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Analysis of Flexural Behavior of Wood-Concrete Beams

M. Li, V. D. Thi, M. Khelifa, M. El Ganaoui

***Abstract*—**This study presents an overview of the work carried out by the use of wood waste as coarse aggregate in mortar. The paper describes experimental and numerical investigations carried on pervious concrete made of wood chips and also sheds lights on the mechanical properties of this new product. The properties of pervious wood-concrete such as strength, elastic modulus, and failure modes are compared and evaluated. The characterization procedure of the mechanical properties of wood waste ash are presented and discussed. The numerical and tested load–deflection response results are compared. It was observed that the numerical results are in good agreement with the experimental results.

***Keywords*—**Wood waste ash, characterization, mechanical properties, finite element analysis, flexural behavior, bending tests.

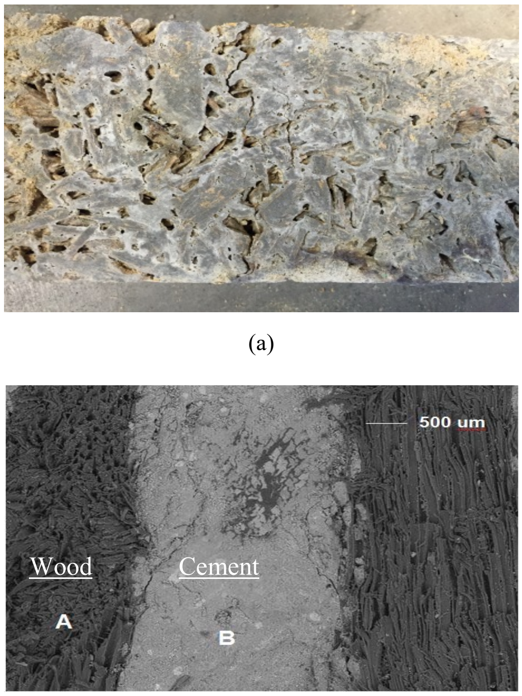
I. Introduction

THE construction industry has shown a renewed interest in the use of composite materials made of wood because of its intrinsic quality of regulating indoor climates. Many studies [1]-[3] have shown that the hygroscopic behaviour of plant materials can regulate humidity. Buildings consume a lot of energy and are responsible for one quarter of all carbon dioxide emissions.

In the case of sustainable construction, the materials used will not only be environmentally efficient, but they will also meet specific criteria [4]. It is not surprising therefore that new wood based materials are increasingly used for their environmental advantages. Manufacturing wood cement-bonded particleboard panels is an example, which encourages the use of by-products from other economic sectors such as the timber industry. Scientific studies [5], whose aim is to understand the behaviour of these materials under different stresses have contributed to the development of wood-cement materials. Thus, the thermo-hydro-mechanical and acoustic properties have been investigated. Nonetheless, they are yet to be fully accepted in the building industry because of the technical difficulties inherent to the experimental characterisation and modelling of their mechanical behaviour.

Wood-cement concretes are mainly used for their thermal and acoustic performances. These properties have attracted the interest of several players in the green building industry. However, the use of wood-cement materials in construction will remain marginal as long as problems limiting their use are not addressed as the characterization of the mechanical properties of wood-concrete panels used in the construction industry. Hence, the aim of this project is to contribute to the characterization of wood-based concrete panels in order to understand their flexural mechanical behavior through the combination of experimentation and numerical modelling.

The paper basically consists of three parts; first part described the testing of specimens under bending according to standard procedure. Second part describes the finite element modelling of the mechanical behavior of wood-concrete beams in bending tests. Third part describes the comparison between the predicted and the tested results.



(a)

(b)

Fig. 1 Wood-concrete material: (a) macroscopic aspect and (b) SEM micrograph

II. Experimental Program

A. Materials

The shavings were wastes from wood industry, and they came from spruce specie wood which belongs to the category of softwood. This timber is very used in construction thanks to its rapid growth and low price. Moreover, it presents good mechanical characteristics.

Table I presents the mix proportioning for all tested wood-

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concrete specimens. Fig. 1 shows the general aspect of tested wood-concrete specimens 90 days after casting. The composite material shows fibrous morphology as it can be seen from Fig. 1 (b).

TABLE I
WOOD-CONCRETE MIX PROPORTIONS

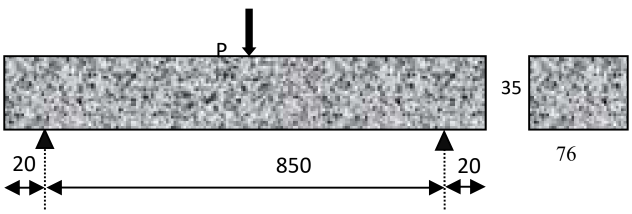
Mix [kg/m^3]	Proportion
Wood	330.4
Cement	267.2
Water	70.1
Glace	96.3

The change in panel mass during tests was measured to determine change in the panels' specific gravity. The average specific gravity of the panel was about 764 kg/m^3. The all specimens were stored at constant temperature and moisture content, 22 °C and 12%, respectively.

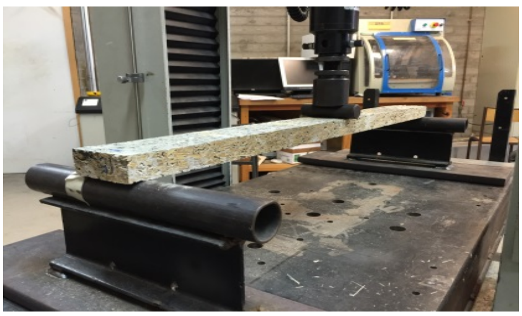
B. Three-Point Bending Test

The experimental program of the present study had to assess the mechanical behavior of wood-concrete panels under full-scale destructive bending tests according to the ASTM D3043[6] and ASTM D 1037 [7] in order to evaluate the stiffness and the load-bearing capacity of wood-concrete beams.

A total of 14 wood-concrete beams with a cross-section of 76x35 mm^2 have been tested. Geometrical and loading characteristics are shown in Fig. 2.



(a)



(b)

Fig. 2 Three-point bending test: (a) geometric and loading characteristics, (b) Test setup. Dimensions in mm

C. Load–Deflection Response of Wood-Concrete Beams

The analysis of the load–displacement curves indicates that there are three distinct stages of behavior during the test that correspond to the level of damage in the constituent composite materials (wood and concrete). Each experimental curve comprised linear and non-linear parts as shown in Fig. 3. Linear part corresponds to the elastic behavior of the material. The behavior of the composite beam remained linear but exhibited reduced stiffness. A reduction in the bending stiffness was observed during the second stage, which corresponds to a non-linear plastic behavior. The third stage represents the last part of curve when the bottom of the composite beam began to crack. The curves which show the load–displacement relationship for the 14 beams are displayed in Fig. 3.

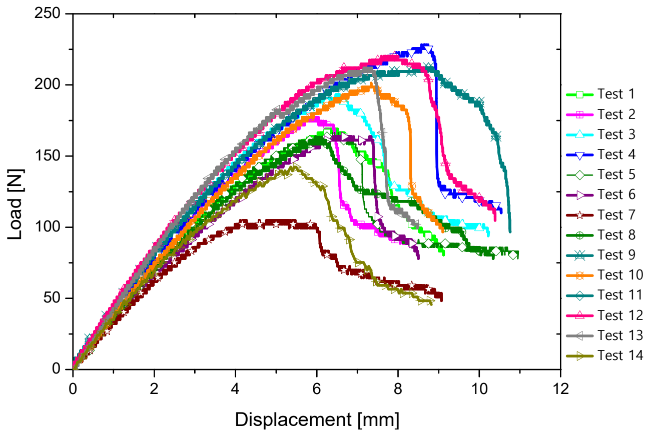


Fig. 3 Load displacement curves for beams

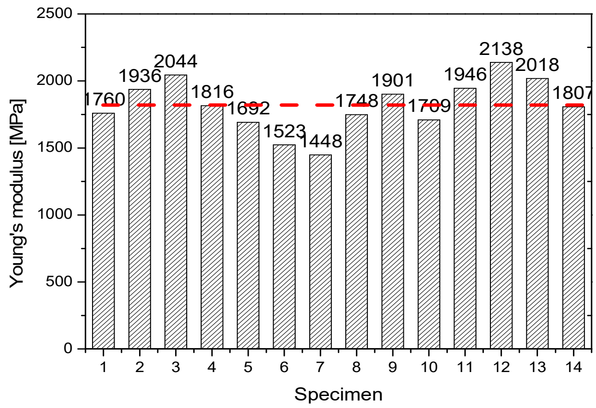


Fig. 4 Comparison of MOE

For three-point loading static bending tests, the elastic modulus MOE (E) and bending strength of rupture MOR (σ_R) were obtained by the following relationships:

$$f = \frac{P \times l^3}{48EI}; \quad I = \frac{b \times h^3}{12} \tag{1}$$

$$\sigma_R = \frac{3P \times l}{2b \times h^2} \tag{2}$$

where P is the applied load; b is the beam width; h is the beam depth; l is the effective beam span, and f is the load-point deflection.

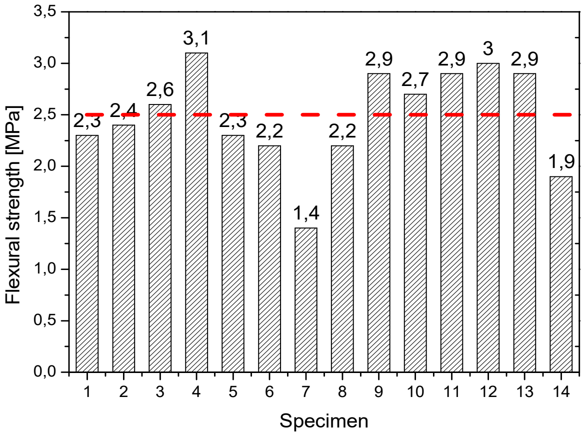


Fig. 5 Comparison of MOR

The data from all tested beams in terms of modulus of elasticity (MOE) and bending strength of rupture (MOR) are summarized in Figs. 4 and 5, respectively.

III. Numerical Approach

A. Basic concepts of Extended Finite Element Method (XFEM)

The extended finite element method was initially developed by Belytschko and Black [8]. It based on the concept of partition of unity, and which allows the presence of discontinuities in a finite element by enriching degrees of freedom using special displacement functions.

The approximation for a displacement vector function using XFEM [9], [10] is:

$$u = \sum_{i=1}^{N} N_i(x)\left[u_i + H(x)a_i + \sum_{\alpha=1}^{4} F_\alpha(x)b_i^\alpha\right] \tag{3}$$

where N_i are the element nodal shape functions; u_i is the nodal displacement vector; $H(x)$ is the jump function; $F_\alpha(x)$ is the asymptotic crack-tip functions vector; a_i and b_i^α are the nodal enriched degree of freedom.

The first term $\sum_{i=1}^{N} N_i(x)u_i$ in (3) applies to all nodes in the model; the second term $H(x)a_i$ applies to nodes whose shape function support is cut by the crack interior; and the last term $\sum_{\alpha=1}^{4} F_\alpha(x)b_i^\alpha$ applies to all nodes in the model cut by the crack tip.

At an enriched element, the crack initiation refers to the beginning of degradation of the cohesive response. The initiation of crack was assumed to occur when a criteria function f involving the maximum principal stress ratios reached unity, according to:

$$f = \frac{\langle \sigma_{max} \rangle}{\sigma_{max}^0} \tag{4}$$

where σ_{max} represents the maximum principal stress vector, and σ_{max}^0 is the maximum principal stress of material, which corresponds to the value of the beginning of damage.

According to the experiment results, wood-concrete material parameters used in simulations are recapitulated in Table II.

TABLE II
Wood-Concrete Material Parameters

Young's Modulus E [MPa]	1830
Poisson's ratio ν	0.2
Elastic limit [MPa]	1.6
Maximum principal stress σ_{max}^0 [MPa]	2.5
Maximum displacement [mm]	5.38

B. Simulations of Three-Point Bending Test

A 2D plane-stress analysis was proposed to model simply supported wood-concrete beams specimens loaded statically in three-point bending.

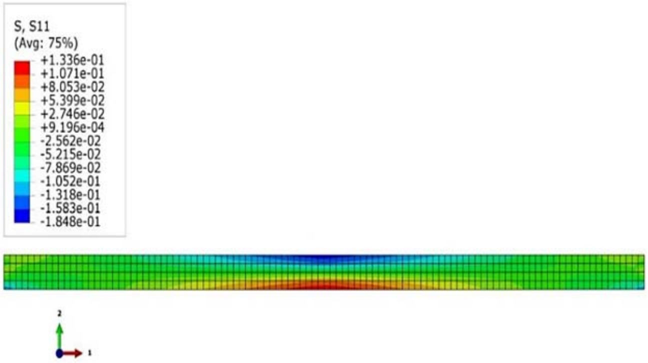
The loading and the boundary conditions are also illustrated in Fig. 2 (a). The extended finite element model of beam consisted of about 424 elements type CPS4R.

C. Numerical Results

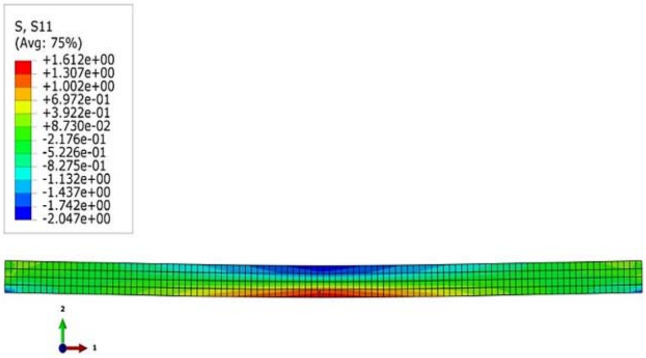
Fig. 6 shows the distributions of normal stresses at different vertical displacements of 0.3, 5.4, and 9.6 mm in the loading direction. In Figs. 6 (a) and (b), it can be noticed that the stress field was uniform and homogeneous. The stress contours widened as the displacement increased. Max normal stress concentrates at the middle of beam. Fig. 6 (b) shows that the initial crack finally penetrates through the beam at vertical displacement v=5.4 mm. The rupture initiated from the tensile zone and propagated to the top in the compressive zone.

IV. Comparison between Modelling and Experimental Results

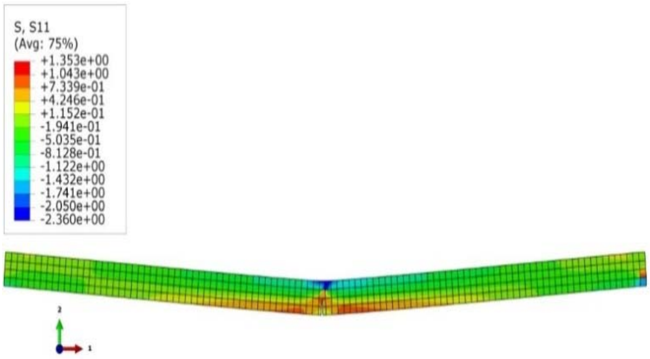
The load–deflection curves obtained are presented in Fig. 7, showing a good agreement between numerical and experimental results. The response was linear up to a displacement of 0.54 mm and a corresponding force of 23.4N. Beyond this limit, the numerical response became non-linear until the force reached 234.2N at a displacement of 9.1mm. The ultimate load calculation was 3.4% higher than the experimental one. Such moderate discrepancy can be assigned to the fact that the model is not fully optimized yet.



(a) Displacement v=0.3mm



(b) Displacement v=5.4mm



(c) Displacement v=9.6 mm

Fig. 6 Contours of normal stress component at different instants

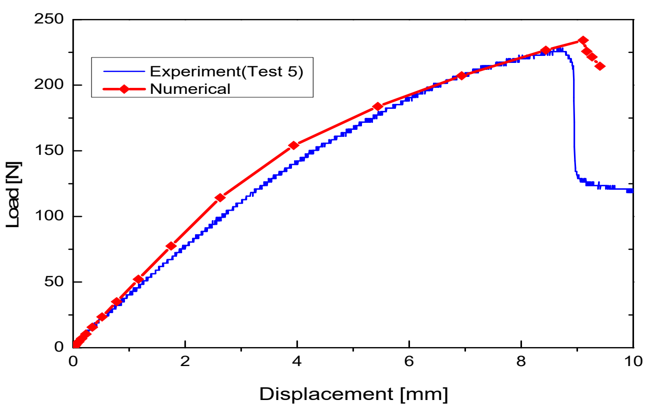
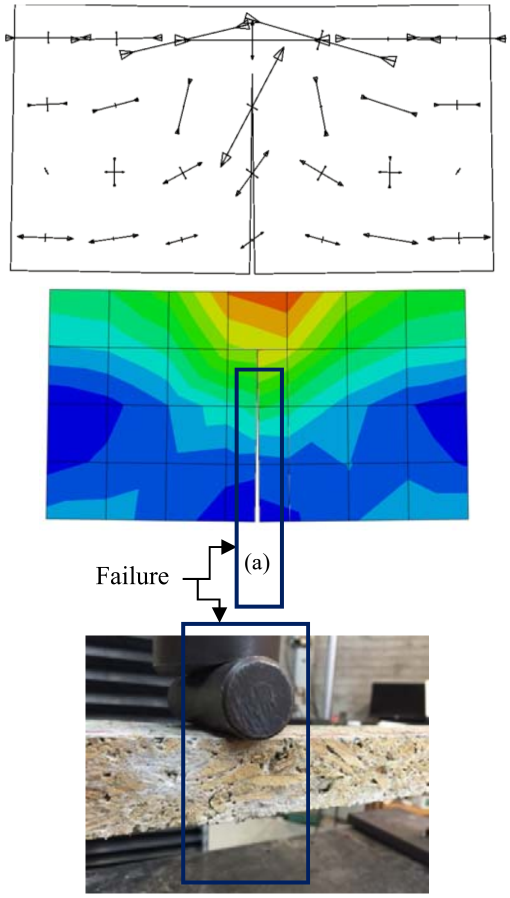


Fig. 7 Load-midspan deflection responses

Fig. 8 shows a comparison between the experimental rupture and that predicted using the presented model. It can be seen that the model predicted the damaged zone in the lower fibers corresponding to the tensile zone, and the experimental failure indeed occurred in the same place.



(b)

Fig. 8 Fracture in bending test for wood-concrete beams: (a) simulated and (b) experimental failures

V. Conclusion

The aim of this study was to develop two techniques for the characterization of wood-concrete beams in flexure. Tests were carried out on 14 timber beams, which will then have been tested in three-point bending. Through an experimental work, data were obtained to develop a numerical procedure. An XFEM approach has been developed and validated using the experimental data.

The two main results of this study are summarized as:

– Using the experimental program, the mechanical properties (MOE and MOR) of wood-concrete material were evaluated.
– Extended finite element method could simulate arbitrary cracking extent path of wood-concrete beams under bending tests.

Further investigations are now in progress to extend this model with the hope of simulating the behavior of wood-cement panels used in construction under severe mechanical conditions. This requires a large number of properties for its characterization. Therefore, the present authors are looking for more extensive sets of experimental data in this field, thus allowing to further develop and test the numerical procedure.

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