Study of the influence of heat transfer of a CLT beam through FEM

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ABSTRACT

The heat transfer through wood in a fire situation is controlled by several processes, such as species, rate of heating and reaction kinetics. The article examines the challenges related to the thermal analysis of Cross-Laminated Timber (CLT) beams under non-standard fire conditions using ANSYS software. In this work, three numerical simulations are developed using Finite Elements (FE). The boundary conditions applied to simulate non-standard thermal conditions are: heat flux, radiation and convection, and temperature. And these boundary conditions are useful to compare heat transfer through Cross-Laminated Timber (CLT). The thermal properties of the wood used are based on the Eurocode 5. To validate numerical models, existing experimental results are used. The results show that the heat transfer through the CLT beam could be adjusted only by conduction. Improving the adjustment with respect to radiation and convection condition.

KEYWORDS: Cross-Laminated Timber; CLT; numerical simulation; heat transfer.
INTRODUCTION

Cross-laminated timber (CLT) is a product made of several layers (lamellae) of softwood timber, stuck together. Each lamella is glued crosswise using a polymer adhesive. This way of construction provides certain structural advantages, such as an increase in strength and stiffness in two directions [1].

The extended use of CLT in the modern construction industry makes it necessary to understand its structural behaviour under fire conditions. The combustibility of timber is one of the main reasons that standards restrict the use of wood. Most of the research carried out in fire field focuses on the charring rates [2].

In fire conditions, when the wood reaches temperatures above 220 ºC, pyrolysis takes place. In this process, wood is transformed into char wood. This char layer has low conductivity values, which causes a reduction of the carbonization range and protects the internal layers from the increase in temperature. However, the char layer is not able to support any load. The Eurocode 5 [3] takes into account a reduction in the cross-section caused by charring.

Both the European and Spanish standards provide methodologies for the design of wooden elements with appropriate behaviour in fire. Many different studies have been carried out using the European standard to determine the temperature distribution in a wood element subjected to an increase in temperature.

Numerical simulation is a powerful tool to investigate the performance of wood structures subjected to fire. Validated numerical simulation is covered in Eurocode 5 [3] part 1.2 in “advanced calculation methods”. The general procedure to determine the mechanical resistance of structural timber includes several steps, such as the determination of temperatures in the timber, of the resistance of cross-sections using the temperature field, and of the resistance of the structure.

However, one of the problems encountered when performing a thermal analysis on wood elements is that, due to simplifications of the model, the thermal properties of timber must be calibrated. Pyrolysis is a key aspect to predict the temperature distribution in any section of the wood element. The thermal conditions applied, and the influence of heat on the thermal properties of the timber are also taken into account in order to fit the experimental and numerical results. Most analytical models use simplified approaches such as the Eurocode 5 [3] part 1.2, which explains the changes in the thermal properties of timber as temperature increases.

Most of the fire modelling research based on finite element method (FEM) [4-7] uses the standard ISO fire curve [8]. This research has achieved improvements in obtaining the charring rate and accurate time and temperature-dependent thermal properties. However, much needs to be done to provide more accurate data under more realistic fire conditions. In the work done by Lineham et al [1], a CLT beam is exposed to the action of fire. This boundary condition differs from the ISO 834 standard curve [8]. In this work, to analyse the heat transfer, three thermal analyses were performed and compared with the thermal results obtained by Lineham et al [1]. The objectives of this paper are to compare heat transfer of an element subjected to a non-standard condition using three boundary conditions: heat flux, convection and radiation, and temperature, and to define a strategy to set up a thermal analysis.

NUMERICAL MODELING

The finite element method (FEM) is successfully used as an advanced calculation method following to Eurocode 5 [3]. In this paper, FEM is used to determine the temperature distribution of timber elements under fire conditions.

The numerical modelling presented in this work uses FEM to simulate the thermal test of two CLT beams carried out by Lineham et al [1]. Following Lineham’s work, two different lay-ups configuration were studied, one with three layers and the other with five Fig. 1.

Fig. 1. Geometrical configuration.
To study the temperature distribution, the geometry used was the same as the exposed part of the tests carried out by Lineham et al [1]. The geometry is shown in Fig. 2. To compare the effects of three different heat conditions a 2D transient thermal analysis of CLT beams was developed using the software ANSYS. These three heat conditions were applied to the model for two configurations: three-layer geometry and five-layer geometry. The thermal boundary conditions were applied in one-dimensional (1D) heat transfer to the CLT beam.

The three heat developed models are explained below:

In the first model, a constant heat flux of 27 KW/m² was applied to the exposed surface. This heat flux matches the real boundary condition applied in the experimental tests. The incident heat flux in the experimental tests was measured using a Gardon gauge.

In the second model, convection and radiation were applied. According to Eurocode 1 [4] emissivity (\(e\)) was equal 0.8 and convection coefficient (\(h\)) was equal to 25 W/m² K. The ambient temperature applied was variable.

The third model applied a variable temperature to the exposed surface. Therefore, the numerical model took into account the heat transfer only by conduction through its layers. If the heat flux exchange is known, the temperature distribution at the exposed surface of the wood can be expressed with [5]:

\[
\dot{q} = q_{\text{Gardon}}
\]

\[
\dot{q} = k_{\text{wood}} \cdot \frac{T_S - T_{C3}}{\varepsilon}
\]

where \(\dot{q}\) represents the heat flux measured using a Gardon gauge; \(k_{\text{wood}}\) is the thermal conductivity of timber; \(T_S\) is the exposed surface temperature and \(T_{C3}\) is the value at the thermocouple inside the CLT beam (Fig 3(a) and Fig 3(b)); and \(\varepsilon\) is the distance between the exposed surface and the thermocouple \(T_{C3}\).

For all the models, a convection coefficient of 9 W/m² K and an initial ambient temperature of 12°C were applied to the non-exposed surface. The value of the convection coefficient is proposed in [6]. In addition, two adiabatic surfaces at the cross section are defined where no thermal condition is applied. (Fig. 2).

To compare the temperature distribution between the simulation and the real tests, ten coordinate systems were created. The coordinate systems and the thermocouples were placed in the same position (Fig. 3(a), Fig. 3(b)).
Different authors have studied the relationship between the thermal properties of timber and the increase of temperature [9-11]. However, the thermal properties (conductivity, specific heat and density) used in this work were associated with Annex B of Eurocode 5 [3]. The use of these properties simplifies the analysis of heat transfer in timber. Furthermore, the specific heat takes into account the latent heat of vaporization of water in the timber [6].

Finally, the following assumptions were considered in the numerical simulations:

- Thermal properties: density, specific heat and conductivity were defined as isotropic properties.
- Effects of moisture migration and char layer formation were taken into account in the values proposed in Eurocode 5 [3].

RESULTS

In order to evaluate the computational efficiency of the FE model the time needed to solve the problems is presented in Table 1.

|                  | Heat Flux | Radiation+Convection | Temperature |
|------------------|-----------|----------------------|-------------|
| 3-Layer configuration | 39        | 5                    | 7           |
| 5-Layer configuration | 70        | 8                    | 14          |

The comparison between the experimental results and the thermal simulations are shown below. Two of the three boundary conditions studied, convection and radiation, and temperature bring the numerical temperature distribution close to the experimental. However, in the first model, the use of the real heat flux as a thermal condition overestimated the temperatures of all the thermocouples.

The following figures (Fig. 4. and Fig. 5.) show the adjustment of the temperature distribution between the experimental and numerical results at different depths. In order to simplify the graphs, the values of only three of the ten thermocouples are plotted for convection and radiation (R+C Sim.), and temperature (Temperature Sim.).
CONCLUSIONS

In this research, simulations were performed under different thermal conditions in CLT beams. These simulations consisted of three different boundary conditions applied to the exposed surface. The results obtained show that the thermal boundary conditions have a great influence on the temperature distribution. Heat flux is not able to simulate the thermal distribution through the CLT beam when it is measured using Gardon gauge. This heat flux sensor is designed to measure the total radiation flux density. However, heat flux defined in Ansys is referred to the rate of heat flow across a unit area.

In a fire situation, radiation and convection are the main conditions to be taken into account. Therefore, these conditions optimize the temperature distribution.

The temperature distribution in a CLT beam can be adjusted by a variable temperature applied on the exposed surface when the boundary conditions are known.

The results obtained in this research are an original contribution to analyse the thermal properties of CLT beams. The simulated temperatures do not stabilize at 100 °C (as shown in Fig. 4.), because localized moisture is not taken into account. The further the thermocouple is from the exposed surface, the worse the simulation results. Thus, as a future line, it is necessary to investigate the influence of parameters, such as the moisture evaporation, mass transfer, pyrolysis, and different thermal properties of contacts between layers, to develop optimized thermal simulations.

The computational time is an important factor when a numerical simulation is developed. Differences between each calculation time show the importance of developing an efficient numerical simulation, as thermal analyses are usually coupled with structural analyses.

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