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Bending test for capturing the vivid behavior of giant reeds, returned through a proper fractional visco-elastic model

Erasmo Cataldo [a], Salvatore Di Lorenzo [a], Vincenzo Fiore [a], Mirko Maurici [b], Francesco Nicoletti [a], Antonina Pirrotta [a,c], Roberto Scaffaro [a], Antonino Valenza [a,*]

[a] *Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali (DICAM), Università degli Studi di Palermo, Viale delle Scienze, 90128 Palermo, Italy*
[b] *Department of Civil, Chemical and Environmental Engineering, University of Genoa, Italy*
[c] *Department of Mathematical Sciences, University of Liverpool, Liverpool, UK*

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ABSTRACT

This paper presents results of experimental investigations made to evaluate the vivid behavior of giant reed *Arundo donax*. In particular, attention was paid to the relationship between visco-elastic properties and moisture content, which is widely recognized as one of the key factor that influences the mechanical properties of all wood-based materials. To this aim, after a controlled drying treatment on samples of reed, stress relaxation tests in three point bending configuration were performed to evaluate the effects of moisture content on visco-elastic behavior of the giant reed. Further, the novel aspect of this paper is that of using an Euler–Bernoulli model embedded with an advanced visco-elastic constitutive law to fit experimental data of bending tests. Such a model of continuum beam takes into account different constitutive laws of viscoelasticity, being natural materials visco-elastic.

1. Introduction

With expansion of manufacturing processes, researchers are interested in the study of functional materials. At the same time, a growing interest in sustainable development has led to a rediscovery of natural materials for several engineering application. In this context, an invasive, inexpensive and low energy intensive product of nature such as giant reed *Arundo donax* could be considered as a renewable source. The culms (the main ascending axis of a plant) of this grass are used to make fences, lattices and sun shelters (Pilu et al., 2012) but its main utilization in construction engineering is related to realization of supports for roof cladding and paneling of walls in ancient buildings. Moreover, from the past to the present day the woodwind musical instrument are made of giant reed culms, since they shows excellent properties in terms of elasticity and resilience (Perdue, 1958). Concerning its alternative use, it is recently considered in the manufacturing of chipboard panels alternative to those wood-based ones (Garcia-Ortuno et al., 2011), and as a source both for fibers (Fiore et al., 2014b) and for particles (Fiore et al. 2014a, c) useful as reinforcement of polymer composites (Fiore et al. 2014b, c). Recently the possibility of its use to replace partially sand in concrete mixes (Ismail and Jaeel, 2014) has studied. Even if various study about this plant have been conducted and its fields of application are very wide, a better understanding of what influences visco-elastic behavior could make it suitable for further applications. This need arises because natural materials exhibit a mixture of the two simple behaviors, elastic and viscous, that is just visco-elastic behavior. In addition, it must be also considered one of the most important

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* Corresponding author.
E-mail address: antonino.valenza@unipa.it (A. Valenza).

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parameter that influences the mechanical, physical and visco-elastic properties of all wood-based materials, i.e. the moisture content (in the next MC). In particular, the various mechanical properties have a different sensitivity to changes in MC, with strength properties more sensitive than stiffness properties and static properties more sensitive than dynamic properties (Gerhards, 1982). With regards to visco-elastic behavior of giant reed (e.g. mechanical relaxation processes), Obataya et al. (1999) stated that it is highly influenced both by the moisture content and by the water-soluble extractive content. However, even if research works about visco-elasticity of giant reed have been performed, the searching of proper model for characterizing the vivid behavior of giant reed is still partial. Hence it is apparent the need of theoretical as well as experimental development of natural materials. To this aim, a different experimental procedure has been adopted. Instead of the tensile tests to capture the visco-elastic properties, here the three point bending test has been performed on a beam that is the giant reed itself. In this way it will be measured a visco-elastic structural response. Consequently, in this paper, the theoretical model to fit the experimental data of relaxation tests is that of a simply supported continuum Euler–Bernoulli beam with a unit imposed strain at the center point of the span. Response in terms of force required to maintain the assigned displacement may be obtained solving the Euler–Bernoulli continuum beam, taking into account the visco-elastic constitutive laws through different mechanical models.

2. Material and methods

The culms of the giant reed (*Arundo donax*) represent slender tube-like structures and grow in height up to about five or six meters with nodal divisions, roughly fifteen to twenty-four nodes per plant. Nodes are solid thickenings of the culm wall that stabilize the culm against local buckling in case of bending (Spatz et al., 1993; Spatz and Speck, 1994). Several structural design principles contribute to make this plant an astonishing and sophisticated structure with impressive mechanical properties. In fact, the giant reed can be considered as a smart composite structure, showing a weight-optimized structure with a material suitable to dynamic load, such as the wind. In Fig. 1 is reported a scanning electron microscopy (SEM) of an internode cross-section that reveals the roughly prevalence of two tissue systems with different mechanical features, meeting all theoretical considerations and needs of the composite structures. Several isolated strengthening vascular bundles enclosed by sclerenchymatous fiber rings are embedded in a matrix of lignified parenchyma. Moreover, the amount of vascular bundles (the load-carrying material) is gradually increased in the direction of the culm's periphery, in keeping with the gradual increase in bending stress as the distance from the hollow pith increases. Finally, a ring of sclerenchyma in the periphery of the culm wall (i.e. the area of highest stress) contributes to the bending stiffness of the culm due to its mechanical properties.

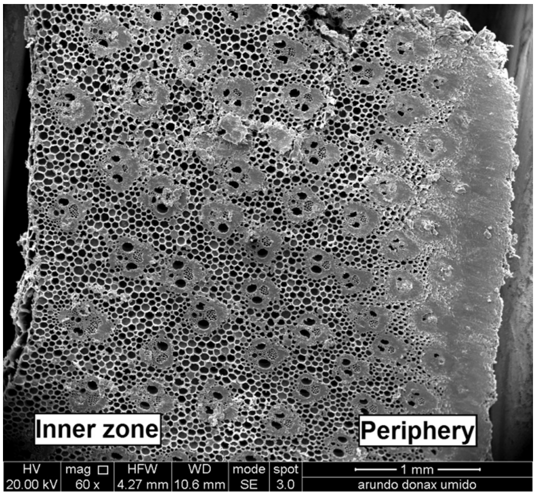

Fig. 1. Cross-section showing a part of the culm wall of an internode.

Furthermore, the pronounced difference in stiffness between vascular bundles and the surrounding matrix of parenchyma is gradual (Rüggeberg et al., 2000). This involves a high damping of wind forces with optimal distribution of the stress before the connection between fibers and matrix fails and the structure disintegrates (Milwich et al., 2006).

Although the mechanical behavior of the giant reed has been clarified, there are limited information about its visco-elastic properties and hygromechanical characterization. For this reason, in this study particular attention was devoted to the influence of moisture content of the giant reed on the visco-elastic behavior, using an Euler–Bernoulli beam model embedded with an advanced visco-elastic constitutive law, to fit experimental data.

Giant reeds were obtained from outdoor cultivations in Sicily and they were harvested in the second year of growth. Afterwards leaves and leaf sheaths were removed and the position of internode was identified by a node number from 1 (bottom) to 20–24 (top). In order to obtain results as reliable as possible, plants with twisted or short internodes were excluded. All morphological and physical features of the chosen culms like total lengths, total mass, internodal lengths, radius, wall thickness, and density were measured. For all the stems from which specimens were cut, the bottom section was chosen at the level of the fifth node above the roots. Fifty specimens subdivided in five sets (i.e. ten specimens for set) were used for relaxation tests in three point bending configuration (Fig. 2). In order to evaluate the effect of variation in MC on visco-elastic behavior of the giant reed, four different hygrometric conditions have been considered. Therefore, immediately after the harvesting, forty specimens were dried under humidity-temperature controlled conditions (i.e. at 30 °C temperature and 50% RH) in a Binder climatic chamber. The specimens were periodically removed after 3, 11, 41, 63 days of controlled conditioning (i.e. at various MC) and mechanically tested. Finally, the last set of ten specimens was oven-dried at 103 °C for 24 h and tested to evaluate the mechanical relaxation properties of the dried