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Effects of the combined action of axial and transversal loads on the failure time of a wooden beam under fire

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ABSTRACT

This paper presents the variations of the failure time of a wooden beam (*Baillonella toxisperma* also called Moabi) in fire subjected to the combined effect of axial and transversal loads. Using the recommendation of the structural Eurocodes that the failure can occur when the deflection attains 1/300 of the length of the beam or when the bending moment attains the resistant moment, the partial differential equation describing the beam dynamics is solved numerically and the failure time calculated. It is found that the failure time decreases when either the axial or transversal loads increases.

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1. Introduction

For a particular wood building, timbers can be regarded as the most important structures. Due to its flammable property, a wooden component can be burned and will fail completely in a matter of a relatively short time when exposed to high temperature (even if the performance is better than that of steel or concrete/steel components). When the structures that hold a building fail, there is no doubt that the building will also fail. Hence, there is a need to increase the fire endurance or fire resistance of wood beams. There are two ways that can be applied in finding the fire endurance of the beams. One of the methods involves a series of experimental tests that are very costly and cumbersome. Another way is by using numerical methods, particularly finite element method [1]. With the advancement of computers, computational time is greatly reduced and it has become a very economical way to predict the fire resistance of the components [2]. After the fire resistance of the wood beam is determined, a series of parametric studies can be easily done in order to increase the life of the component and stiffness.

Numerous studies on the structural fire design of wood have been carried out [3–7]. Charring rates were found to be the dominant factor for performance of the structural heavy timber during exposure to fire. To assess safety characteristics, variability in fire endurance should be taken into account through consideration of variability in the properties of the member (e.g., charring rate, strength, and stiffness), variability in anticipated applied load and variability in fire severity. For members stressed by bending during fire exposure, failure occurs when the maximum bending capacity is exceeded due to the reduction of the section modulus, and also when the elevated temperature causes the subsequent loss in strength of the member [4,5]. The fire resistance for specific load-bearing and non-load-bearing structures can be determined using reference to ready-to-used tables or design procedures such as the component additive method found in National Building Codes of Canada [6]. Fire resistance can also be evaluated using validated numerical models, which are becoming available with the advent of performance-based codes.

In the previous studies, the dynamical structural response of a wooden beam under transversal loading and fire was accessed [7,8]. This study describes the action of the axial load on the failure time of the wooden beam under fire. The wood species considered is the *Baillonella toxisperma* also called Moabi. It is od D50 resistance class according to the norm EN 338 and largely used in Cameroon and other parts of tropical countries for the building of different structures.

2. Equation of wood beam submitted to fire

The general equation governing the dynamical behavior of the beam at ambient temperature is given by [9]:

$$\rho S(\partial^2 W/\partial t^2) + EI(\partial^4 W/\partial x^4) + P(\partial^2 W/\partial x^2) = f_m(t) \quad (1)$$

where W is the displacement of the structure, I is the moment of inertia, E is the Young modulus, ρ is the mass per unit of length and f_m is the external excitation, t is the time, x is the position along the beam

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and P, the axial load (see Fig. 1). This excitation can have various forms such as a constant load, a sinusoidal load, a mobile load or a stochastic load. In this paper, the case of constant load is considered.

2.1. Influence of fire on a wooden beam

Submitted to fire, thermo-mechanical properties of the structure change with the temperature and eventually with the position. Eq. (1) becomes:

$$\rho(x,t,T)S(x,t,T)(\partial^2 W(x,t,T)/\partial t^2)+E(x,t,T)I(x,t,T)(\partial^4 W(x,t,T)/\partial x^4) + P(\partial^2 W(x,t,T)/\partial x^2)=f_m(t) \quad (2)$$

Taking into account a uniform distribution of temperature on the beam; $T(x,t) = T(t)$ and Eq. (2) becomes:

$$\rho(T)S(T)(\partial^2 W(x,t)/\partial t^2) + E(T)I(T)(\partial^4 W(x,t)/\partial x^4) + P(\partial^2 W(x,t)/\partial x^2) = f_m(t) \quad (3)$$

When a structural member, particularly a beam, is subjected to an increasing axial load, it will reach a point where the member is no longer able to resist the applied load and fails instantly. This phenomenon is known as member buckling or column buckling. The compressive stress developed in the heated, elastic, axially restrained beam may reach the critical buckling load which is defined by the Euler formula as [9]:

$$P_{cr} = 2.008\pi^2 EI/l^2 \quad (4)$$

where P_{cr} is the elastic buckling-load, E is the modulus of elasticity of the resisting member, I is the moment of inertia.

2.2. Design fires

The design fire is one of the main assumptions in the designs and one of the required inputs in almost all fire growth computer analyzes. It is usually specified as a heat release rate which varies over time for specific fuel burning in the open air. Some standard fires such as ISO 834 fire, Eurocode parametric fire and T-square fire are defined by temperature varying over time in a burning compartment. The temperature of a wooden beam submitted to one of those standards is different. In this paper the ISO 834 has been used [10].

2.2.1. ISO fire

The ISO 834 fire is the international standard of time–temperature curve which is defined by:

$$T(t) = T_0 + 345\log_{10}(8t + 1) \quad (5)$$

where t is the time in minutes and T_0 ($T_0 = 20\,^\circ C$) is the ambient temperature in degree Celsius.

2.2.2. Temperature distribution in the wooden beam

Wood is a composite structure made of sections which react differently to heat. Numerical and experimental studies have been carried out to determine the temperature distribution in different points of a wooden beam submitted to fire. Mathematical models to predict the temperature history for wood columns have been studied by many researchers [11]. Thermocouples placed at different points as from the center to the surface of a timber member

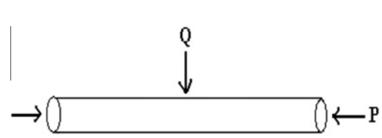

Fig. 1. Wooden beam axially restrained under the action of transversal and axial loads.

report that the temperature distribution is different for the different sections of the timber [12]. However, a spatiotemporal mathematical expression of the temperature distribution in the beam is not available. To overcome this difficulty, we have made a rough assumption of a homogenous temperature distribution in the wooden beam as given by the following equation:

$$T(t) = T_0 + 280[1 - \exp(-\gamma(t/2)^2)] \quad (6)$$

where $\gamma = 2.4454957 \times 10^{-3}$ and $T_0 = 20^\circ C$.

This relation is obtained by approximating experimental results [12–15]. Although this is not perfectly the case, the approximation can be accepted in the case of beam with small section and also taking into account the fact the carbonization rate completes the description, indicating the spatial evolution of temperature inside the beam (see hereafter).

2.3. Thermo-mechanical properties of a wooden beam submitted to fire

When temperatures above ambient are applied to wood, thermo-mechanical properties of the structure (mass, module of elasticity, resisting moment and bending moment) usually change as described below.

2.3.1. Mass of the structure

The global section and the moment of inertia of the structure are assumed to be constant: $I = S\,r^2$ At a certain temperature, a part of the structure is transformed into charcoal. This leads to the variation of the mass per unit of length of the beam [7].

Thus

$$\rho(t)S(t) = m/l(t) = \rho_b S_0 - \rho_b S_c + \rho_c S_c \quad (7)$$

with

$$S_0 = \pi r_0^2, \quad S_b = \pi(r_0 - \beta t)^2, \quad S_c = \pi r_0^2 - \pi(r_0 - \beta t)^2$$

where ρ_b, ρ_c, S_b, S_0, r_0, β are respectively the mass density of wood, mass density of charcoal, remained section of wood, section of charcoal formed, initial section of wood, initial section of the beam and the design charring rate of wood. Eq. (6) means that the mass of the structure will vary as from the initial mass of the wooden beam to the mass of the structure totally charred. The charring rate β of wood gives at each time step the charcoal section formed, thus the mass of the charcoal and eventually the mass of the structure at each time step.

2.3.2. Variation of the module of elasticity

The module of elasticity is a function of temperature and is given by the following equation [8,16–18]:

$$E = E_0(1 - (T - 20)/(2T_{char})) \quad (8)$$

$$E = 0 \quad \text{for } T \geqslant T_{char} = 300\,^\circ C$$

where T is the wood temperature, T_{char} is the charring temperature, and E_0 is the modulus of elasticity at ambient temperature.

2.3.3. Resisting moment of the joist

The internal forces of the wood beam allow it to resist a moment up to a certain value. The magnitude of the resisting moment is dependent on the yield stresses in both tension and compression. When loaded from above, the beam will be in tension below the neutral axis and in compression above the neutral axis. The corresponding yield stresses run in the axis direction of the structure, and in opposite directions and create a couple around the neutral

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