Non-linear simulation of Cross-Laminated Timber (CLT) delamination under fire conditions using FEM numerical model.

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Summary. Cross-laminated timber (CLT) is an engineered timber product manufactured with an odd number of timber layers placed crosswise to each other. These structural elements are widely used in the construction field. Although the behaviour of CLT under fire conditions is known, there are challenges of knowledge that require more in-depth research, such as flame spread, thermal degradation, self-extinction, and delamination during heating. This work focuses its research on the simulation of delamination during heating. Numerical simulation using finite element methods (FEM) is widely used to predict and simulate the thermal behaviour of CLT elements under heating conditions. The objective of this study is to develop a numerical model using FEM to simulate the delamination of CLT under fire conditions using existing data from the literature. Delamination occurs when one layer falls off the main mass of timber. Under fire conditions this is due to an alteration of the cohesive properties of the adhesive between the layers. In order to simulate delamination, the Birth and Death element can be used to deactivate contact elements between layers in a thermal analysis, reducing the section and modifying the properties of the interface layer. The thermal properties of timber, such as thermal conductivity, density and specific heat are a function of temperature. The results of this work show that the developed model can predict temperature profiles and char formation, as well as delamination during the heating process. This work combines advanced numerical

techniques to simulate delamination of CLT under fire conditions. As a future work, the FE model should be calibrated and validated by comparing the results with experimentally measured data.

1 INTRODUCTION

Cross-laminated timber (CLT) elements are becoming progressively more popular in the construction field in Europe. CLT elements are usually manufactured from sawn coniferous wood such as spruce, pine and silver fir. They consist of an odd number of layers (lamellae), depending on the purpose and requirement. Each layer is glued crosswise to the next by means of an adhesive [1]-[2].

Under fire conditions, the fire-exposed surface of CLT starts to change its properties due to the charring and pyrolysis process. Furthermore, depending on the thickness, these processes can affect the behaviour of CLT under fire conditions, reducing the risk of delamination and decreasing the effective charring rate [2].

Delamination (fall off, or debonding) is a phenomenon in which the layer exposed to fire is separated from the main mass of timber due to the loss of bonding adhesive properties at high temperature. This could happen locally at specific points, or to entire layers, when the temperature of the adhesive reaches 300°C [3]. After a layer has fallen off, there is an increase in the temperature of next layer. The insulation of the other layers and the potential for auto-extinction is reduced and the fire is prolonged [4].

In recent years, some authors have studied the influence of types of adhesive and their sensitivity to temperature, to understand the delamination phenomena on CLT. The work done by Andrea Frangi [1], presents an experimental analysis of CLT under fire conditions. The results showed that delamination of CLT panels is strongly influenced by the properties of adhesives at high temperatures. Thus, the fire behaviour is also influenced. The research done by Daniel Brandon [5] assesses the ability of different adhesives to avoid the delamination of CLT under fire conditions. The results show that delamination is influenced by the type of adhesive.

The Finite Element Method (FEM) is an effective method to research the thermal and structural behaviour of CLT systems under fire conditions without expensive fire testing. Most of the studies carried out in the numerical field simulate the fire resistance of CLT by applying standard fire curve. Furthermore, all the models predict the thermal degradation of these elements. In the last years, the amount of FE research has increased, studying processes such as charring and pyrolysis. However, there are no FE delamination studies available in the literature. Thus, it is interesting to develop numerical models and calibrate them with experimental results to understand more about the delamination process under fire conditions.

The objective of this work is to develop a preliminary FE model to analyse the delamination process. The numerical model uses the thermal properties of timber and the Birth and Death element to simulate the de-bonding of the contact layer when it reaches 300°C. It provides an acceptable estimation of delamination. Furthermore, particular attention is paid to the distribution of temperature when a layer falls off due to delamination.

2 NUMERICAL SIMULATION

To analyse delamination, an advanced calculation was performed using FE modelling. A 2D FE thermal model of a CLT beam was developed in ANSYS® 18.1. The specific CLT beam was defined as spruce timber. Furthermore, 1800 seconds were defined as the time for simulation. This criterion is selected for two reasons: (1) it is the moment when the temperature in the contact between layer 1 (L1) and layer 2 (L2) exceeds 300 °C, and (2) to reduce the computational cost.

2.1 Setup of heat transfer

The definition of the numerical model in layers followed the real properties of a CLT beam. Therefore, a five-layer model was defined. The five-ply beam was 500 mm long and 100 mm thick. Each ply was 20 mm thick (Figure 1). Each layer is defined with an orientation: layers L1, L3 and L5 are oriented longitudinally, and layers L2 and L4 are oriented perpendicularly.

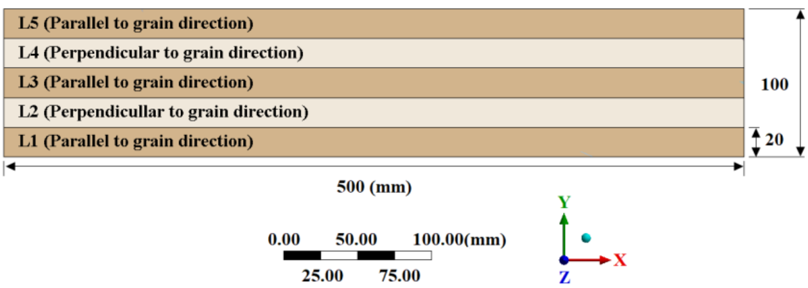


Figure 1. Dimensions of five-layer model.

The thermal properties of timber, density, specific heat and thermal conductivity, change with the temperature. The thermal properties of spruce timber can be found in the literature [6]-[7]. Eurocode 5 [8] gives the same value for longitudinal and perpendicular directions. However, some authors [9] consider that in the longitudinal direction (parallel to fibre) the values of Eurocode 5 [8] should be increased.

Density and specific heat were defined as isotropic properties, whereas thermal conductivity was defined as an orthotropic property. Therefore, density and specific heat values follow Eurocode 5 [8]. Thermal conductivity in the perpendicular direction is also associated with the values of Annex B of Eurocode 5 [8] whereas, according to [9], in the longitudinal direction the values of Eurocode 5 [8] must be multiplied by two.

Usually, the study of any structure under fire conditions includes radiation and convection phenomena in the exposed surface. However, in this work, in order to simplify the problem and reduce the time of the calculation, variable temperature is applied.

Therefore, in this numerical model, to study the temperature distribution and delamination, a one-dimensional (1D) transient thermal analysis is developed. Thus, the thermal boundary condition represents the standard time-temperature curve ISO 834. This curve is applied in several steps that are chosen manually. Each step has different temperature conditions according to the ISO 834 curve. The ISO 834 curve is a logarithmic function with an initially steep slope (see equation (1)).

$$T = 20 + 345 \cdot log_{10}(8 \cdot t + 1) \tag{1}$$

where T is the temperature in °C and t is the time in minutes.

Finally, a convection coefficient of 9 W/m^2 K and an initial ambient temperature of 12ºC were applied to the non-exposed surface. The value of the convection coefficient is proposed in [10]. The boundary conditions applied in the FE model are shown in Figure 2.

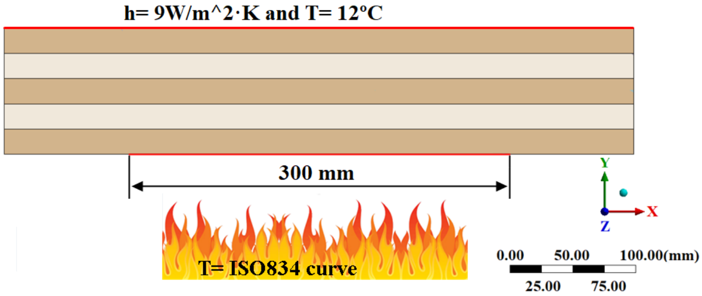


Figure 2. Boundary conditions applied

2.2 Birth and Death Element

The Birth and Death element [11] allows the model to activate or deactivate a specific selection of elements. This advanced element is very useful in this problem because those elements which reach a certain temperature can be deactivated.

The element used to mesh the model was PLANE77 [12]. It has 8 nodes with only one degree of freedom (temperature) at each node. It can be used in both stationary and transient thermal analysis. The contacts between all layers is a linear contact type bonded, assuming perfect glue contact between them.

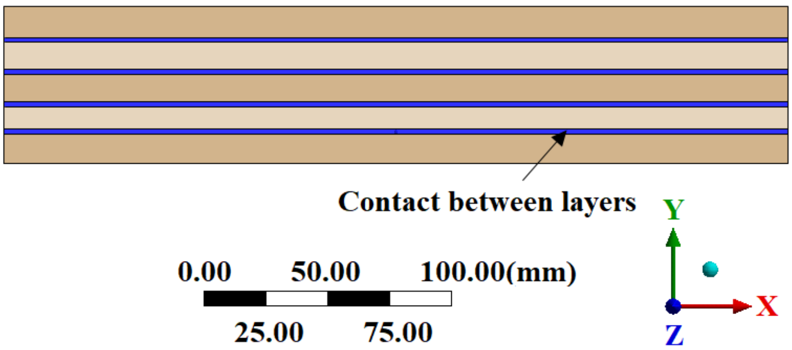


Figure 3. Contact elements

3 NUMERICAL MODEL RESULTS

To study temperature distribution, nine local coordinate systems were created, as shown in Figure 4. In order to compare and validate the results, a preliminary model was developed to check the temperature distribution without using the Birth and Death element. This model shows the variation of temperature over time within the CLT beam.

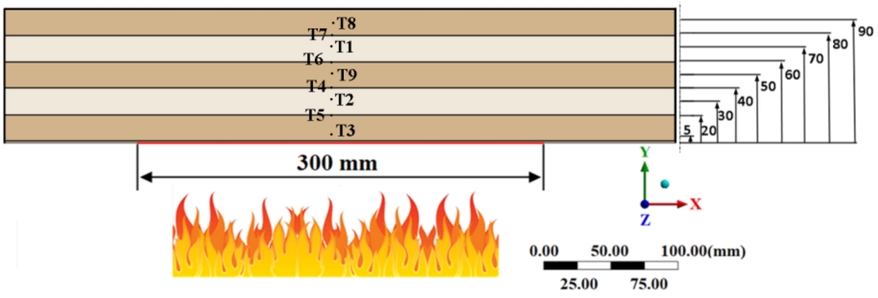


Figure 4. Coordinate systems used. (Distance of thermocouples from the exposed surface in mm).

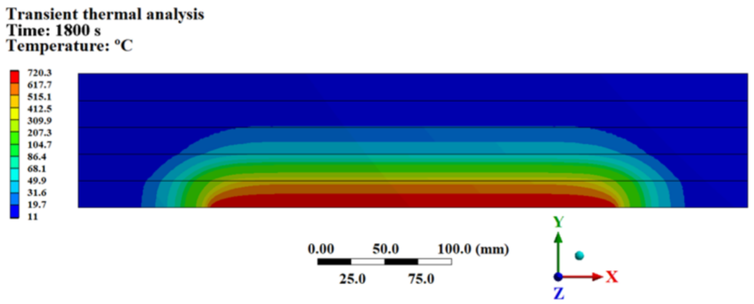
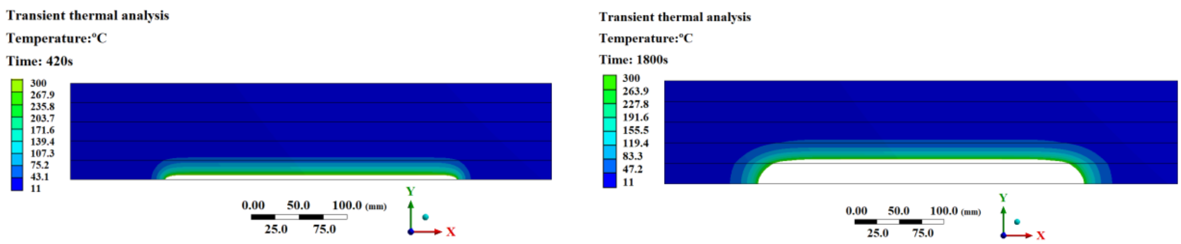


Figure 5. CLT temperature distribution in the preliminary model.

To compare the two numerical models, the temperature distribution is displayed. A contour region of 300 ºC is selected as it is the temperature at which delamination begins. Figure 6 and Figure 7 show temperature distribution at different times of exposure.



(a) (b)

Figure 6. Temperature distribution in the preliminary model at: (a) 420 seconds, and (b) 1800 seconds.

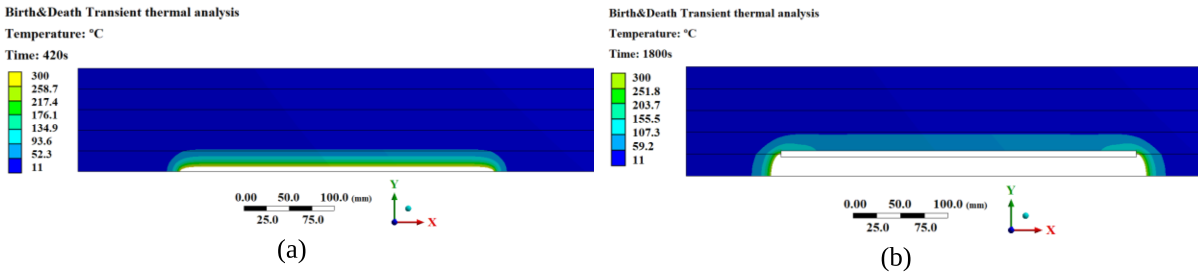


Figure 7. Temperature distribution in the Birth and Death model at: (a) 420 seconds, and (b) 1800 seconds.

Figure 8 and Figure 9 show the temperature development over time in the first layer (L1) and in the contact zone between L1 and L2. The results of the preliminary model show a constant increase in temperature within the beam according to the thermal properties. The temperature results of the Birth and Death model follow the same trend as the preliminary model until the temperature in the contact layer reaches delamination temperature. At this moment, there is an increase of the temperature values in L1 and in the contact zone between L1 and L2.

In spite of starting delamination temperature is 300°C, this phenomenon does not appear until the last part of the numerical simulation (Figure 9) and, consequently, of the steps chosen.

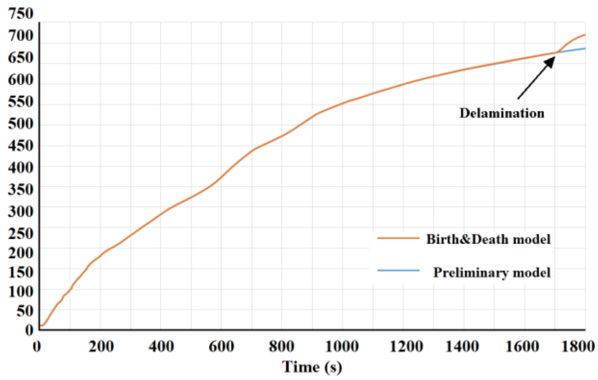


Figure 8. Temperature in Layer 1 (L1)

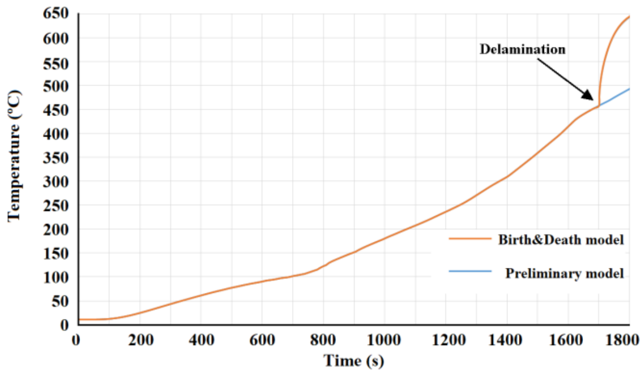


Figure 9. Temperature in the contact zone between L1 and L2.

4 CONCLUSIONS

The aim of this work is to simulate delamination of CLT structures using ANSYS Parametric Design Language (APDL) to design an advanced numerical model. The use of the Birth and Death element is an advanced technique which requires APDL commands to be calculated.

The most important conclusions of this work are the following:

- For the development of the FE model, it is important to know the critical bond line temperature that leads to delamination in order to identify the temperature at which the elements of the contact layer will be deactivated.
- Using the Birth and Death element with the delamination numerical model is a novel technique to simulate delamination. Elements does not remove from the model, rather they are deactivated by multiplying their stiffness by a severe reduction factor. Thus, it is important to adjust the value of the reduction factor to avoid convergence issues.
- Load steps should be carefully chosen, to set the right moment of delamination.

Future work includes research and experimental tests in order to validate and adjust the results of the FEM delamination model.

5 ACKNOWLEDGEMENT

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