Influence of the loading regime on the uniaxial compressive behaviour of density graded *Citrus Maxima* peel

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Abstract

To conceive more efficient protective structures, it is possible to draw inspiration from natural structures. However, the origin of the mechanical absorption properties of natural structures is not always clear. Among the multitude of existing natural structures, the density graded peel of the *Citrus Maxima* was studied in this work to characterize its mechanical behaviour under uniaxial compression, from the quasi-static regime to the dynamic regime. The resulting behaviour is very different from a classical foam behaviour as no linear part is observed for small strains. Furthermore, the mechanical behaviour is deeply influenced by the loading regime: a stair-case response appears under dynamic loading.

Keywords: bioinspiration, mechanical behaviour, architected material, microstructure, density gradient

1. Introduction

The protection of goods and people is a societal subject in full development with the generalization of mobility. It can be found in the fields of sport (helmets), transport (car protection) or energy (transport of radioactive waste). To conceive new protections, it is possible to draw inspiration from natural structures. Over the millennia, some natural structures have indeed developed a multi-scale architecture in order to cope with impact mechanical loading conditions. However, it can be complex to decorrelate which structural feature could be a source of bio-inspiration.

Despite that, many bio-inspired structures have been proposed over the years for energy absorption during impact [1, 2, 3, 4, 5]. However, the link between the multiscale structure and mechanical properties in natural structures is not always clearly established. This prohibits the development of efficient synthetic bio-inspired protective structures.

Among the multitude of existing natural structures, *Citrus Maxima* [6], a citrus fruit native to China weighing up to 6 kg and capable of dropping from a height of 20 m (fig. 1), demonstrates interesting mechanical properties, particularly in terms of impact resistance and mechanical energy absorption [7, 8, 9, 10]. According to recent research, these properties could be linked to its especially thick peel (fig. 1). Like other Citrus fruits, the peel of the Citrus Maxima consists of epidermis, parenchymatous flavedo (exocarp), albedo (mesocarp) and endocarp. The density gradient presents within its peel (fig. 1) is usually cited as the possible cause of its specific mechanical behaviour. However, the mechanisms at the origin of its mechanical energy absorbing properties have not yet been clearly explained.

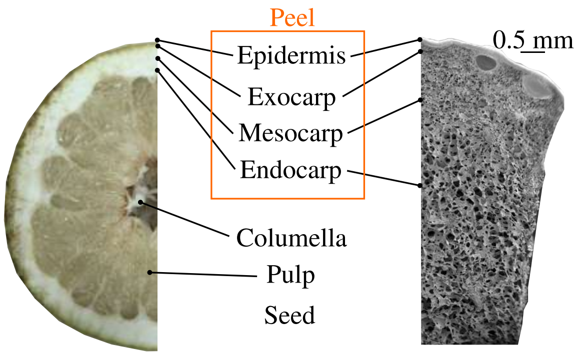

Figure 1: Cross section of a *Citrus Maxima* and SEM picture of its peel.

In this work, the compressive mechanical behaviour

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of *Citrus Maxima* was studied under quasi-static and dynamic loadings to study the rate-dependency of its peel.

2. Method and Materials

2.1. Microstructure characterisation

Peel samples were dried beforehand. They were placed in a furnace for 1h at 60°C. After that, a thin layer of gold was sputtered at the sample surface. A tension of 2 kV and an intensity of 200 pA were used to observe the samples with a FEG-SEM Zeiss Sigma600.

2.2. Mechanical behaviour

2.2.1. Quasi-static tests

Compression tests were run at 1 mm/min (1.67 10^{-3} s^{-1}) on parallelepiped samples of peel until a macroscopic engineering strain of 40%. The initial section S_0 and height h_0 were used with the force $F(t)$ and the displacement $d(t)$ data to calculate the nominal stress $F(t)/S_0$ and nominal strain $d(t)/h_0$).

2.2.2. Dynamic regime

A fly wheel was used used to reach intermediate dynamic strain rates (fig. 2). The rotation speed is controlled by an asynchronous motor and was set to 3 Hz. A mechanical module of compression was previously developed to perform dynamic compression tests on polymeric foams and bio-sourced composites [11]. The resulting displacement speed was 4.4 m/s corresponding to a macroscopic strain rate of 400 s^{-1}.

The compressive force is measured by a Kistler piezoelectric sensor (model 9011A, force range 15 kN) placed between the rigid cross-head and the upper punch. The displacement of the lower punch is measured by a laser displacement sensor (model OptoNCDT LD 1607-20) with a 20 mm range of displacement. The signals from these two sensors are recorded with a National Instrument acquisition card at a 100 kHz frequency.

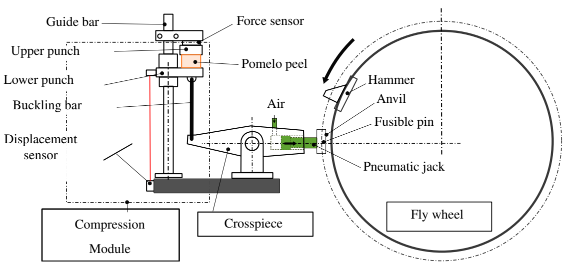

Figure 2: Scheme of the fly wheel apparatus.

3. Results & Discussions

3.1. Microstructure

The SEM observations of the *Citrus Maxima* peel demonstrate a very heterogeneous structure (fig. 3). As mentioned by others, a density gradient can be observed through the peel [1, 12, 13]. The density decreases from the epidermis to the endocarp.

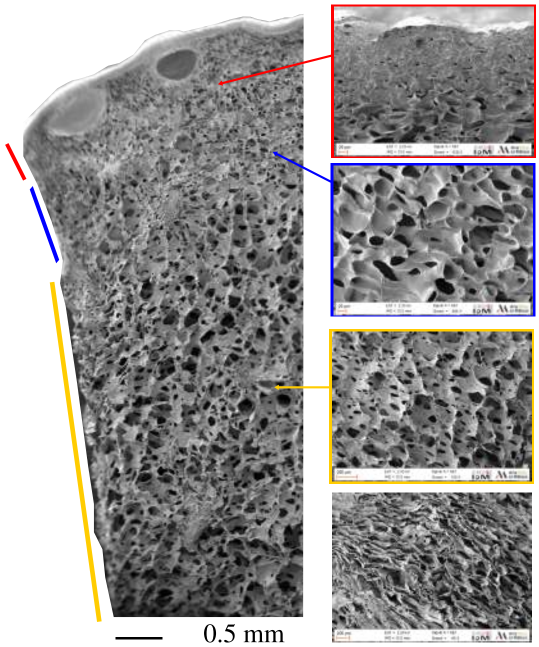

Figure 3: SEM pictures of the *Citrus Maxima* microstructure.

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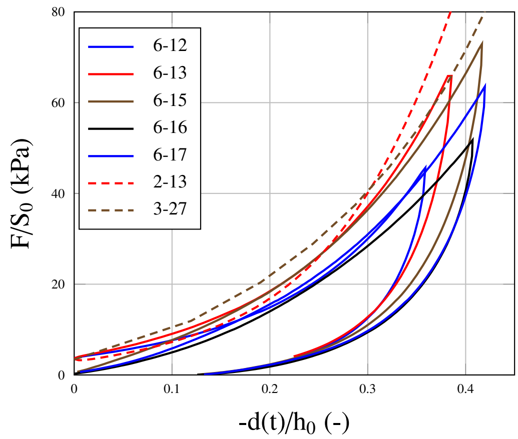
3.2. Mechanical behaviour

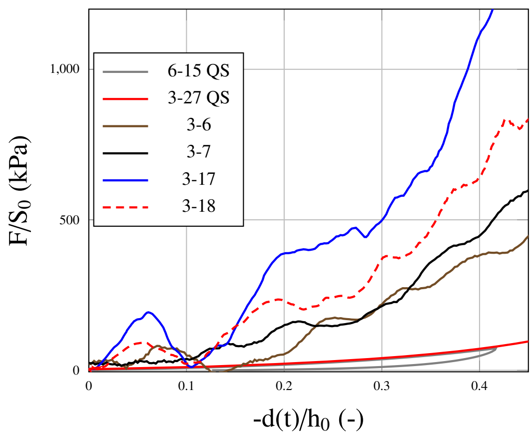
The compressive mechanical behaviour of the *Citrus Maxima* peel has a certain variability that is typical of biological materials (fig. 4(a)a). The peel displays a mechanical behaviour different to classical cellular materials. No linear elastic behaviour can be observed at small strains. This behaviour could be linked to the continuous density gradient in the peel structure. Synthetic discrete density graded cellular structures demonstrate a staircase-like behaviour [14, 15, 16, 17], alternating between linear elasticity and plateau region. This corresponds to the deformation of increasingly dense layers. Synthetic continuous density graded cellular structures do not display this staircase-like behaviour but a plateau phase with a much higher slope [18]. Given the really low density of the first millimetres of the inside of the *Citrus Maxima* peel, it seems that the linear elastic part totally disappears. Only the plateau phase is thus visible in fig. 4(a). The associated mechanisms should be cell-wall bending.

The mechanical behaviour under dynamic loading is very different from the one in quasi-static (fig. 4(b)). Firstly, the stresses are much higher as expected from a viscoelastic material [19]. At a strain of 0.2, σ_{QS} is between 15 and 25 kPa, while σ_{dyn} stands between 150 and 400 kPa.

Furthermore, instead of a smooth stress/strain curve, under dynamic loadings, the *Citrus Maxima* peel displays a mechanical behaviour alternating between a linear evolution and stress drops. At higher strain rates, it would appear that in contrast to the quasi-static regime, each layer is compressed one after the other, explaining why linear and stress plateau are observed successively (fig. 4(b)). This could be due to the density gradient. For synthetic density graded structures, it has been shown that the shock wave is transformed into a double shock wave, which ultimately limits the stress on the opposite side of the impact [20].



(a) Quasi-static regime



(b) Dynamic regime

Figure 4: Stress-strain curve obtained from compressive loading on *Citrus Maxima* peel at room temperature under different strain rates.

4. Conclusions

The mechanical behaviour of the *Citrus Maxima* peel does not display the classical 3-phase behaviour of foam materials. The density gradient present in the peel seems to cause this full non-linear behaviour in quasi-static regime. Furthermore, under higher strain rates, the macroscopic behaviour of the peel was very different from the one in quasi-static. More local observations would be necessary to confirm the origin of such influence.

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