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From bio-sourced to bio-inspired cellular materials: a review on their mechanical behavior under dynamic loadings

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Abstract

Natural cellular materials can be used directly or as a constituent of bio-sourced composites for industrial applications involving dynamic loadings, usually for the purpose of absorbing mechanical energy. These biological materials can also be used as an inspiration to conceive more efficient heterogeneous structures for impact mitigation. In this review letter, we present two natural materials for which the properties have been studied dynamically: balsa wood and cork-based agglomerates. Both display an important strain-rate dependence but because of their different microstructure, this dependence is not the same. Consequently, a better understanding of the relationship between the hierarchical structure of natural cellular materials and their mechanical behavior, from quasi-static to dynamic, would be beneficial for the conception of new bio-inspired architected structures. We then focus on two types of bio-inspired architected structures: the functionally density graded cellular structures and the multi-layered architected structures. These two types of structures are gaining interest, but it appears that their dynamic behavior still lacks studying and understanding. More research linking the local strain mechanisms to their macroscopic mechanical behavior in quasi-static and dynamic would allow further architected structure optimization for mechanical energy absorption.

Keywords: bioinspiration, bio-sourced material, architected materials, dynamic loading, impact

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1. Introduction

Ideal protective structures in many in transport-related applications (car, train, airplane) feature a combination of lightweight, exceptional stiffness, strength, energy absorption and damage tolerance. Usually, cellular structures can be used to try to achieve these properties. In this context, several natural cellular materials are used directly (wood, balsa) or as a constituent of bio-sourced composites (cork) for industrial applications involving dynamic loadings [1-3]. Others are currently developed to meet environmental requirements like cork agglomerates with bio-sourced resins [4]. Some natural cellular structures indeed display a high energy absorption capacity/mass ratio thanks to their hierarchical organization at small scale, allowing them to stay competitive in comparison to synthetic ones, even for severe loadings like impact. For this reason, more and more bio-inspired synthetic architected structures are also presented in research articles.

This review article aims at linking research made on bio-sourced and bio-inspired cellular materials under severe mechanical loadings. To do that, the classical methodology of bio-inspiration or biomimetics design was followed. The first part of this short literature review highlights the behavior of tree-based materials -more precisely balsa and cork-, their microstructure and their mechanical behavior at a macroscopic scale. The influence of the strain-rate on their mechanical behavior is presented. In the second part, bio-inspired cellular structures are presented: Functionally density graded cellular structures and multi-layered structures. Their mechanical behavior is described, taking into account the influence of the loading regime, when this has been studied.

2. Bio-sourced cellular materials

a. *Balsa wood*

Wood is one of the most ancient and commonly used materials as an energy absorber in many applications, especially nowadays for the transport of spent nuclear fuel [1-3]. Like all the other types of wood, balsa displays a transversely isotropic behavior: it is stiff and strong -like a composite structure- in the direction of the fibers (fig 1b and fig 1c), also called the axial direction (fig 1a), and compliant like a foam in the tangential and radial directions to its growth rings (fig 1a). Its cellular structure allows the application of large deformations, and the fine composite nano-architecture of wood cell material (fig 1c) increases its specific strength and stiffness, giving rise to a high specific energy dissipation capacity.

Balsa wood is one of the lightest woods and can be found in a wide range of densities from 40 to 380 kg/m^3 depending on the average size and the wall thickness of cells (larger cells result in lower wood density while thicker cell wall result in higher wood density). It thus provides the flexibility in design since the strength is a monotonic function of its density.

Many uniaxial quasi-static experimental investigations have been carried out to determine the mechanical properties and deformation mechanisms of balsa wood in longitudinal and/or transverse directions [5-8]. However, in 2003, Vural and Ravichadran noted that the dynamic compressive behavior of balsa wood (and wood in general) has received limited attention with tests mainly focused on one density [9-11]. That is why they developed a systematic investigation on the dynamic response of balsa wood for different specimen densities thanks to Split Hopkinson Pressure Bars (SHPB). In this study, they showed that initial failure strength of balsa wood is very sensitive to the rate of loading (50–130% increase over corresponding quasi-static values) (fig 1d) while plateau stress remains unaffected by the strain rate [8]. This difference in response to increasing strain rate is explained in terms of the differences in the kinematics of deformation, associated with the inertia of the microstructure walls and the level of stress perturbations during initial failure and progressive deformation. The strain at the onset of the densification is both function of the density and the loading rate. It appears that the strain at the onset of the densification of balsa wood degrades with the rate of deformation. As in quasi-static loading, buckling and kink band formation were identified with post-mortem SEM (Scanning Electron Microscopy) observations to be two major failure modes in dynamic loading as well [9]. These results were confirmed (fig 1d) and completed by Palamidi and Harrigan as they tested balsa wood along the three main directions of the tree trunk [12].

Due to the limitations of the SHPB apparatus in term of force equilibrium, the macroscopic behavior of balsa was investigated as a function of density and strain rates between 100 and 3000 s^{-1} but the elastic modulus was not identified by Vural and Ravichandran in 2003 nor by Palamidi and Harrigan in 2006. Since then, it does not seem that further work was made in that direction. Research have rather focused on the simulation of the mechanical behavior of balsa wood and balsa-based structures like sandwich structures. A shock model was first proposed in 1997 [11]. It was based upon a rate-independent, rigid, perfectly-plastic, locking (r-p-p-l) idealization of the quasi-static stress-strain properties of the woods (fig 1e). This model proved less successful for 0◦ specimens and lower velocities and the need for further

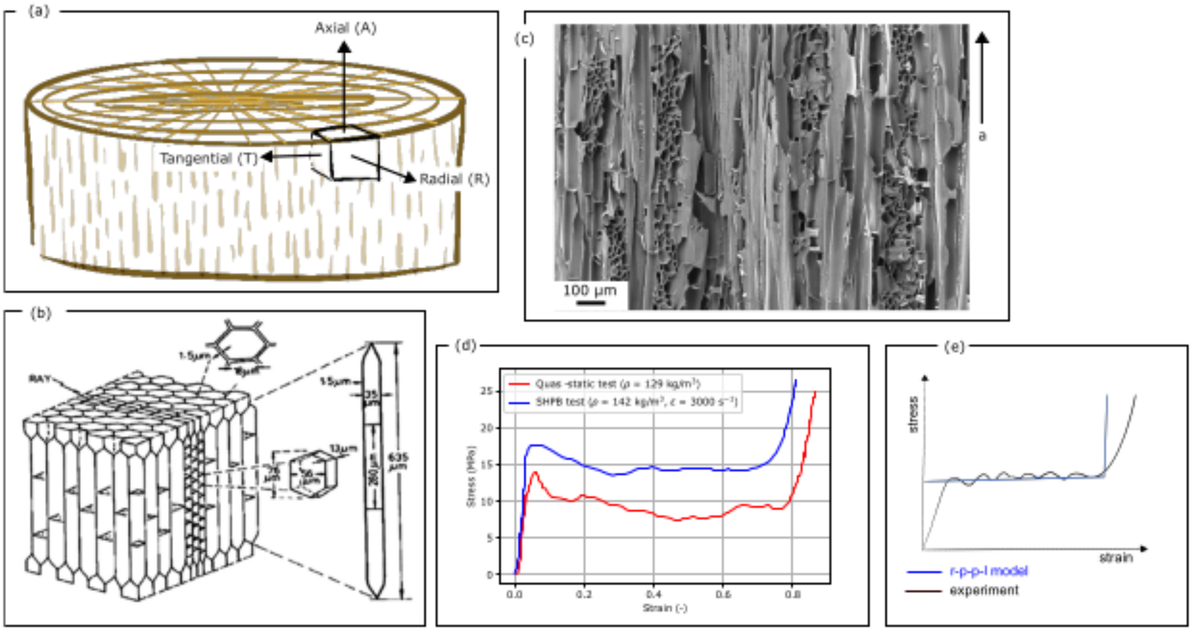

Figure 1 Microstructure and resulting dynamic behaviour of basla wood. (a) Directions related to the tree trunk. (b) Scheme of the cellular structure (from Toson et al., 2014 [13]). (c) SEM picture of the cellular structure of balsa wood. (d) Dynamic behavior of balsa wood depending on the density (from Palamidi and Harrigan, 2006 [12]).(e) Presentation of the r-p-p-l model in comparison to a scheme of the experimental behavior of balsa wood in compression.

investigation was highlighted. However, no distinction was made between the two transverse directions (tangential and radial directions). After it, other models were developed, considering all the specific characteristics of the wood: anisotropy, compressibility, softening, densification, strain rate dependence but also fracture of the balsa wood when loaded in tension [13].

b. Cork and cork agglomerates

Cork is another tree-based material. Therefore, similar directions as presented in fig 1a are associated to its microstructure (fig 2a and 2b). Cork chemical composition is however different from wood. Indeed, in addition to lignin, cellulose, and hemi-cellulose, suberin, a linear polymer, also constitutes the cork cell walls. Thanks to this combination of polymers and its honeycomb structure, cork is much less fragile than wood and presents a unique set of properties (fire resistant, impact absorbing, phonic isolation...) [14]. It is therefore an excellent candidate for a wide range of application domains, especially under its composite shape: cork agglomerates (fig 2c). One of these application domains is aeronautics and space for the development of parts exposed to severe loading conditions that can vary from an impact due to a tool drop to the protection of the structure from fragment impact in the space. As cork agglomerates are considered for energy absorption applications, their mechanical behavior under high strain rates has been studied, principally by testing cork structures through impact tests achieved with a drop tower [15-19]. An increase in macroscopic stresses was usually noted with the increase in the initial strain-rate [18]. However, most of the studies focus on energy absorption capacity but not on the dependence of various material parameters on the strain-rate, which makes it complicated for in-depth modelisation and simulation. SHBP were also used to test cork-based materials at high strain rates [20]. The results suggested that beyond a certain strain-rate, the mechanical behavior does not vary anymore. Indeed, between 200 s^{-1} and 2500 s^{-1}, stress/strain curves are very closed. It can yet be noted that raw signals presented a lot of noise [20]. The strain-rate varied also during the compression loading [21] which induces error for material parameter identification. Recent works using Digital Image Correlation (DIC) highlight the actual strain distribution at a cork agglomerate sample surface tested with SHPB. 2D DIC results showed a significant strain heterogeneity within each sample surface. However, these tests in dynamic regimes did not allow to reach important strains [22].

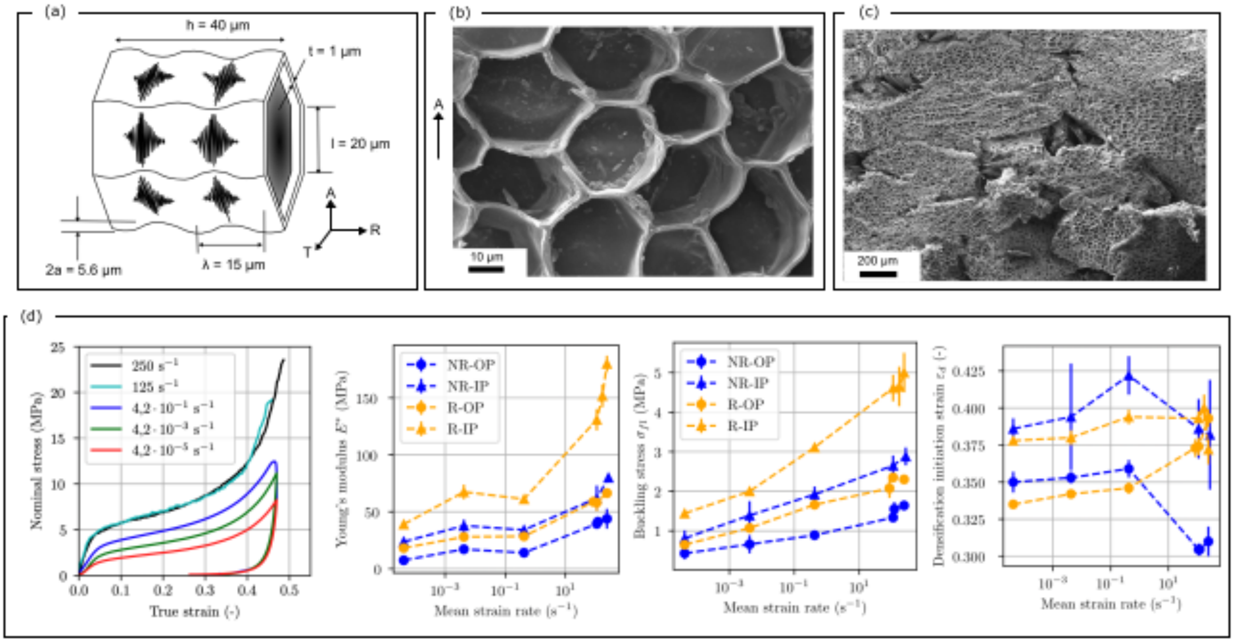

Figure 2 (a) Scheme of the cork cell and trunk related directions [14]. (b) SEM picture of the cork cellular structure (radial direction). (c) SEM picture of the cork agglomerate structure. (d) Strain-rate dependence of cork agglomerates and resulting mechanical parameters of several types of cork-based material [23].

The recent use of a flywheel apparatus enabled the study of the mechanical behavior of cork composites under constant intermediate strain rate until densification at various temperatures [23]. It showed that because of the glass transition temperature of cork being around 20°C, the whole mechanical behavior is highly dependent on the strain rate (Young's modulus, buckling stress, absorbed energy) (fig 2d). However, unlike balsa wood, the strain at the onset of densification does not depend on the loading rate.

Generally speaking, unlike balsa wood, cork agglomerates display a much more isotropic mechanical behavior with no stress drop after the yield stress and a visco-elastic behavior until large strain (instead of a fragile behavior for balsa wood) [23]. This is due, on the one hand, to the chemical composition of the cork cell walls and, on the other, to the structure of the agglomerated cork at the cork cells scale (micro-scale) and the bead scale (meso-scale) [23].

3. Bio-inspired cellular materials

With the advances of new manufacturing processes like additive manufacturing or ice-templating [24], it is today possible to mimic the hierarchical structure of natural materials. The conception and manufacture of synthetic materials with tailorable properties, more efficient that their bio-sourced counterparts because they are optimized for a specific application, are in high demand today. Many bio-inspired materials have thus been developed for different applications, including applications involving dynamic loadings [25-27]. Different general architectures at the micro and meso-scale can be identified in biological materials [25, 28]. These include functionally density graded cellular structures and multi-layered structures displaying distinct interfaces which serve as crack dissipators.

a. Functionally density graded cellular structures

Many natural cellular structures show a density gradient at the mesoscopic scale, like some varieties of wood such as bamboo (fig 3a), fruit peel of *Citrus Maxima* or Elk antler. Some synthetic structures have taken inspiration from one of these natural structures (fig 3b and 3d) [29,30]. In synthetic structures, the introduction of a density gradient within an architected structure (stochastic or periodic) appears to be an effective way to improve the mechanical properties while keeping a low-density [31,32].

Usually, monotonous density gradient [33] or bilinear ones [34] (fig 3c) were studied, mostly numerically for dynamic loadings. Several research works show that this type of feature allows to modify the strain mechanisms in periodic structures. While single density structures deform in compression by a single shear band at 45°, a layer-by-layer

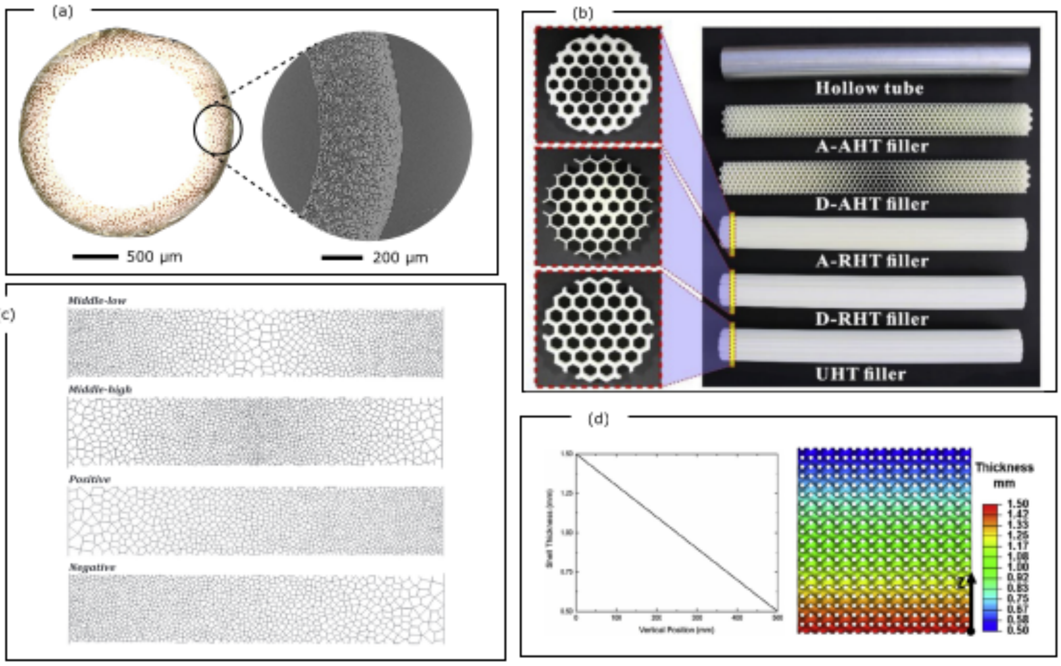

Figure 3 Functionally density graded cellular structures. (a) Bamboo structure observed with optical microscope and x-ray tomography. (b) Different homogeneous and graded 3D-printed honeycomb filler [29]. (c) Four types of density distribution studied by Zheng et al [34]. (d) Example of gyroid cellular structure with graded thickness [30].

deformation appears for graded architectural structures when they are loaded in the gradient direction [35]. Because of different strain mechanisms activated, layer-by-layer collapse usually leads to lower dynamic crushing stress and extended plateau period. The mechanical energy absorption capacity of the graded structures is then strongly increased.

In stochastic structures under dynamic loadings, due to the apparition of several shock waves, numerical analysis showed that homogeneous cellular structures would be the most efficient from an energy absorption point of view [34]. But these multiple shock waves present the advantage to limits the stress on the opposite side of the impact. Similar results were obtained for functionally density graded gyroid structures. Peng and Tran demonstrated with finite elements analysis that these graded periodic structures noticeably improved the performance of sandwich panel subjected to shock impact [30]. While no remarkable differences in total energy absorbed was noted, the stress transmitted decreased for graded cellular structures. Furthermore, a more uniform stress distribution was noticed, reducing localised stress and thus fracture within the core. Another parameter for impact protection is the duration of the high acceleration. In the head protection industry, some criteria rely on it. Functionally density graded cellular structures appear to reduce this duration during an impact event [33]. A lack of detailed understanding of the underlying strain mechanisms of biological and bio-inspired structures during mechanical loading and their dependence on the strain rate, up to dynamic regimes however remains. A better understanding of the specific microstructure shell behavior of *Citrus Maxima* during its drop could be for exemple a source of inspiration to improve the knowledge of gradient cellular material in the protection during impact. More globally, density distribution and shock effect are two significant factors on the protective structures' efficiency. No general conclusion exists today on the role of functionally density gradient under different type of impact loadings.

b. Multi-layered bio-inspired structures

To minimize crack propagation in stiff materials and prevent early catastrophic failure, layered architected structures are numerous in biological materials: nacre [36], wood, cork, hooves, and many others [25]. From this observation, bio-inspired struts have been designed and tested [37]. In their work, Mueller et al. showed that the fracture strain and toughness of multi-layered struts alternating gaps and stiff material can be increased by over 100%, when compared to conventional reference struts, while fully maintaining the density, stiffness, and strength (fig 4a). Gaps could also be replaced by a soft material [37].

More recently, full multi-layered 3D architected structures have been developed taking inspiration from cork [38]. Only the multilayer character was inspired by cork. The single cell is a Triply Periodic Minimal Surface (TPMS) as it facilitates the design and manufacturing of such heterogeneous structures. Two types of materials - one with a rigid and slightly ductile behavior and the other one with an elastomeric behavior – are present in the structure cell walls (fig 4b). It allows the architected structure to switch from a fragile behavior to a classical energy absorber behavior (fig 4b). While the stiffness and the strength were reduced, the absorbed energy was increased by 400% thanks to a very large fracture strain and the apparition of an extended plateau period.

These multi-layered structures produced with a flexible core-elastomeric interface brittle shell motif exhibit both high stiffness and toughness and are thus very promising for the development of high-performance low-density energy absorbers. However, all these structures, from the single strut to the full 3D structures were not loaded in dynamic regime. To confirm their suitability for protection structures applications, dynamic regime should thus be considered in further investigations.

4. Conclusions

Cellular biological materials are an important resource for mechanical engineering and applications involving severe loadings like impacts. They can be used directly in protective structures (balsa wood), for bio-sourced composites (agglomerated cork) or as an inspiration for new architected cellular structures to develop efficient energy absorbers. It appears that a better understanding of the relationship between the hierarchical structure of natural cellular materials and their mechanical behavior, from quasi-static to dynamic, would benefit many industrial applications.

While bio-sourced materials seem to have received particular attention in term of severe loadings, particularly balsa wood, studies on the mechanical behavior of bio-inspired materials designed for energy absorption lack analysis of the influence of strain rate on mechanical behavior and local strain mechanisms.

Because of their low impedance, the study of the mechanical behavior of cellular materials – synthetic and natural ones - from low strain (Young's modulus) to large one (densification) can however be challenging. Furthermore, there is sometimes a gap between quasi-static loadings and dynamic strain-rates reached thanks to SHPB systems that apparatus like fly wheel could fill.

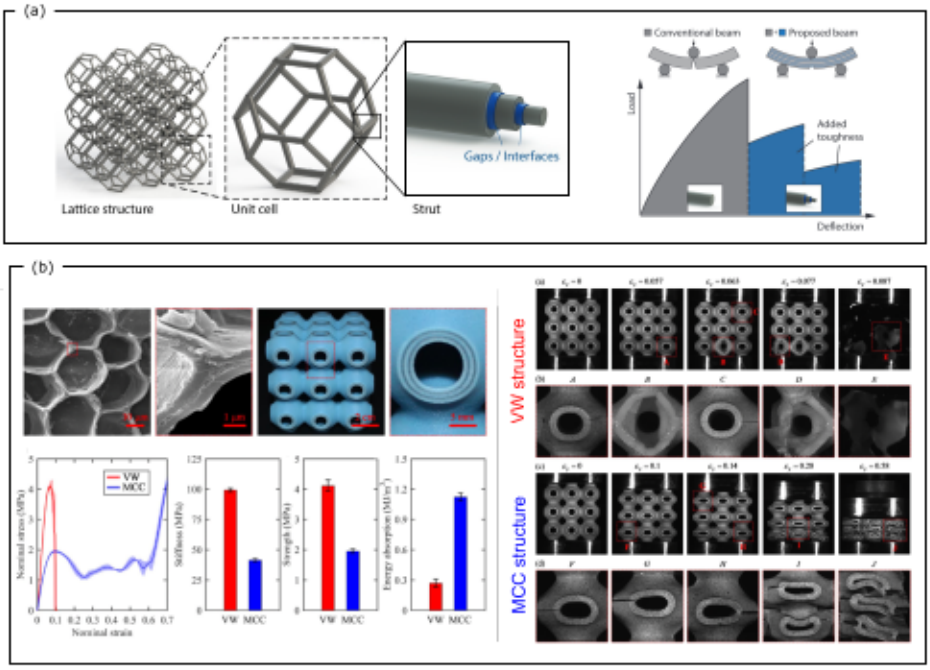

Figure 4 Multi-layered bio-inspired architected structures. (a) Principe of rods with multi-layered structure [37]. (b) Cork bio-inspired architected structure and resulting mechanical behavior under quasi-static compression with pictures of the deformation during the compression tests [38].

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