Engineering Structures 143 (2017) 11–21

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Finite element analysis of heat transfer through timber elements exposed to fire

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ARTICLE INFO

*Article history:*
Received 8 October 2015
Revised 5 April 2017
Accepted 6 April 2017

*Keywords:*
Timber construction
Thermal analysis
Heat transfer
Finite element modelling
Fire safety
Eurocode 5

ABSTRACT

Since timber is a combustible material, its safe use in construction will depend on a proper knowledge and modelling of the physical and chemical reactions involved in the pyrolysis, that affect the temperature growth and thus the performance of timber in fire. Based on the comprehensive one-dimensional analytical models of the pyrolysis available in the literature, it is required to implement a predictive FE model via a user-defined subroutine in the dedicated commercial software in order to describe more closely the real physical phenomena that undergo timber exposed to fire. This paper presents the implementation of the UMATHT subroutine in the Abaqus software. The obtained results showed a fairly good agreement with experimental ones from the literature. However, at this stage of the study the pyrolysis is taken into account implicitly in the developed UMATHT through gradually modified thermo-physical properties of the timber, as commonly adopted in the published literature. Work is now in progress to implement explicitly the different reactions of the pyrolysis in the developed UMATHT.

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## 1. Introduction

Fire safety is the means by which structures are designed in a manner such that life is fully protected and damage to property and the environment are minimized. Building design procedures, like Eurocode 5 [1], are defined on the basis of one or more fire growth scenarios in such a way that these goals are achieved.

The performance of timber exposed to fire has to be analysed in the context of the characteristic time scale. The problem of timber material in fire is mostly a structural problem that should focus on the mechanical behaviour of the degrading material. Since timber is a combustible material, its safe use in construction will depend on a proper design, which involves a correct knowledge of the physical phenomena that affect the performance of timber structure in fire. When subjected to high temperature or radiant fluxes of the magnitude of those encountered in fires, timber undergoes physical, chemical and structural changes. Initially, it heats up and the moisture contained in its voids will begin to evaporate. This will generate a pressure build up, which causes a flow of vapour and liquid water in some cases to the outside of the timber matrix and also to the inner, colder regions, thus increasing the moisture content in those areas [2]. As heating of the timber continues for an extended period of time, involving higher temperature, generally up to 300 °C, the pyrolysis takes place producing combustible gases, accompanied by a loss in mass (thermal degradation). The pyrolysis will then move into the virgin section located at deeper positions. The char layer is not able to support any loads, causing an increase of the stress of the reduced section. In the same time, the virgin section will heat up, which will cause a decrease in the mechanical and strength properties. But it is well-known that the char layer causes the most known mode of failure of timber under fire. The Eurocode 5 considers a reduction in the cross section caused by the charring, and normally the charring rate is taken as a constant. Thus, knowing the fire-exposure time of the timber to a fire allows determining the remaining cross section which is still load bearing.

Nowadays, the need for predicting the structural behaviour of timber structures exposed to fire has gained increasing interest in the context of more and more intensive use of timber in modern constructions. On the other hand, the need for predicting the behaviour of timber exposed to fire is expected to more increase in the coming years particularly in the context of multi-storey timber structures. Consequently, the numerical simulation using the finite element method is a powerful tool to investigate cost-effectively the performance of timber structures under fire, in order to avoid drawbacks associated with experimental procedures. When dealing with numerical analysis of the thermal behaviour of a timber element under fire, the modelling of the pyrolysis is of major importance and a key task for accurate prediction of the realistic

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http://dx.doi.org/10.1016/j.engstruct.2017.04.014
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**Nomenclature**

| | |
|---|---|
| T | temperature [K] |
| t | time [s] |
| x,y,z | location coordinates [mm] |
| $c_p$ | specific heat [J/(kg K)] |
| λ | thermal conductivity [W/(m K)] |
| ρ | density [kg/m$^3$] |
| $\rho_0$ | initial density [kg/m$^3$] |
| $Q_r''$ | energy source [kW/m$^3$] |
| $h_{conv}$ | convection coefficient [W/(K m$^2$)] |
| $\sigma_{Boltz}$ | Stefan-Boltzmann constant [W/(m$^2$ K$^4$)] |
| $\varepsilon_{emis}$ | emissivity |
| $T_\infty$ | ambient temperature [K] |
| Tiso | ISO standard temperature [°C] |
| T0 | ambient temperature [°C] |
| Text | furnace temperature [°C] |
| $\underline{n}$ | outward normal direction |
| u | horizontal depth [mm] |
| v | vertical depth [mm] |
| $X_c$ | charring depth in direction (x) [mm] |
| $Y_c$ | charring depth in direction (y) [mm] |
| $x_{exp}$ | experimental charring depth in direction (x) [mm] |
| $x_{num}$ | numerical charring depth in direction (x) [mm] |
| $y_{exp}$ | experimental charring depth in direction (y) [mm] |
| $y_{num}$ | numerical charring depth in direction (y) [mm] |

temperature distributions within the timber section. In fact, the pyrolysis is a complex phenomenon: the wood is converted to char, which acts as an insulator to protect the virgin section from heating, and to gas that undergoes flaming combustion as it leaves the charred wood. All these energy sources should be taken into account in the energy balance equation in order to obtain a close-to-reality description of the wood behaviour in fire.

In recent years, numerous comprehensive analytical models have been proposed for the thermal analysis of wood including the modelling of the pyrolysis; see for example [3–5], among others. These models have the advantage to be more predictive since they are based on a realistic representation of the physical phenomena. On the other hand, several simplified approaches, conceptually similar to the Eurocode 5 proposal [1], are available in the literature [6–8]. Theses simplified approaches, take into account the charring (pyrolysis) by gradually modifying the thermo-physical properties of wood as temperature increases (effective properties) rather than realistic thermo-physical properties.

Physical reality of modern timber structures is generally associated with a certain amount of drawbacks related to their behaviour under fire. In fact, the prediction of the behaviour of modern timber connections, made by combining different materials including steel dowels and plates, under fire is complex and challenging due to the influence of the constitutive materials on the temperature distributions, on the charring of timber members and to their thermal interactions as well [8]. The ultimate goal of this work is to implement a predictive multiphysics finite element model in the Abaqus software via a user-defined subroutine. Implementing multiphysics model in advanced numerical software, like Abaqus, is one way to describe more closely the real physical phenomena that undergo the timber under fire (pyrolysis) and so to accurately simulate complex 3D situations, such as steel-to-timber joints. This paper describes the implementation of a user-defined subroutine called UMATHT in the Abaqus software. At this stage of the study, however, the different reactions involved in the pyrolysis are taken into account implicitly through gradually modified thermo-physical properties of wood, which is standard in the literature [1,6–8], among others. The implementation and the computational efficiency of the developed UMATHT are verified by comparison against results gathered from the literature.

## 2. Finite element modelling

### 2.1. Governing equation

To analyse the heat transfer within the wood sample in fire, three modes of heat transfer, namely conduction, convection and radiation should be considered. In a fire test furnace, heat fluxes flow to the outermost surfaces of the wood sample and heat transfer by convection and radiation, whereas heat transfer occurs within the wood member through conduction. At high temperature, wood undergoes pyrolysis and it is converted to char, vapor and gas resulting in a reduction in the wood's density. The gas undergoes flaming combustion as it leaves the charred wood.

According to the one-dimensional analytical models available in the literature [3,4,9], the evolution of the temperature gradient, incorporating the energy source due to the pyrolysis, in a 3D wood sample can be described by the energy conservation equation as follows:

$$(\rho_w C_w + \rho_c C_c + \rho_l C_l)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda_x \frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda_y \frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[\lambda_z \frac{\partial T}{\partial z}\right] + Q_r'' \tag{1}$$

Where T is the temperature;$\lambda_x$, $\lambda_y$, $\lambda_z$ denote the temperature-dependent thermal conductivities in the three directions, x, y and z.,$\rho_w$, $\rho_c$, $\rho_l$ are the densities of wood, char and liquid respectively,$C_w$, $C_c$, $C_l$ are the specific heat capacities of wood, char and liquid respectively. $Q_r''$ is the sum of reaction heat of the different pyrolysis reactions at the temperature T, depending on the reaction rate, activation energy and heat reaction of every pyrolysis reactions (see [3–5] for a better reading on these aspects) and t is the time variable.

The solution of the above governing equation for transient heat conduction requires the initial temperature distribution and proper boundary conditions. The initial temperature distribution at t = 0 is described by:

$$T(x,y,z,t)|_{t=0} = T_0(x,y,z,t) \tag{2}$$

where $T_0(x,y,z,t)$ is the ambient temperature of the considered specimen.

The heat fluxes exchange heat with the exposed surfaces of the wood sample by convection and radiation, which can be expressed by means of the following boundary conditions:

$$-\lambda_i \frac{\partial T}{\partial \underline{n}} = h_{conv} \times (T - T_\infty) + \sigma_{Boltz} \times \varepsilon_{emis} \times (T^4 - T_\infty^4), \quad i = x,y,z \tag{3}$$

where $\underline{n}$ represents the outward normal direction of the wood sample surface; $T_\infty$ represents the fire temperature measured in the furnace; $\sigma_{Boltz}$, $\varepsilon_{emis}$ and $h_{conv}$ are the Stefan-Boltzmann constant, the emissivity and convection coefficient. The numerical value of these constants are taken from the literature [1,7,8] and are equal to $5.67 \times 10^{-8}$ W/(m$^2$ K$^4$), 0.8 and 25 W/(m$^2$ K), respectively.

The proposed model was implemented into finite element code Abaqus [10] via the user subroutine UMATHT.

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