustibility, which raises questions about their fire safety. Indeed, the flammability of cladding panels, particularly in high rise buildings, poses a serious safety issue. Fig. 1 shows a facade panel of the Grenfell tower in London exposed to a real fire on the 14th June 2017, which, unfortunately, left more than 80 dead. In this case, the use of CLT panels in construction could constitute a solution because the formation of a char layer acts as an insulator and protects the inner core of the virgin timber, at the same time, it does reduce the effectiveness of the cross-area to carry loads as shown in Fig. 2 and reported in refs [2-5]. However, their use in construction will remain marginal until the fire safety issue is resolved. In addition, there is also a lack of experimental evidence on their fire performance. Moreover, there is very little data available the fire performance of CLT panels and most of it is empirical. Although they are used as structural elements, there are virtually no design methods available, which limits their use commercial use. The aim of the present work therefore work is to study the fire performance of these panels.

Fig 1. Facade of the Grenfell tower in the aftermath of the fire.

(a) (b)

Fig. 2. Charcoal protective layer of (a) CLT panel [2] and (b) solid timber beam [5].

Few researchers have simulated the fire behavior of CLT panels using numerical procedures based on finite element models. Frangi et al. [6] presented and discussed the results of an extensive testing program on the fire performance of CLT panels under the standard fire as provided by ISO 834-1 [7]. The fire tests were performed in the laboratory on small specimens exposed on one side to fire. In [6], a particular attention was given to the effect of the adhesive on the fire behavior of CLT panels compared to solid timber panels.

The thermal models, available in the literature, can be roughly developed using procedures based on purely experimental observations in the absence of an understanding of the mechanism. This situation stems, first, from the complex fire behavior of the CLT panels used in construction and, second, from its lack of information on the characterization procedure of different thermal proprieties of timber material. In our opinion, there are no advanced finite element models considering the variation of thermal proprieties of timber material during the heating process.

The objective of the study is to develop a three-dimensional thermal model for predicting the thermal behavior of CLT panels exposed to fire. The developed model here can predict temperature profiles and char formation during the fire exposure. The developed 3D finite element model is incorporated into the Abaqus software [1] using a user subroutine. Thus, the fire behavior of CLT panels is investigated by the Umatht procedure. The finite element model is calibrated and validated by comparing its results with experimentally measured data.

2. NONLINEAR HEAT TRANSFER FORMULATION

In this section, the governing 3D heat conduction equations for timber material are derived. The material properties in the heat transfer equations, such as thermal conductivity λ, density ρ and specific heat c_p are assumed to be dependent on the temperature T.

2.1. Heat constitutive equations

The internal volumetric heat energy rate $\dot{\overline{Q}}_i$ produced inside the solid V can be expressed as:

$$\dot{\overline{Q}}_i = \int_V \frac{\partial}{\partial t}(\rho Q_i)dV = \int_V \rho(T)\frac{\partial Q_i}{\partial t}dV \quad (1)$$

$\dot{Q}_i$ is the internal heat energy density per unit mass, and ρ is the density. The rate of the internal energy density can be rewritten as:

$$\frac{dQ_i}{dt} = \frac{dQ_i}{dT(x_i,t)}\frac{dT(x_i,t)}{dt} = c_p(T)\frac{dT(x_i,t)}{dt} \quad (2)$$

$T(x_i,t)$ is the current spatial temperature, t is the time and x_i denotes the location coordinates in 3D space.

Substituting Eq. (2) into Eq. (1), the internal energy density yields becomes:

$$\dot{\overline{Q}}_i = \int_V \frac{\partial}{\partial t}(\rho Q_i)dV = \int_V \rho(T)c_p(T)\frac{dT(x_i,t)}{dt}dV \quad (3)$$

Fourier's law assumed that the heat flux rate transferred through surface A is proportional to the heat conductivity times the spatial gradient of the temperature. Thus, the total external energy rate $\dot{Q}_e$ can be obtained by:

$$\dot{\overline{Q}}_e = \int_A q.n_i dA = \int_A \left[\lambda(T)\frac{dT(x_i,t)}{dx_i}\right].n_i dA = \int_V \frac{d}{dx_i}\left[\lambda(T)\frac{dT(x_i,t)}{dx_i}\right]dV \quad (4)$$

where q is the surface heat flux vector, λ is the thermal conductivity and n_i is the unit vector outward normal to the surface.

Combining Eq (3) and (4), the Partial Differential Equation (PDE) can be rewritten as:

$$\rho(T)c_p(T)\frac{dT(x_i,t)}{dt} = \frac{d}{dx_i}\left[\lambda(T)\frac{dT(x_i,t)}{dx_i}\right] \quad (5)$$

In this study, the thermo-physical properties (λ, c_p and ρ) are functions of temperature. Thus the PDE becomes a nonlinear, and a more complex numerical technique is required for general solution, e.g. timber under high temperatures [8-12]. We note that the different thermal properties (λ, c_p and ρ) values of the timber material, used in this study, are those given and defined by Thi et al. (2016) in [12].

2.2. Finite element implementation

In solving the governing equations, Eq. 5, we must determine the thermal strain and the temperature. There is one user subroutine provided by Abaqus for more flexible and wider engineering application. The subroutine is Umatht, which is used to define the thermal constitutive equation (heat transfer equation, Eq. 5).

Variables necessary to be defined in Umatht for solving the heat transfer equation are:

- internal thermal energy per unit mass U;
- variation of U with respect to temperature $\frac{\partial U}{\partial T}$;
- variation of U with respect to the spatial gradients of temperature $\frac{\partial U}{\partial(\partial T/\partial x_i)}$ $(i = 1,2,3)$;
- heat flux vectorf is defined so that: $q = -f.\underline{n}$, where q is the heat flux per unit area flowing into the solid;
- variation of f with respect to temperature $\frac{\partial f}{\partial T}$; and the variation of f with respect to the spatial gradients of temperature $\frac{\partial f}{\partial(\partial T/\partial x_i)}$ $(i = 1,2,3)$. These terms need to be calculated at the end of each time increment.

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3. RESULTS AND DISCUSSION

A CLT beam tested by Fragiacomo et al. [13] is simulated with the developed finite element model. The geometrical details, the loading and the boundary conditions are shown in Fig. 3. The fire test was carried out according to ISO 834-1[7]. The average initial density ρ_0, the moisture content ω, the coefficient of convection h_c, and the emissivity ε, are respectively equal to 450 kg/m^3, 12%, 25 W/(m^2.K) and 0.8. The beam is meshed with 8400 C3D8T solid elements.

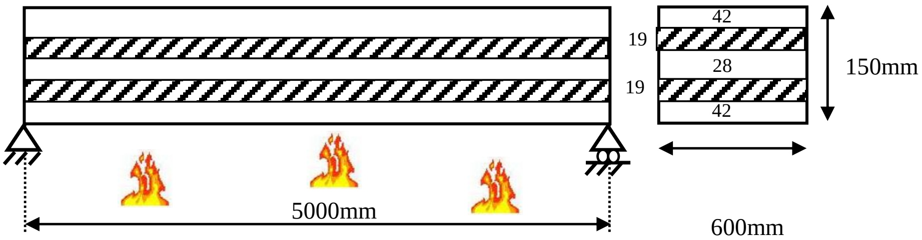
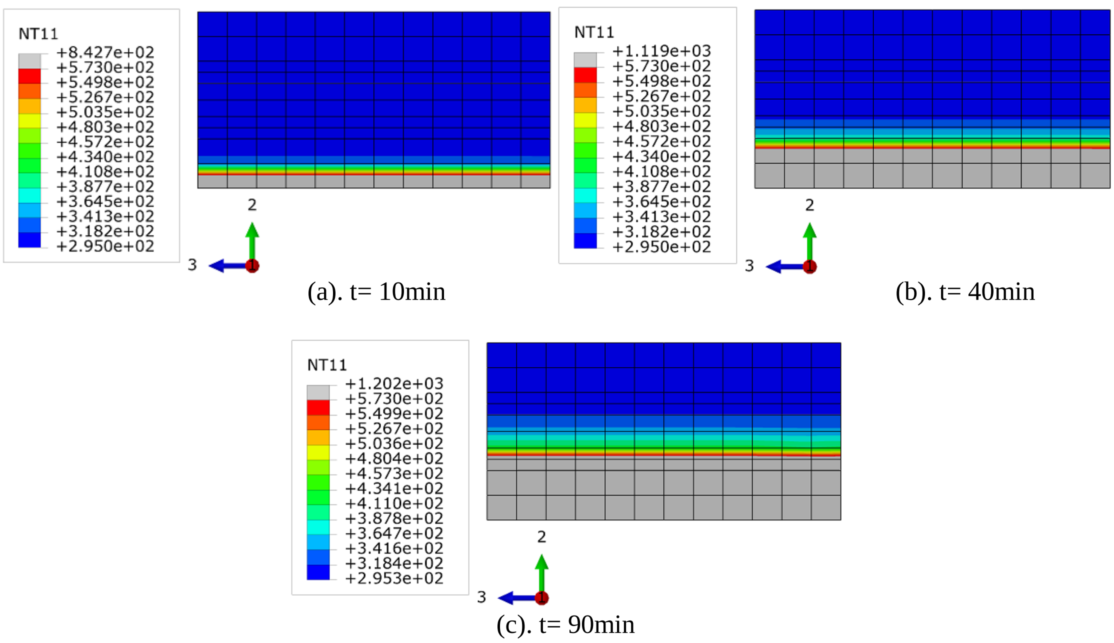


Fig. 3. CLT beam in flexure in a fire environment [2,13].

The temperature distribution across the cross section at different times of exposure is shown on Figs. 4. The formation of the charred layer starts to at temperatures above 300°C. The temperature profile shows clearly that the charred layer is uniform across the section. The residual cross section reduces with time of exposure. The beam fails in a catastrophic manner when the thickness of the residual section is not sufficient to resist the applied moment. It can be seen that temperature gradients are higher at the exposed surface (fire side). At the beginning, the formation of the char is faster and then due to the reaction of the char gradually decreases with time.

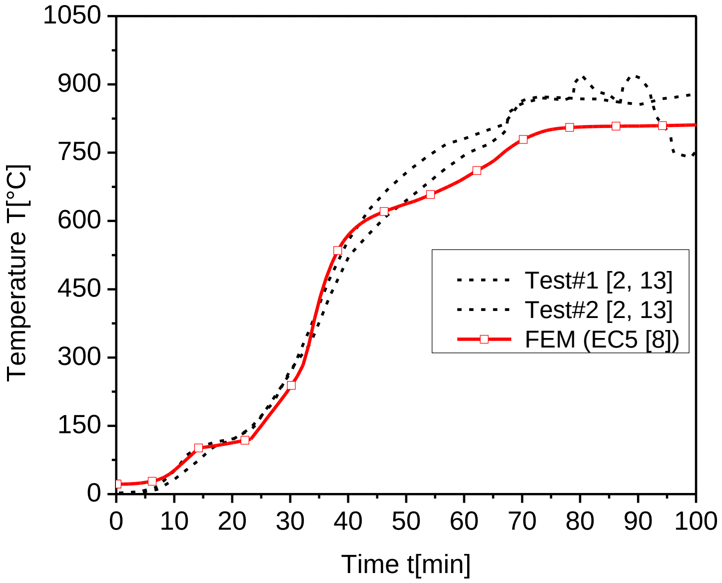


(a). t= 10min (b). t= 40min

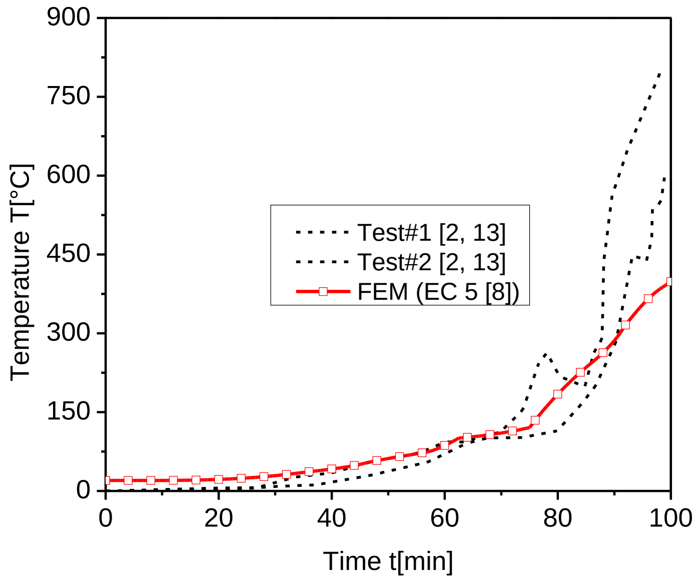
(c). t= 90min

Fig. 4. Temperature profiles T[K] across the cross section at different times of exposure.

Fig 5 shows the predicted temperatures at two different positions of the thermocouples. Fig.5a shows that the temperature remains stable, about 20°C, for a very short time of less than five minutes. Beyond this time, the temperatures start to increase progressively. The same observation is also made at the position (at 22 mm below the exposed surface) of the second thermocouple as illustrated in Fig. 5b. It can be seen that the predicted temperatures agree quite well with the experimental ones



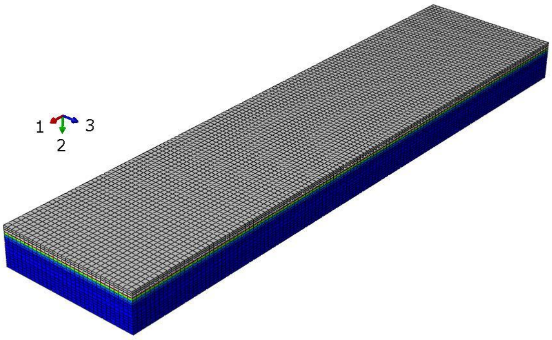
(a). At 21 mm below the exposed surface.



(b). At 22 mm below the exposed surface.

Fig. 5. Predicted and measured temperatures at two different thermocouple locations.

Fig 6 shows a comparison between the experimental formation of char and that predicted for CLT beam at fire exposure time t=100 min. In the absence of experimental data for different charring depths, in the presented work in refs [2, 13], only the formation zones of char are compared (see Fig. 6). It can be seen that the predicted char zones are similar to those obtained experimentally by Fragiacomo et al.[13] and Menis A.[2].



(a) (b)

Fig. 6. Formation of char after the fire test: (a) numerical and (b) experimental [2,13].

4. CONCLUSION

A 3D finite element model is developed to solve the partial differential equations of heat conduction numerically. Accordingly, the user subroutine Umatht has been implemented in Abaqus code to define their thermal constitutive relations in the finite element calculation. According to the predicted results, the validity and effectiveness of Umatht are confirmed. This study lays a foundation for the modelling of fire performance of laminated timber members used in engineering structures.

Further investigations are now in progress to extend these finite element models with the hope of simulating the thermomechanical behavior of timber structures using various geometrical and loading conditions and to provide more information for engineering applications used in timber construction.

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