Bio-inspired protective structures for marine applications

Giulia PALOMBA[a,1], Vincenzo CRUPI[a], David TAYLOR[b]
[a] *Department of Engineering, University of Messina, C.da di Dio. Messina, Italy*
[b] *Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Dublin, Ireland*

Abstract. Materials and structures for marine applications often require to combine high mechanical performance with lightness. Sandwich structures based on polymeric or metallic cores are traditional lightweight solutions for marine applications. However, common sandwich structures do not always offer a suitable protection from some ordinary in-service events such as low-velocity impacts with floating and submerged objects or with docks. The design of more efficient lightweight protective systems for marine applications, may take inspiration from nature, which developed incredible solutions throughout millions of years of evolution. In the current work, bamboo structure was studied and subjected to mechanical tests. The results of the analysis allowed the identification of some structural characteristics which make the investigated materials efficient in impact absorption. Consequently, some bio-inspired designs were suggested with the aim of improving low-velocity impact resistance of some marine structures, providing good structural performance and lightweight properties.

Keywords. Lightweight, biomimetics, marine structures, impact

1. Introduction

Design of marine structures is often subjected to a double constraint: providing excellent structural performance and reducing weight. Lightness is an essential feature for marine structures and materials for several reasons [1], ranging from fuel consumption stability issues. Low-velocity impact resistance is one of the structural requirements that marine structures have to provide, since low-speed collisions occur as a result of ordinary in-service events [2].

Common lightweight solutions for marine industry are fibre-reinforced composites, which provide interesting properties, but are also vulnerable to impact damage [2]. Innovative alternatives may be suggested by the observation of nature, according to the principles of biomimetics, which can inspire original engineering designs. However, an effective imitation of natural structures requires deep investigations [3].

An example of lightweight natural structure which drew scientists' attention was bamboo. Bamboo stems constitutive structure [4] includes fibres oriented along the longitudinal direction, whereas in the radial direction has a graded cellular microstructure, with decreasing density from the outside to the inside. Bamboo properties have been investigated from several points of view. For instance, Keogh et al. [5] studied the fatigue phenomena in bamboo. Some

[1] Corresponding Author, Giulia Palomba, Department of Engineering, University of Messina, Contrada di Dio, Sant'Agata (ME), 98166, Messina, Italy; E-mail: gpalomba@unime.it

bamboo-inspired structures can also be found in literature. An example is provided by Fu et al. [6], who introduced a tubular energy absorbing structure, with the outer and inner walls connected by longitudinal elements.

Bamboo has attracted also the attention of the marine industry. Though, except for some simple structures, such as rafts [7], the main marine applications currently available for bamboo are limited to composites based on bamboo fibres ([8], [9]).

A common feature of many natural materials is the presence of a hierarchical organization, which affects their functions and properties. Zhang et al. [10] combined this concept with the energy absorption capabilities of honeycomb structures, to develop crashworthy bio-inspired hierarchical honeycombs. Crashworthy honeycomb-based structures were also developed by Crupi et al. [11] and by Palomba et al. [12] enhancing the performance of traditional aluminium honeycomb sandwich structures respectively with glass fibre-reinforced skins or by combining two different honeycomb layers.

The current work is focused on the mechanical investigation of bamboo, in order to examine the structure-property relationships, with particular attention to impact response. The obtained results may suggest some potential bio-inspired designs for lightweight impact-resistant structures, with possible applications in the marine industry.

2. Experimental investigation

The preliminary experimental investigation on a natural structure was performed on samples of a bamboo called Moso (Phyllostachys Pubescens), which is one of the most common bamboo species for structural applications. Bamboo culms were obtained from a local supplier (Bamboo Suppliers of Ireland, Dublin). The graded structure of bamboo may affect the energy absorption in the radial direction, which was never studied in literature, thus more information on such behaviour is required.

In the current work, low-velocity impact tests were performed both on the inside and on the outside of the bamboo structure. Tubular samples of bamboo, were obtained from bamboo culms avoiding the nodes. Each tube was sectioned in the longitudinal direction to obtain semi-circular samples. In order to obtain similar conditions during the two types of impact tests, a rigid support was provided under the specimens tested on the outside. The impactor was a rounded-ended steel cylinder of 1.325 kg, whose impact energy was varied by causing it to fall from different heights. The applied device allowed a maximum impact energy of 9.4 J. The test setup is schematised in Figure 1.

3. Preliminary results

Specimens were divided on the basis of their thickness t into three groups: 4 mm $\leq t \leq$ 5 mm; 5 mm $< t \leq$ 6 mm and 6 mm $< t \leq$ 9 mm. Each group was tested at different impact energies, in order to assess the critical energy E_c required to produce a crack propagation.

The critical energy was evaluated as the average between an energy level which produced only local indentation and the following one which produced crack propagation. The average thickness of each group and the corresponding critical energy are reported in Figure 2. It is evident that both from inside and outside impacted specimens, critical energy varies almost linearly with the thickness. Impact side seems to not influence E_c values, except for the group with the larger thickness.

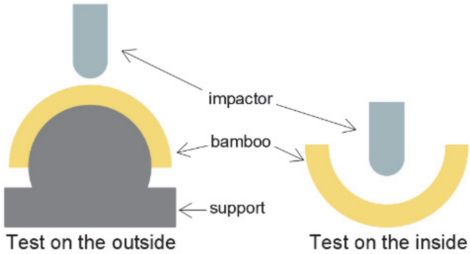

Figure 1. Impact test setup.

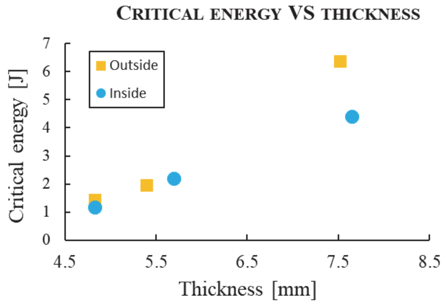

Figure 2: Critical energy VS thickness.

Specimens impacted on the inside surface at the critical energy experienced a wider local damage in the impact area and a propagation of a crack, starting from the inside to the outside. However, critical impact energy on the inside did not produce a complete failure of the samples, instead crack propagated across the thickness but stopped before reaching the outer surface.

Further tests were performed in order to find the energy required to produce the complete failure of specimens impacted on the inside. The maximum feasible impact energy, equal to 9.4 J, was applied to three specimens with an average thickness of 9.5 mm. However, none of the tests produced the complete failure of the samples, instead crack propagated up to about the 80% of the thickness. The different behaviour between outside and inside impacted specimens can be observed in Figure 3.

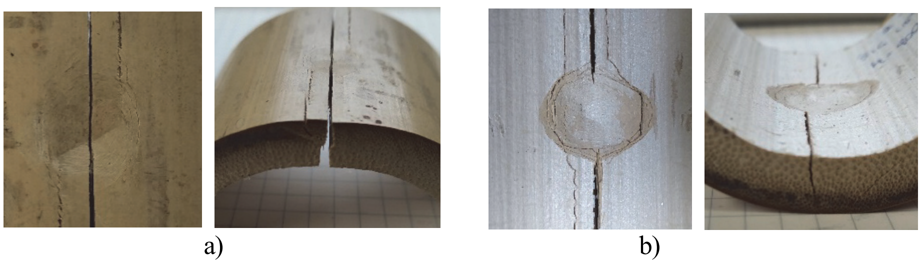

Figure 3. Damaged area and crack propagation of specimens impacted a) on the outside and b) on the inside.

The above observations suggest that bamboo's graded structure may have a significant role on the impact response. The softer inside layers, characterised by lower fibre density, may act as an energy absorbing structure, with a gradual crush of the cells. Such phenomena may enhance the impact resistance of the structure when impacted from the inside. In addition, when a crack propagates from the inside to the outside, it meets outer layers richer in fibre content, which may be responsible for crack stopping.

According to Low et al. [13], bamboo hardness decreased from the outside to the inside. Similar conclusions were reported also by Tan et al. [14]. In the same they also demonstrated that inside notched specimens had a higher resistance curve than the outside crack samples. Such difference was attributed to crack tip shielding through cellulose crack bridging, which was more evident in inside layers.

4. Preliminary conclusions and ongoing activities

The detected impact response of bamboo can be related to a combination of mechanisms strongly related to the graded structure. Further investigations are needed to deepen the knowledge of the interactions among different phenomena and the variables influencing them. However, preliminary observations suggest that graded structures are potential candidates to improve crashworthiness in several applications, also in the marine industry. Taking inspiration from the phenomena involved in bamboo impact response, a graded structure may be designed for marine industry applications which require a good low-velocity impact response combined with lightweight properties.

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