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Analytical model to simulate the behavior of notched wood beams (temperate species) under creep behavior in outdoor conditions

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Abstract

During their lifetime, wood structures are subjected to loadings and environmental changes, which can lead in some cases to their collapse. The present paper proposes an analytical model that allows predicting the behaviour of a notched wood beam subjected to a long-term loading (4-points bending) test in outdoor conditions. The proposed model considers the impact of cracks propagations (the specimen is made in a way to allow a linear crack propagation from the notch until total collapse of the beam) and the intensity of the load applied on the beam. The analytical model of the notched beam compliance (J_N) is based on the Timoshenko beam theory assumptions which consider the effects of shear and accounts for the geometry of the tested beam. The proposed model shows satisfactory results (good fit between the experimental deflection curves and analytical deflection curves for short period of times (approximately a month)). Experimental and analytical comparisons however underline the necessity to improve the proposed model in a way to account for the effects of moisture content (MC) variations in the beam during time (which is expected to be the object of a future paper) as well as creep.

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Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Using wood in the construction industry has become more and more popular during the past few years as such material can play a major role in reducing the environmental footprint of the building sector. Wood in comparison with other materials such as concrete and steel (for example), presents many advantages such as a reduction of the cost of productions and exploitation as well as advantageous recycling features (Ramage *et al.*, 2017). In addition, wood appears as an abundant resource to the extent that the policies regulating its exploitation and transformation are well developed. This is the reason why several studies aiming in characterizing its mechanical behavior were conducted (e.g., experimental (Angellier *et al.*, 2017; Odounga *et al.*, 2018; Pambou Nziengui *et al.*, 2019; Pelletier *et*

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al., 2019), analytical (Perkowski and Czabak, 2019), (Kong *et al.*, 2015) and numerical (Kim and Harries, 2010; Kravanja 2018), studies).

Experimental studies are often used to characterize the mechanical behavior of wood, but this type of studies has some disadvantages, such as the cost of the experimental setup used and the complexity of reproducing experiments in the same conditions (Henriques *et al.*, 2013). To overcome that, a possible solution is to develop analytical and numerical models which can simulate the effects of different types of loadings on wood structures (Kim and Harries, 2010; Reishel and Kaliske, 2015; Hoseinpour *et al.*, 2018). Developing analytical models is not a simple task and can become very difficult for complex problems (Henriques *et al.*, 2013; Teoderescu *et al.*, 2017). Simulating the behavior of wood structures is more particularly difficult since wood is a natural material that presents complex chemical, mechanical, and physical properties as well as an important structural variability. (Even for wood specimens taken from the same tree, the same species, and the same family).

The aim of this paper is to present a comparison between experimental data and analytical results driven from a model developed to study the evolution of deflection in a notched beam subjected to a creep loading under uncontrolled environment (the experimental campaign was largely presented in (Pambou Nziengui *et al.*, 2019)). The model 1, considers a level of crack propagation α , coupled with the intensity of loading and the geometry of the notched beam tested. This model is based on the beam theory of Timoshenko considering the shear effects of notched beams in 4-points bending test. The paper starts with presenting the experimental tests conducted to develop the model. Then, the analytical model developed for the compliance of a notched beam is presented. Finally, an experimental and analytical comparison is performed for validation.

Nomenclature

J_N	Notched beam (NB) compliance
y^G	General deflection measured by LVDT sensor
$\alpha, \Delta\alpha$	Crack length and crack increment
H	Height
a	lever arm
e	Thickness
L	Length of the beam
A	Constant taking into account beam's geometry
k	Constant ratio
F_0	Intensity of total load applied on the beam
E_N	Elastic modulus of notched beam

2. Materials and Methods

The paper undertakes a comparative analysis using data obtained from two distinctive approaches: an experimental study, as detailed in (Pambou Nziengui *et al.*, 2019), and an analytical examination conducted on notched beams made from temperate species, specifically Douglas fir and white fir sourced from the Massif Central region in France.

2.1. Experimental study

For the experimental study, the initial step involved notching the beams, as depicted in Fig. 1a, followed by subjecting them to outdoor environmental conditions for creep tests, as illustrated in Figs. 1b and 1c. The primary parameter under consideration in this study was deflection, which was measured using an LVDT sensor (Fig. 1a), strategically positioned beneath the center of each beam. Additionally, a pair of dial gauges were employed for each beam and placed symmetrically from both notches to monitor the extent of crack opening on one face, specifically at positions A and C (see Fig. 1a). To facilitate accurate crack length measurements, graduated lines with 1 cm increments were affixed to both faces at positions A, B, C, and D, as depicted in Fig. 1a. Creep loading was applied using a concrete block, as shown in Figs. 1b and 1c, while the entire experimental setup was located outdoors, in close proximity to the laboratory building, as outlined in Fig. 1c, (previously detailed in (Pambou Nziengui et al., 2019)). Deflection of each beam was monitored continuously, while crack opening, crack length and moisture content (MC) were collected manually every day.

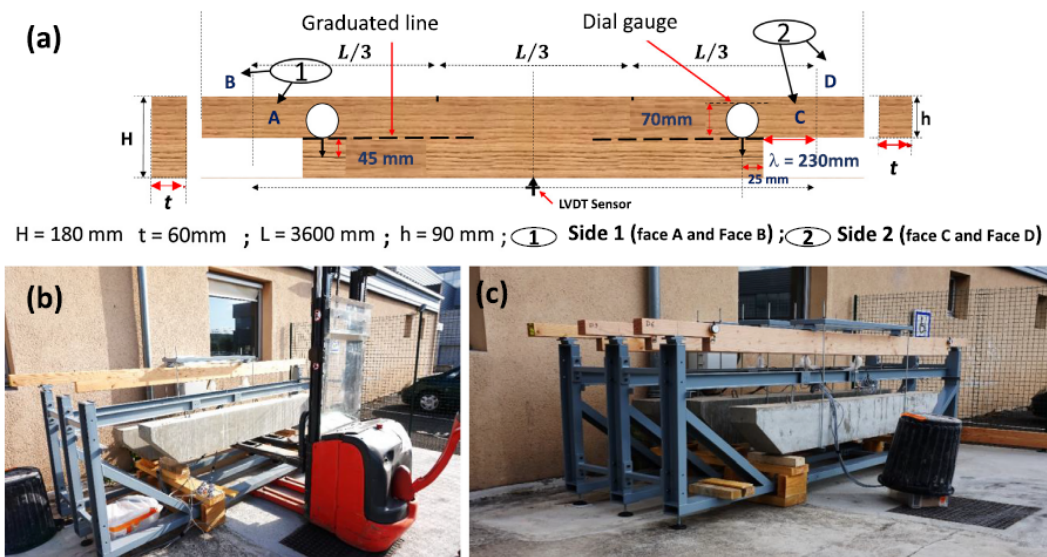


Fig. 1. Typical experimental setup used during the creep test (as presented in (Pambou Nziengui et al., 2019): (a) typical specimen used for the test; (b) loading block process of the beam; (c) creep tests performed outdoor.

2.2. Analytical study

Using experimental results obtained during the tests an analytical model simulating the evolution of the beam compliance was developed. The model is based on the assumptions of the beam theory. In such model, the symmetry of the system is accounted for which allows studying only half of a notched beam (HNB) as presented in (Pambou Nziengui et al. 2021).

Considering all these assumptions, the evolution of deflection could be represented by the following expression:

$$y^G = \left(\frac{23}{36}\right) \times \left(\frac{aL^2}{eH^3}\right) \times \left(1 + \frac{189}{23}\alpha^3\right) \times \left[1 + \frac{108}{115} \cdot \left(\frac{H}{L}\right)^2 \cdot (k) \cdot \frac{1 + \left(\frac{3}{2}\right)\alpha}{1 + \left(\frac{189}{23}\right)\alpha^3}\right] \times \left(\frac{F_0}{E_N}\right) \quad (1)$$

See the nomenclature for the description of mechanical and physical quantities in pages 2.

As presented in (Pambou Nziengui et al., 2021), the compliance for this kind of system without considering moisture content (MC) effect on the beam is as follow:

$$J_N(\alpha, t) = \frac{y^G(t)}{A \cdot F_0 \cdot f(\alpha, k)} \tag{2}$$

Where J_N represents the compliance of the notched beam (NB) at the time t for a crack appearing at the corner of the beam. This expression of the compliance J_N proposed considers, the mechanical behavior and the geometrical effects of the beam.

Fig. 2 presents the typical behavior of notched beam observed under creep loading. Fig. 2a presents the different quantities considered for the analytical model (where $y^G = y^M + y^V$ represents the general deflection measured by LVDT sensor) and Fig. 2b the evolution of shear force for this kind test.

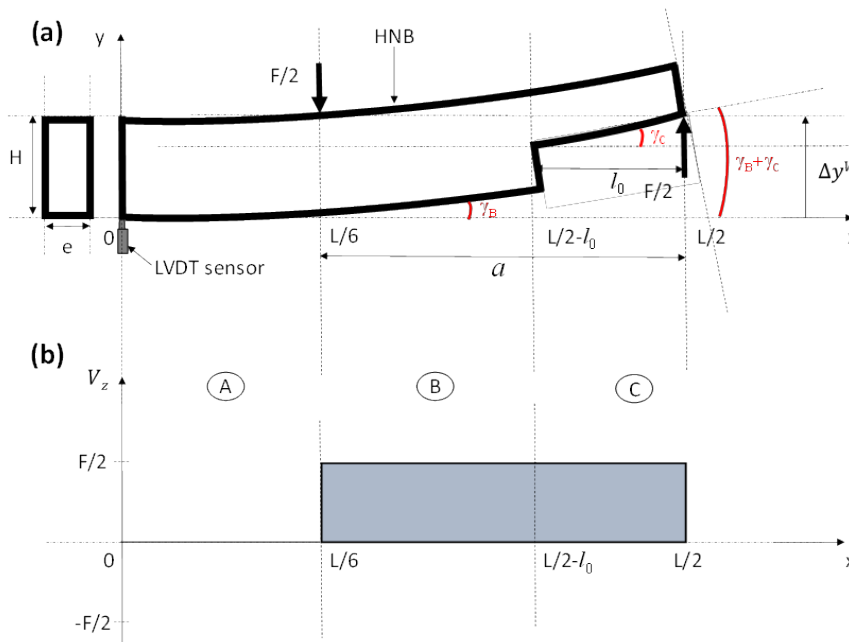


Fig. 2. Assumption of the typical behavior of notched beam during the creep test: (a) Half notched beam (HNB) in 4-points bending test; (b) Diagram of shear force V (Pambou Nziengui et al. 2021).

This analytical model was built to improve and predict, by doing some calibrations, the natural behaviour of wood in structure.

3. Results and discussions

To verify the adequacy of the model, a comparison was done between experimental and analytical evolutions of deflections as shown in Figures 3 and 4.

Curves of Figures 3b, 3c and 4a show that there is a good match between experimental and analytical results for the three notched beams compared. In Figures. 3a, 3d and 4b we can however notice two main behaviours. For beam DF1 (Fig. 3a), for example, we can see that for the period going from July 09, 2018, until July 15, 2018, there is a good fit between experimental and analytical curves but after this date, until the collapse of the beam, there is a pronounced gap between the two curves. The same observations were done for notched beams WF9 and WF2. From these results, it is possible to say that for short time loadings (during approximatively 1 month) of the beam, the model fits well experimental data but for a longer time loading (approximatively after 2 months, Fig. 3b) there is an important gap between analytical and experimental curves. Based on these observations it could be logical to say that the impact

of e creep over a long period of time is not well captured by the actual model. The impact of moisture content changes over time should also be accounted for in an upcoming revised version of the proposed model.

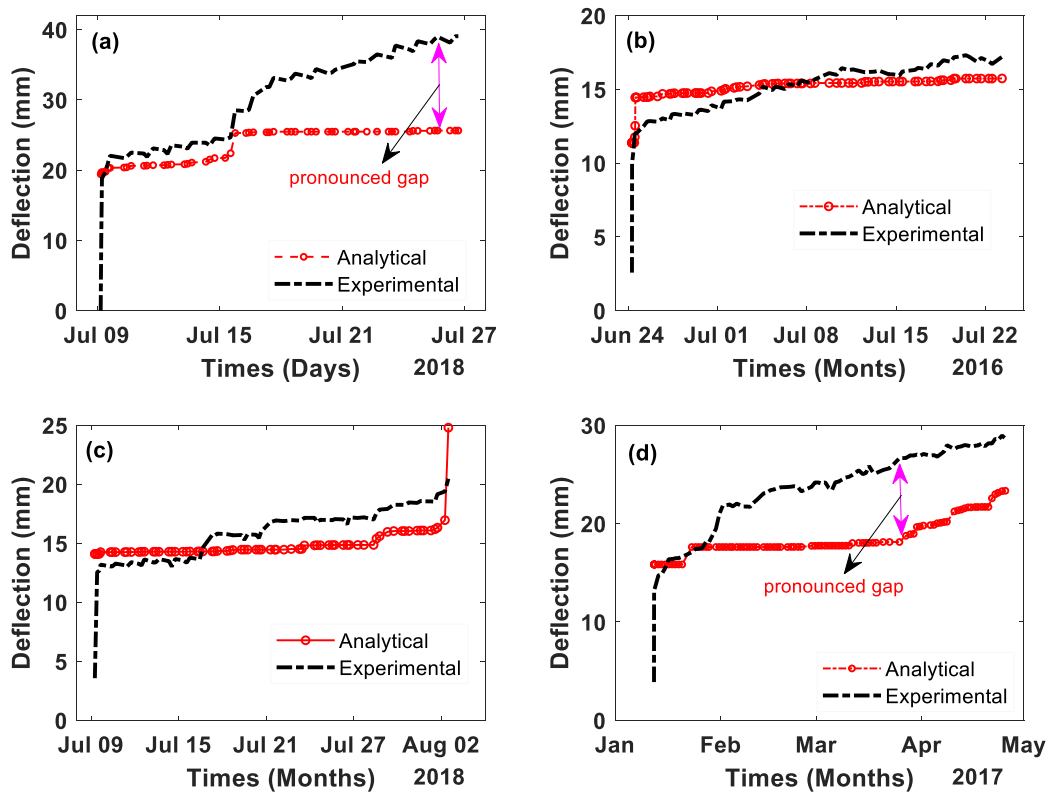


Fig. 3. Comparisons between the deflections measured xperimentally and the ones determined using the analytical proposed model for notched beams DF1 (a), DF9 (b), WF6 (c) and WF9 (d).

Table 1 presents the main characteristics of these notched beams.

Table 1. Main parameters of the notched beams considered.

	Beams	H (mm)	e (mm)	L (m)	F ₀ (kN)	E _N (GPa)
Douglas fir Species	DF1	178	59.7	3.6	4.44	8.21
	DF3	174	59.1	3.6	4.49	15.45
	DF9	176	59.4	3.6	4.49	15.53
White fir species	WF6	178	60.4	3.6	4.44	11.50
	WF9	179	59.9	3.6	3.61	11.65
	WF12	179	60	3.6	3.55	9.27

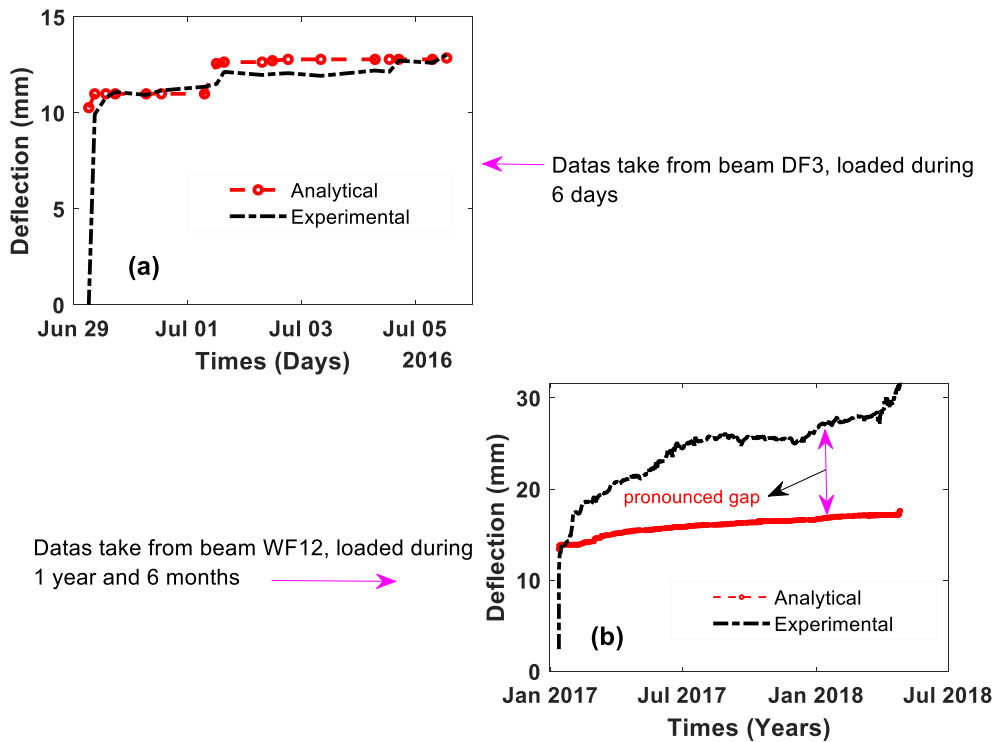


Fig. 4. Comparison of analytical and experimental deflection of DF3 (a) and WF12 (b).

4. Conclusion

In this paper, an analytical model of the compliance J_N of a notched wood beam was presented. This model was used to simulate the behavior of notched beams under 4-points bending tests (creep tests) in outdoor conditions. The model is essentially based on the formalism of classical beam theory. The specificity of the model is that it considers the coupling effects of crack propagation at the corner of the beam, the intensity of the load applied, and the geometry of the beam. The approach is based on the beam theory of Timoshenko which by the determination of the modulus of elasticity E and the shear modulus G , of the notched beam in 4-points bending test, allows calculating the deflection taken by the notched beam during the long-term loading. The calculated expression considers a level of crack “ α ”, which assumes that the crack spreads linearly from the corner of the beam until its total collapse. The comparisons done between the experimental deflections of the notched beams and the ones obtained with the model show satisfactory results for short-term periods of times (1 month). Climate variations were not accounted for in the proposed model (environmental conditions are considered constant). Long term creep effects (over a period of over a year) were not well captured by the model. In an upcoming article, the proposed model will be adjusted in a way to account for, the effects of climate variations on the mechanical behavior of wood beams, this will be possible by quantifying the variations of moisture content and coupling hydro and mechanical effects (due to the loading of the beam over time) by modifying the expression of the compliance.

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