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Experimental and numerical study of the thermomechanical behaviour of wood-based panels exposed to fire

Guillaume Cueff [a,b], Jean-Christophe Mindeguia [a,*], Virginie Dréan [b], Denys Breysse [a], Gildas Auguin [b]

[a] University of Bordeaux, UMR CNRS 5295, I2M – Dpt GCE, 351 Cours de la Libération, A11-Bis, 33405 Talence, France
[b] EFECTIS France, Bat. Manager St-Jean 19/23 Quai Paludate, 33800 Bordeaux, France

HIGHLIGHTS

- Experimental and numerical study of the fire behaviour of wood panels is proposed.
- A thermomechanical model is developed, including thermal reactions in the material.
- Main Thermomechanical properties of the wood panels are measured.
- Simulations show good results and could help the fire development of the products.

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ABSTRACT

A research programme has been set up whose main objective is to build a thermo-mechanical model for simulating fire resistance tests on door sets composed of wood-based materials. Based on simulated temperature field and on estimations of the global bending of the fire door, the model should allow parametrical studies to be carried out in order to determine the behaviour of the product in a real fire resistance test. This should lead to a reduction in the number of high-cost real tests. A numerical model for fire degradation of wood-based products was developed first. Then, the results of thermal and mechanical characterisations of wood-based products (particle boards) are presented. Finally, simulations of thermal transfers and the thermomechanical behaviour of a small-scale door were carried out. The numerical results are compared to experimental data and show good agreement on thermal transfers and temperatures on the unexposed side of products. The simulated deformation of the panel is similar to the observation during the test. Nevertheless, the evolution of the displacement during the fire is not yet well transcribed. Possibilities for improving the mechanical model are then indicated.

1. Introduction

Fire safety is a major concern in the field of civil safety and mainly in the case of building construction. It is based on the combination of active and passive protection, including means that prevent or slow the spread of smoke and flames. New manufactured products must satisfy technical approvals, including fire resistance tests, which are experimentally assessed in accredited laboratory furnaces [1].The validation process of a product regarding a fire resistance test is complex and this can slow down any innovation. In such a context, the use of simulation tools can offer an alternative to real fire resistance tests in determining the fire resistance behaviour of a product, for instance during preliminary design stages. The concept of a “Virtual Furnace” is therefore being developed in some laboratories [2–4] in order to model a fire resistance test. The concept is based on the coupled simulation of (i) the gas temperature and flux (using computational fluids dynamics software) and (ii) the thermal or thermomechanical behaviour of the structure (most often carried out with finite element solvers). Such a tool recreates virtually the thermomechanical behaviour of the tested product when it is exposed to a standard fire in a laboratory furnace. Using a “Virtual Furnace” allows better analysis and evaluation of a large number of technical alternatives, before a conclusive fire resistance test is carried out. Moreover, numerical simulations may improve the testing conditions, including heating power (control of the furnace) and metrology. In the fire research field many studies are available regarding the behaviour of solid wood under exposure to fire [5–8] the reason for this being the widespread use of wood as a structural product in constructions (timber). On the other hand, wood-based products such as linen particleboard are mostly used for claddings, furniture or door

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* Corresponding author.
E-mail address: jean-christophe.mindeguia@u-bordeaux.fr (J.-C. Mindeguia).

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Nomenclature

$A_{w,s}$	Pre-exponential factor for water vaporisation and wood pyrolysis [/s]
$\lambda_{w,s,char}$	Thermal conductivity of water, dry wood or char [W/m·K]
$Cp_{w,s,char}$	Specific heat capacity of water, dry wood or char [J/kg·K]
$\rho_{w,s,char}$	Bulk density of water, dry wood or char [kg/m^3]
λ_{tot}	Thermal conductivity of the cellulosic material [W/m·K]
Cp_{tot}	Specific heat capacity of the cellulosic material [J/kg·K]
ρ_{tot}	Bulk density of the cellulosic material [kg/m^3]
γ	Charring rate after pyrolysis (by initial mass of wood) [−]
β	Initial moisture content [%]
D	Thermal diffusivity [mm^2/s]
$Q_{w,s,c}$	Energy source/sink term for the water vaporisation or wood pyrolysis [W/m^3]
H	Convective heat transfer coefficient [W/m^2·K]
ε	Emissivity coefficient of the cellulosic material [−]
σ	Stefan-Boltzmann constant [W/m^2·K^4]
$k_{w,s}$	Reaction rates for the water vaporisation or wood pyrolysis [/s]
$Ei_{w,s}$	Activation energy for the water vaporisation or wood pyrolysis [J/mol]
$\chi_{w,s}$	Degree of reaction for the water vaporisation or wood pyrolysis [−]
$d\chi_{w,s}/dt$	Kinetic of degradation reactions for the water vaporisation or wood pyrolysis [/s]
$Hr_{w,s}$	Heat of reaction for the water vaporisation or wood pyrolysis [J/kg]

manufacture. Since they are not considered as load-bearing elements, their behaviour at high temperature is much less studied. For that reason, an experimental programme has been established, aiming to overcome the lack of data from the literature. Concerning the simulation of wood-based products at high temperature, many numerical models are available in the literature to describe the pyrolysis of wood [9–11]. These models are based on multi-step mechanisms for the degradation of wood at high temperature and they take into account the mass transfer into the material, but this involves many input parameters that are difficult to measure [10]. Civil engineers generally use simple thermomechanical models, with material properties at high temperature and charring models given by regulation codes, like for instance Eurocode 5 [12]. Such an approach generally leads to very conservative structure design and does not allow any distinction between the behaviour of different products at high temperature. Moreover, in the case of Eurocode 5, material properties and charring models can only be used for an ISO-834-1 fire exposure. Based on this observation, a new thermomechanical model has been developed, aiming to simulate the fire behaviour of wood-based products, that allows the specificities of each type of product at high temperature to be taken into account and which is adaptable to any type of thermal exposure, while limiting the number of input parameters. An attempt was made to use material parameters that are easy to measure. The main goal of the model developed is then to provide an engineering tool to simulate the thermomechanical behaviour of a wood product during a fire resistance test.

In the first part of the paper, the thermomechanical model for simulating the fire behaviour of wood-based products is presented. The numerical model is divided into two parts: (i) a model for the heat transfer into the material at high temperature and (ii) a model for the mechanical degradation induced by the pyrolysis reaction. The thermal model is able to take into account the thermal degradation reactions of wood or wood-based materials, namely the vaporisation of water, the pyrolysis of wood particles and resin and the thermally-induced variation of thermal properties. The thermal model consists in a 1st-order vaporisation and pyrolysis reactions controlled by two independent Arrhenius laws. The orthotropic mechanical model allows the mechanical degradation of the material due to pyrolysis reaction to be taken into account. Calculations have been performed by using the CAST3M finite element software [13].

In the second part of the paper, the characterisation of a wood-based material (linen particleboard) is presented. The main necessary input parameters for the model are assessed. The thermal properties are measured at ambient temperature as the thermal model automatically calculates their variation at high temperature. The thermal degradation of the product is characterised by carrying out thermo-gravimetric analysis tests. Mechanical properties are measured by a compression test. Finally, thermal expansion coefficients of the material are measured at high temperature.

Lastly, the thermal transfer under severe heating has been assessed on small and large panels in order to validate the model. In particular, the influence of the initial water content of the sample and the heat exposure has been analysed. Mechanical displacements of a wood-based (linen particleboard) panel during a fire resistance test have also been analysed.

2. Numerical model

2.1. Thermal model

2.1.1. Heat conduction

The heat conduction in the material is resolved using a modified Fourier law (E1) in which energy sources were added, which aimed to take into account the thermally-induced reactions. Q_w and Q_s are sources of energy respectively linked to the vaporisation of internal water (negative term, i.e. energy sink) and the pyrolysis of wood (positive term, i.e. energy input).

$$\rho_s C p_s \partial T/\partial t = \nabla(\lambda \nabla T) + Q_w + Q_s \tag{E1}$$

The two thermal reactions, vaporisation and pyrolysis, are governed by two independent Arrhenius laws that are presented in Section 2.1.2.

2.1.2. Thermal reactions and linked energy sources

Since water vaporisation and cellulosic material pyrolysis are thermally-activated reactions, it was decided to simulate them by using two independent Arrhenius laws. For each law, the degree of reaction $\chi_{w,s}$ is linked to the kinetic of reaction $\frac{d\chi_{w,s}}{dt}$, according to Eq. (E2).

$$d\chi_{w,s}/dt = k_{w,s}(1 - \chi_{w,s}) \tag{E2}$$

Eq. (E2) is a first-order Arrhenius law, representative of the thermal reactions schematized in Fig. 1.

In Eq. (E2), $k_{w,s}$ is the rate constant, which is dependent on temperature according to Eq. (E3).

$$k_{w,s} = A_{w,s} exp(-Ei_{w,s}/RT) \tag{E3}$$