APPLICABILITY OF AN INCLUSION-BASED HOMOGENISATION APPROACH TO MODELLING OF BALSA-LIKE POROUS MATERIALS

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Keywords: *Balsa wood, polymeric foams, inclusion-based homogenisation method, micro-compression tests*

1 Introduction

Balsa wood and polyvinyl chloride (PVC) foam are popular core materials for lightweight sandwich structures used, for example, in shipbuilding and windmill industry. Due to the limited availability, materials from natural sources are usually expensive. Their annual supply and quality can vary with climatic conditions. These disadvantages explain an increased interest and efforts towards development of artificial cellular materials that can substitute balsa wood in the above applications. Rigid PVC foams have comparable to wood properties and replace timber in some applications. On a cost/volume basis PVC foams are more expensive than wood [1], therefore, engineers are still looking for cheaper alternatives.

Promising candidates to replace balsa and PVC foams are low-cost polymeric foams, such as foamed polypropylene (PP) and polyurethane (PU). They are especially relevant nowadays, in the era of nano-materials, as used in a combination with nano-reinforcements (such as nanotubes, graphene sheets etc), they have a potential to deliver unprecedented material performance. Achieving the exceptional mechanical properties of balsa in these foams would be difficult without the help of nano-reinforcements and strong built-in anisotropy in the foam microstructure.

To date, understanding of nano-scale materials and their properties has been achieved primarily through empirical or discovery-based research. While this approach will continue to make important contributions, a systematic understanding of physics fundamentals through modelling approaches is also needed.

In this work, we discuss the applicability of the inclusion-based methods to predict elastic properties of balsa-like cellular materials and results of the micro-compression tests performed inside a chamber of a scanning electron microscope (SEM) for the same materials.

2 Materials Description

2.1 Structure of balsa wood

On the meso-level balsa wood consists of three distinct types of cells (Fig. 1). Two of them have an important mechanical function: 1) *tracheids* are cells that have a bean pod shape and are highly elongated and aligned in the axial direction of a tree stem. Their average length/diameter ratio varies from 16 up to 25 [2]. Tracheids are responsible for the stiffness and axial strength of a tree trunk; 2) *rays* are smaller, more rectangular cells that are organized in radial arrays, which penetrate tracheids. The main functions of ray cells are to transport nutrients radially and contribute to the radial strength of the wood [3].

2.2 Structure of nano-reinforced polymeric foams

The nano-reinforced polymeric foams have a closed-cell structure, which is more random than balsa's organization (Fig. 2) and highly influenced by the production technique. Addition of nano-fillers to the polymer increases nucleation efficiency but usually leads to an inhomogeneous structure with cells of different sizes and shapes. Most cells have spherical or ellipsoidal shape with an average length/diameter ratio equal to 2.

3 Modelling approach

Macroscopic properties of heterogeneous materials based on their micro-structural parameters can be predicted using many available methods of the micromechanics. They are based on volume (or ensemble) averaging operations (homogenisation procedure) within a representative volume element

(RVE). The inclusion-based models [4] (for example, Mori-Tanaka homogenisation scheme, self-consistent method) are a popular class of methods for the prediction of the elastic constants of materials containing inclusions. Examples of such materials are composites reinforced by particles of different sizes and shapes, unidirectional fibre-reinforced composites, porous materials (pores also can be treated as inclusions with zero stiffness) etc. The inclusion-based homogenisation approach was chosen in the present work.

4 Results and discussion

The inclusion-based homogenisation approach was applied to the RVE of balsa wood (Fig. 3) and polymeric foams in order to calculate effective elastic constants of these materials.

Porosity, aspect ratio and orientation of cells, the cell wall properties and the presence of different families of pores were used as an input data for the model.

The cell wall properties are important parameters that significantly influence predictions of the model. Elastic constants of cell walls are difficult to measure because of their small sizes. Therefore in the literature there is a large scatter of these properties. In this work typical values of 35 GPa for modulus in the axial direction of the cell and 10 GPa [2] in the radial and tangential directions was used for balsa. Solid polymers are isotropic materials therefore only one value of Young's modulus was used: 2 GPa [5], 0.5 GPa [6] and 3 GPa [7] for PP, PU and PVC foams respectively.

For balsa wood the predicted values of the Young's modulus of the RVE in the axial direction were in good agreement with experimental data of [2]. But for balsa in the transversal directions (radial or tangential) and for foams the predicted values of the elastic constants were overestimated (approximately 3 times higher than experimental ones).

The reason for this discrepancy was found in a different response of the material microstructure to the applied load. In order to prove or disprove this statement, compression tests of different cellular materials were performed on the micro-scale.

Cubic samples with the edge of 5 mm were cut from balsa and foam panels using a razor blade. Great attention was paid to the parallelism of the top and bottom surfaces of the samples. This issue is important in compression tests because the uniform loading conditions should be obtained. If the specimen ends are not parallel to the load surfaces, the non-uniform loading can result in early failure at the corners or edges of the specimen. The surface parallelism is especially relevant for tests on the micro-scale.

Samples were compressed using a stage shown in Fig. 4. Applied displacements were controlled manually by means of a screw. The stage was placed inside of the SEM chamber where images were taken.

When balsa is compressed axially (Fig. 5a-f), no bending moments are applied to the length of the cell walls. Instead, the walls suffer axial compression. Failure occurs in the ends of tracheids and by forming of bands in the collapsed cell walls (Fig. 5e).

When wood is loaded in the radial or tangential directions (Fig. 6a-f), the cells deform by the progressive bending of the cell walls [2]. Even in the elastic mode (2% of strains) balsa's honeycomb structure loses stability and local buckling of cell walls occurs, which is clearly seen in Fig. 6b.

Similar behaviour can be observed in polymeric foams (see Fig. 7 for a PU foam and Fig. 8 for a PVC foam). The dominant mechanisms of deformation are wrinkling of the cell faces (PU foam) or bending of the cell walls (PU and PVC foam). Cell faces are the weakest parts of the PU foam. Their thickness is much less than one of the struts. The deformation tends to localize thus causing rupture of the cell faces (Fig. 6e). In PVC foams cells have hexagonal shapes and polymer is homogeneously distributed within the cellular frame. Cell walls tend to bend (Fig. 8c-d) due to the low elastic modulus of the cell wall material in comparison with balsa and defects in the structure caused by a production process.

The inclusion-based methods follow from a dilute solution of a single inclusion problem in an infinite matrix [4]. Because of the latter these approaches do not account for the bending/wrinkling effects and cannot predict the elastic properties of highly porous materials accurately. They seem to give accurate predictions of the elastic moduli of wood [8], metal and ceramic porous materials [9, 10]. For balsa wood in the axial direction, the methods work even for high volume fractions of pores (up to 0.95)! The reason is that internal microstructures of these materials are stable to bending deformations. For cellular polymeric materials the inclusion-based method, however, needs to be advanced in order to account for bending deformation mechanisms that are typical for foams.

Acknowledgments

We thank the European Commission for financing this work within the FP7 program through the NanCore project ("Microcellular nanocomposite for substitution of Balsa wood and PVC core material").

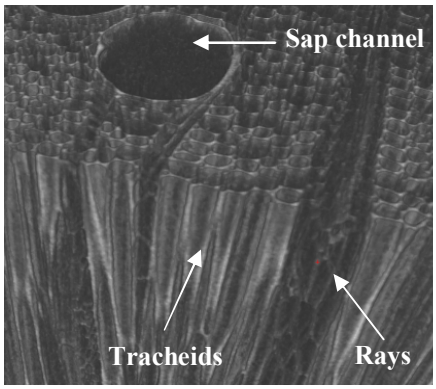

Fig.1. Micro-CT image of balsa wood.

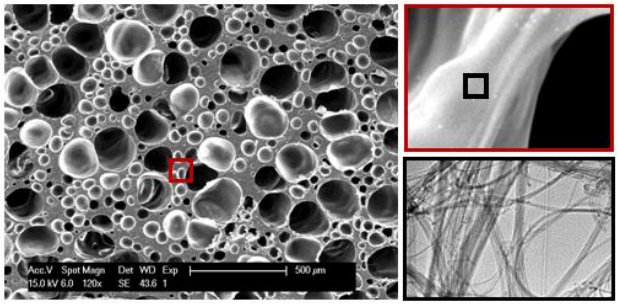

Fig.2. Structural hierarchy of nano-reinforced PP foams.

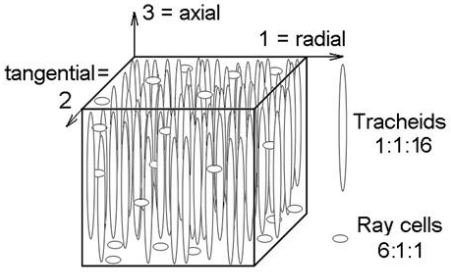

Fig. 3. Schematic of the balsa wood model.

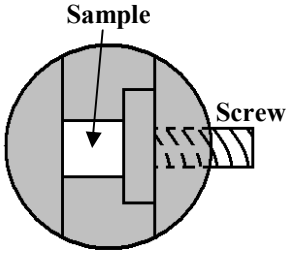

Fig. 4. Schematic of the stage for micro-compression.

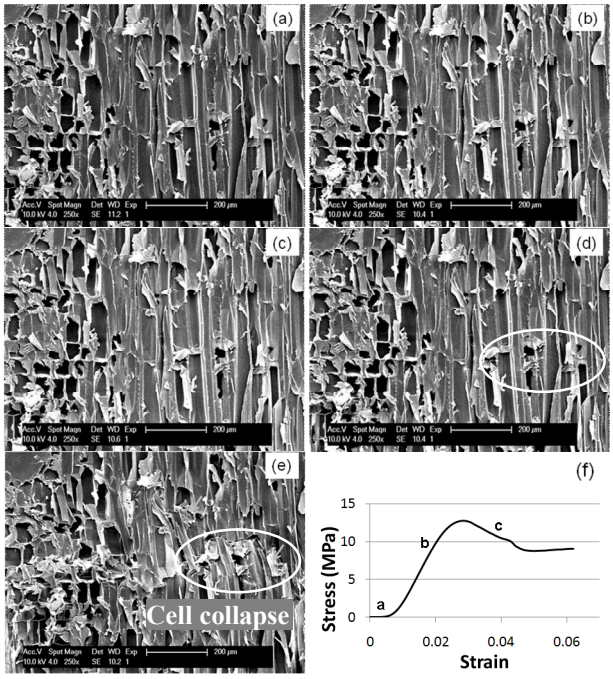

Fig. 5. SEM images of balsa under axial loading: a – 0%, b – 2%, c – 4%, d – 8%, e – 10% of strains; f – typical stress-strain curve.

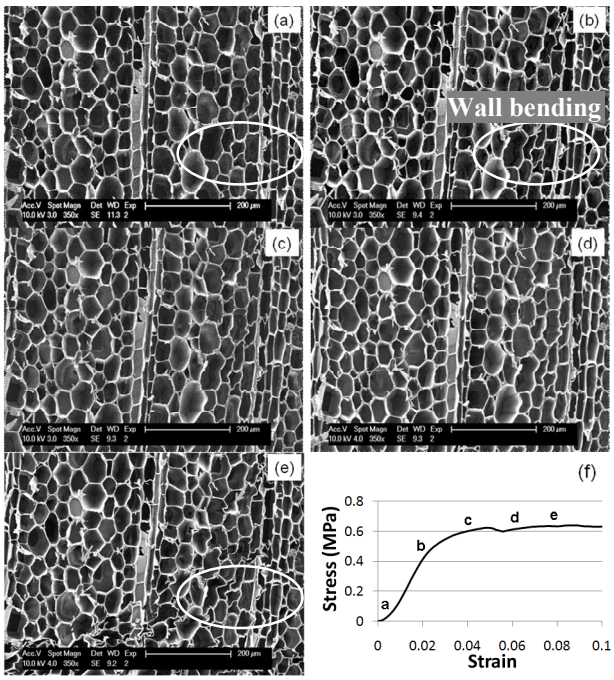

Fig. 6. SEM images of balsa under loading in the radial direction: a – 0%, b – 2%, c – 4%, d – 6%, e – 8% of strains; f – typical stress-strain curve.

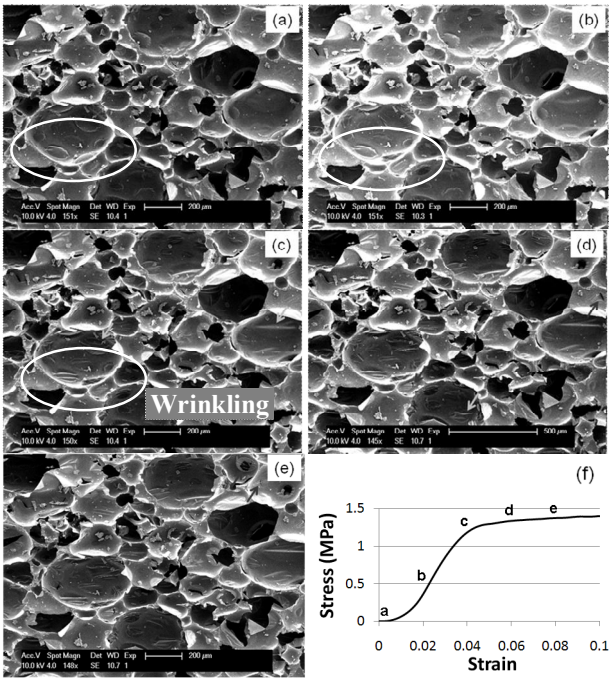

Fig. 7. SEM images of nano-reinforced PU foam under a compressive load: a – 0%, b – 2%, c – 4%, d – 6%, e – 8% of strains; f – typical stress-strain curve.

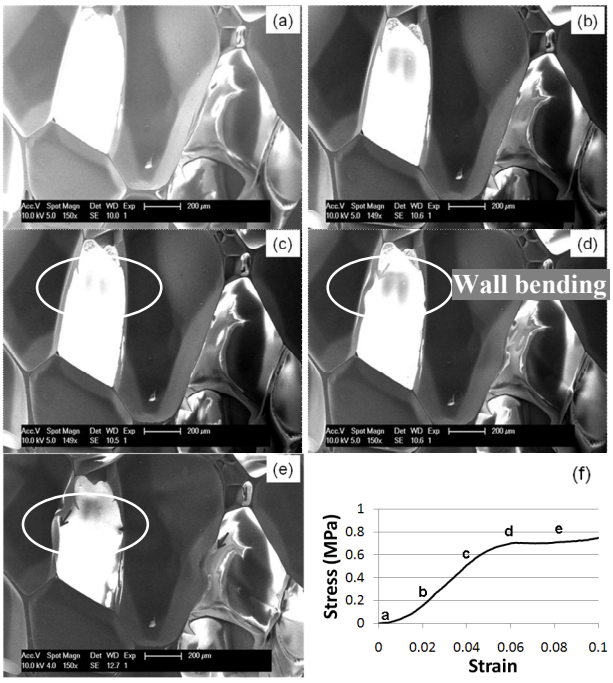

Fig. 8. SEM images of PVC foam under a compressive load: a – 0%, b – 2%, c – 4%, d – 6%, e – 8% of strains; f – typical stress-strain curve.

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