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## Étude du comportement mécanique de matériaux isolants a base de fibres de bois : caractérisation a partir de techniques d'imagerie non destructives

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# 2D/3D mechanical behavior of highly porous wood-based fiberboards using non-destructive imaging techniques

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## Résumé :

*The compressive behavior of highly porous wood-based fiberboards is characterized at the mesoscopic and microscopic scales using Digital Image Correlation (DIC) and Digital Volume Correlation (DVC). These two methods give the full strain field on the surface and in the bulk of the material respectively. DIC results are related to numerical images of the surface texture obtained by using a CCD camera. The microstructure of fibrous network at different compression states is reconstructed in 3D images from X-ray microtomography and is used by the DVC process. The material shows a strongly heterogeneous behavior where an intimate relation between strain and arrangements of pores and fibers is observed.*

## Abstract :

*Le comportement en compression de panneaux à base de fibres bois de forte porosité est caractérisé aux échelles mésoscopique et microscopique grâce aux techniques de corrélation d'images numériques (DIC) et de corrélation d'images volumiques (DVC). Elles nous donnent accès au champ de déformation respectivement en surface et au cœur du matériau. La DIC utilise les images numériques de la texture de surface obtenues à l'aide d'une caméra CCD. La DVC est basée sur l'évolution de la microstructure des réseaux fibreux, reconstruite en 3D à différents états de compression à partir d'images obtenues par microtomographie X. Le matériau présente un comportement fortement hétérogène où une relation intime entre déformation et arrangement des pores et des fibres est observée.*

**Keywords:** Fibrous material, Wood, Compression, X-ray microtomography, Digital volume correlation, 2D/3D full strain field.

## 1 Introduction

The mix between wood fibers and polyester fibers creates a kind of wood-based fiberboard which is an environmental composite with excellent thermal or acoustic performance and often used for building comforts. The relation between the elaboration process and the structure and the properties of fiber network are the subjects of numerous studies which aim at improve the manufacturing and the performance of material [1-3]. It is obvious that the mechanical behavior of the material is as important as the performance will be influenced by mechanical solicitations, especially during the transport, the stocking and the execution in the construction site. However, very few studies are devoted to this topic [4].

Being given the spatial distribution of fibers, the material can be classified as a 3D random fibrous network, whose global behavior follows well the most popular model proposed by Van Wyk [5, 6] for 3D random assemblies. The question arises as how this fibrous network will behave at smaller scales. Digital image correlation (DIC) and Digital volume correlation (DVC) are two techniques based on the same process, the image correlation technique, allowing us to access the strain field. DVC is a recent technique and allows us to study the 3D strain field inside a material or a structure at the scale of several micrometers. It has been applied to analyze and characterize several heterogeneous materials [7-9] and recently fibrous materials [10, 11].

The objective of this paper is to investigate the compressive behavior of the wood-based fiberboard whose full strain field is obtained through the image correlation method while taking into account the evolution of the microstructure on the mechanical behavior. The microstructure is extracted thanks to the morphological mathematics [13, 14].

## 2 Material and Method

### 2.1 Material

The studied wood-based fiberboard is a prototype elaborated from the non-woven process in the framework of an industrial project [15]. Exhibiting a strongly 3D heterogeneous structure, the material contains about 80% of maritime pine and 20% of polyester fibers which also hold the adhesive role (FIG. 1). Because of the consolidation process which uses a pressing process to obtain the desired thickness, the material shows a privileged orientation of fibers perpendicular to the sample thickness.



FIG. 1 – Wood/PES fiberboard (100x100x65mm)

### 2.2 Experimental tests

In order to investigate the behavior of material at the mesoscopic and microscopic scales, two types of the compression tests are proposed which are adapted to each studied scale: the compression test under the CCD camera for 2D analysis and the compression test under the microtomography X for 3D analysis.

The mesoscopic test is carried out on the large sample (100x100x65mm) up to 31% on an Instron Model 1185 testing machine with 10T of load capacity, operating at a displacement rate equal to 5mm/min, and the sample is faced to the CCD camera. Images are acquired at 0.5fps (frame per second) at the resolution of about 0.065mm, corresponding to each loading step and then exploited by the image correlation method, in order to obtain the surface strain field.

The microscopic test or the compression test under conic-beam X-ray microtomography (Nanotom Phoenix X-ray, U=65kV, I=240 $\mu$ A, 1000 projections) is carried out on the cylindrical sample (height 9mm, diameter 9mm), with the spatial resolution of 6 $\mu$ m, at eight different loading steps (from 4.8% to 32% of strain), with the strain increment equal to 4.9%. This increment value is required by the DVC process, in order to obtain a good correlation between two consecutive states. Microtomographic images are taken once the applied load is stable.

### 2.3 Microstructural analysis

Sub-volumes are extracted from the initial microtomographic images in order to avoid the edge effects caused by the conic beam and then its microstructural properties are analyzed. As reconstructed in grey levels in microtomographic images, different phases of the material (fibrous including wood/PES and porous phase) need to be segmented in order to obtain several microstructural characteristics such as the fiber arrangement, the porosity and the size distribution of pores, thanks to mathematical morphology tools [13, 14]. The fibrous phase is separated from the porous phase by applying a global thresholding on the whole image. An algorithm based on size criteria is developed to segment the wood fibers from the PES fibers [16].

### 2.4 2D/3D Full strain field measurement

Even though employed for different applications, the principle of DIC and DVC always stays the same. It can be splendidly found in the literature [7-12] and so only briefly described in this paper. DVC is the 3D extension of DIC which was originally applied to measure displacement and strain fields on the surface of the sample during mechanical solicitations. The technique gives the displacement field and the Green-Lagrange strain field by finite differences after matching small domains of pixels (2D) or voxels (3D) (or so-called correlation domain) between two consecutive images (the referenced and deformed images). The

obtained strain fields on the whole zone of interest (ZOI) are composed of many local ZOI whose deformation is supposed to be homogeneous. The mean deformation is calculated from 8 peaks of the whole sample.

### 3 Results and Discussions

#### 3.1 Mechanical behavior at the mesoscopic scale

A whole zone of interest of about  $79 \times 54 \text{ mm}^2$  (or about  $1210 \times 830$  pixels) is studied through 247 local ZOI of  $64 \times 64$  pixels at the initial state. The size of the correlation domain is 64 pixels as illustrated in FIG.2 which is depends strongly not only on material surface pattern but also on the chosen resolution of CCD camera in the compression test.

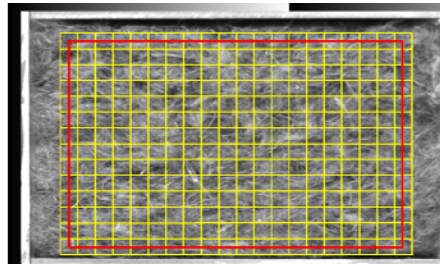


FIG. 2 – Total zone of interest on the sample surface

FIG. 3 shows the full field of strain parallel to the loading direction on the sample surface at three compression states with mean strain and standard deviation as:  $5.2\% \pm 3.6\%$ ,  $26.91\% \pm 4.8\%$  and  $30.1\% \pm 4.2\%$ . Local strain variations are observed, however, the evolution is not the same for all zones. It is distributed in several layers where the two layers at about  $1/3$  and  $2/3$  of the sample thickness are deformed more than the others and retain this tendency during the whole compression process (dotted line in FIG.3b, c). This phenomenon of strain localization may be due to the multi-layer constitution of the material created during elaboration process and relates to the surface pattern of the material.

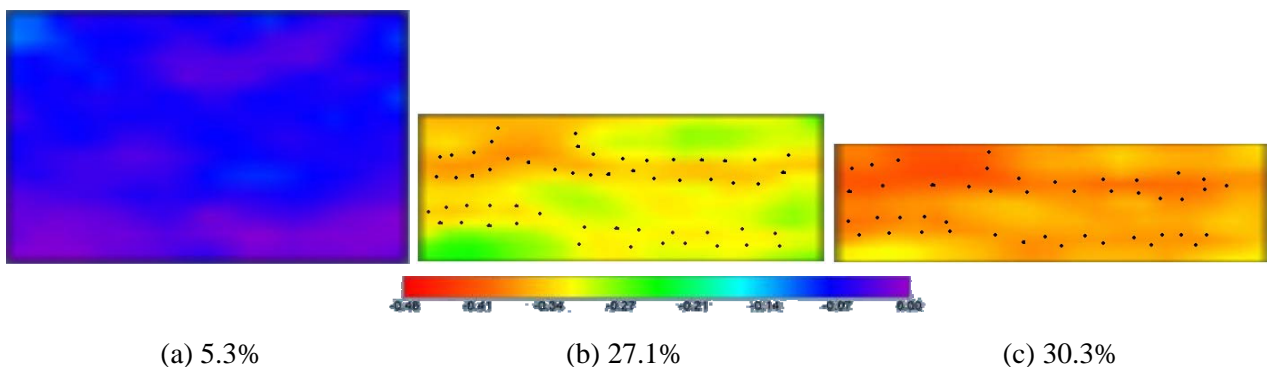


FIG. 3 – 2D vertical strain fields at different loading steps obtained by DIC.

DIC produces good results but only reflect the strain behavior of the sample surface which is not sufficient for such a heterogeneous and complex 3D structure as in wood-based fibrous material. A 3D study of the strain behavior is expected and carried out in the next section.

#### 3.2 Mechanical behavior at the microscopic scale

At the microscopic scale, DVC is performed on microtomographic images using correlation domains of  $90 \times 90 \times 90$  voxels on a system of 4950 points whose distance between grid points is 60 voxels. Microtomographic images are reconstructed with a resolution of  $18 \mu\text{m}$  to boost the computational process without influencing the DVC results. The mean DVC strains on the whole image are found to be equivalent to imposed strains which the most difference of about 1.1% showing that the analyzed sub-volume is mechanically representative to the full sample. The material shows strongly heterogeneous strain fields where transversal and shear strains can be ignored when compared to the longitudinal strains  $E_{zz}$ . This strong heterogeneity is due to the complex microstructure.

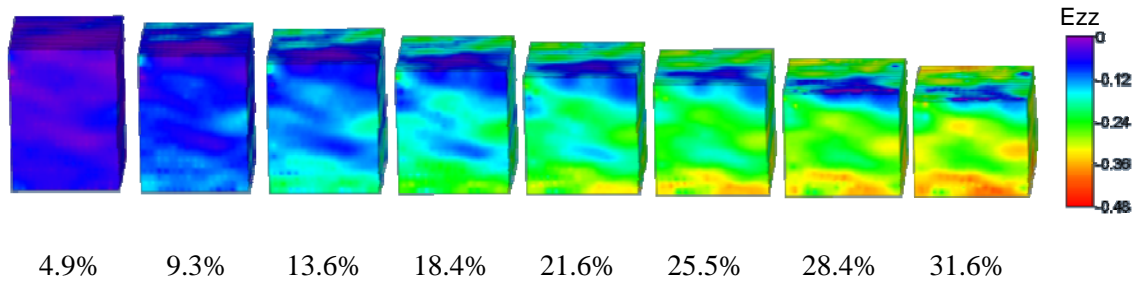


FIG. 5 – Longitudinal strain fields ( $E_{zz}$ ) at eight different states

There is a relation between the deformation and the evolution of pores as well as the fiber arrangement. During the compression, the size distribution of fibers is unchanged while the pore size is decreased (FIG. 5). This fact shows that up to the studied compression rate, the deformation happens only by excluding the pores out of the sample. The relation between the Green-Lagrange global strain in loading direction  $E_{zz}$  can be then expressed through the porosity of the sample as shown in FIG. 6:

$$p = 1 - \frac{1 - p_0}{\sqrt{1 - 2E_{zz}}} \tag{2}$$

where  $p$ ,  $p_0$  are the porosity of sample at the deformed and the initial state.

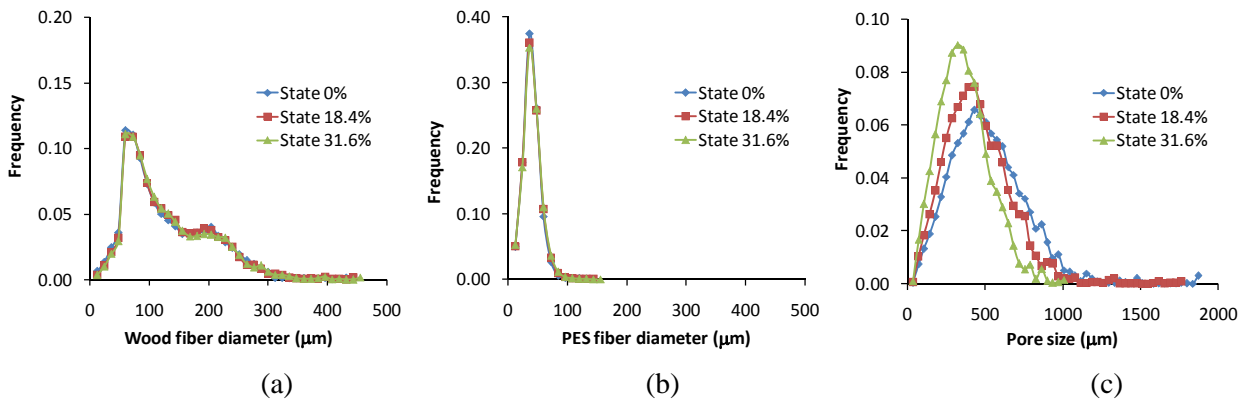


FIG. 5 – Size distribution of pores at three compression states: 0%, 18.4% and 31.6%

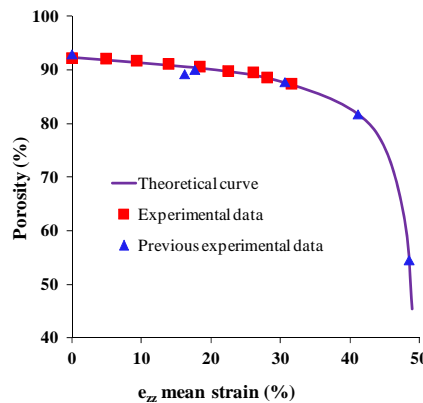


FIG. 6 – Theoretical and experimental curve  $E_{zz}$  mean strain vs. porosity [2, 4]

The relation between the pore, the fiber arrangement and the deformation is then graphically confirmed in FIG. 7 where the strain fields are superposed with the segmented wood/PES assemblies at three compression states 0%, 18.4% and 31.6%. We observed that fibers have the tendency to move vertically during the compression, especially wood fibers (white voxels). It approaches to each other while preserving its form. At one loading state, local areas do not be deformed at the same rate showing that the pores do not evolve with the same velocity. Nevertheless, we can always observe that the more deformed areas are found where the porosity is high. The compaction of the material is developed, making the materiel distribution more

uniformed and resulting a behavior to be more homogenized. This fact confirms the tendency found in the 2D case.

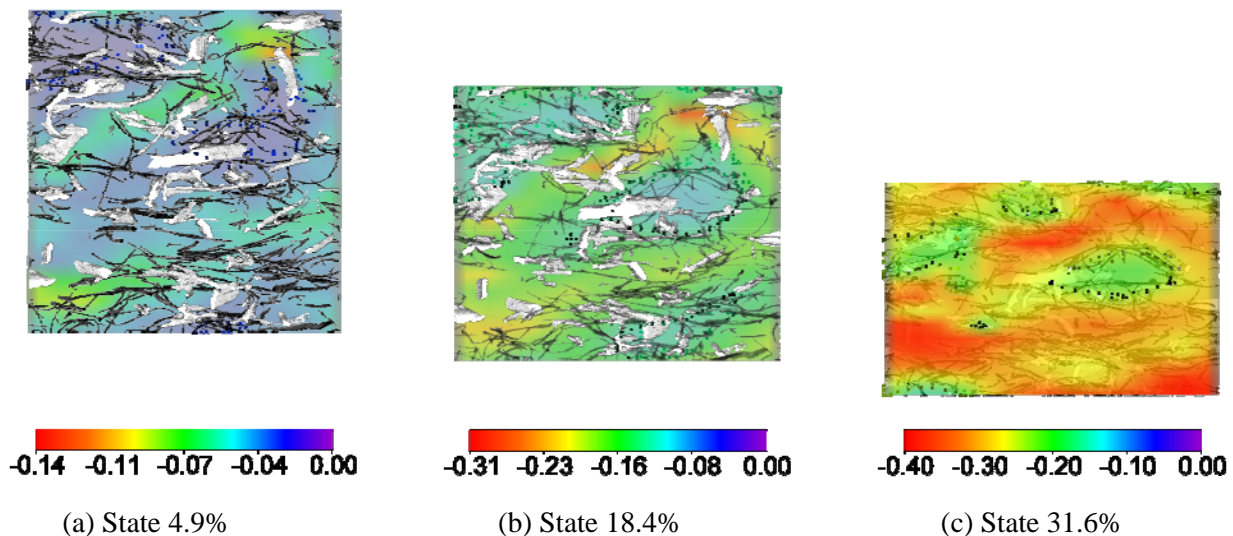


FIG. 7 : Superposition of microstructure (white = wood, black = PES) with Ezz strain for one slice, dashed lines represent less deformed zones

## 4 Conclusions

In this paper, Digital image correlation and Digital volume correlation are employed to characterize the 2D on the surface and 3D full strain field in the bulk of the wood-based fiber board under compression. Even though all strain fields are strongly heterogeneous, we still notice that the spatial distribution of pores and fibers has a strong effect on the material response. Same relation is described in Van-Wyk' study as well as in others' researches on the fibrous material under different forms at the macroscopic scale. The proposed multi-scale characterization shows its potentiality when applied on the studied material as well as in fibrous-like materials. This result motivates us to find a model of mechanical behavior of this material and to initiate the numerical simulation.

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