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Research Paper

The structure–mechanical relationship of palm vascular tissue

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ABSTRACT

The structure–mechanical relationship of palm sheath is studied with numerical and experimental methods. The cellular structure of the vascular tissue is rebuilt with an image-based reconstruction method and used to create finite element models. The validity of the models is firstly verified with the results from the tensile tests. Then, the cell walls inside each of the specific regions (fiber cap, vessel, xylem, etc.) are randomly removed to obtain virtually imperfect structures. By comparing the magnitudes of performance degradation in the different imperfect structures, the influences of each region on the overall mechanical performances of the vascular tissue are discussed. The longitudinal stiffness and yield strength are sensitive to the defects in the vessel regions. While in the transverse directions (including the radial and tangential directions), the parenchymatous tissue determines the mechanical properties of the vascular tissue. Moreover, the hydraulic, dynamic response and energy absorption behavior of the vascular tissue are numerically explored. The flexibility of natural palm tissue enhances its impact resistance. Under the quasi-static compression, the cell walls connecting the fiber cap and the vessel dissipate more energy. The dominant role of the fiber cap in the plastic energy dissipation under high-speed impact is observed. And the radially-arranged fiber cap also allows the palm tissue to improve its tangential mechanical performances under hydraulic pressure.

1. Introduction

The ability of palm (Fig. 1a) to survive a tornado is attributed to its highly-evolved materials composition and structural arrangement. At the tissue level, the vascular bundle (VB) is the supporting element of the major organs (Renninger et al., 2013; Killmann, 1983). Palm tissue can be considered as a fiber-reinforced composite with the VB embedded in the parenchymatous tissue (Fig. 1c). Therefore, the structure of the vascular tissue (the combination of a single VB and its surrounding parenchymatous tissue) governs the mechanical properties of palms. Due to the nature of monocots, palms cannot create additional vessels as they age (Renninger et al., 2013; Tomlinson and Huggett, 2012), reflecting the valuable function of the existing vascular tissues. The structures of the VBs in different organs are also diverse (Rich, 1987). The VBs

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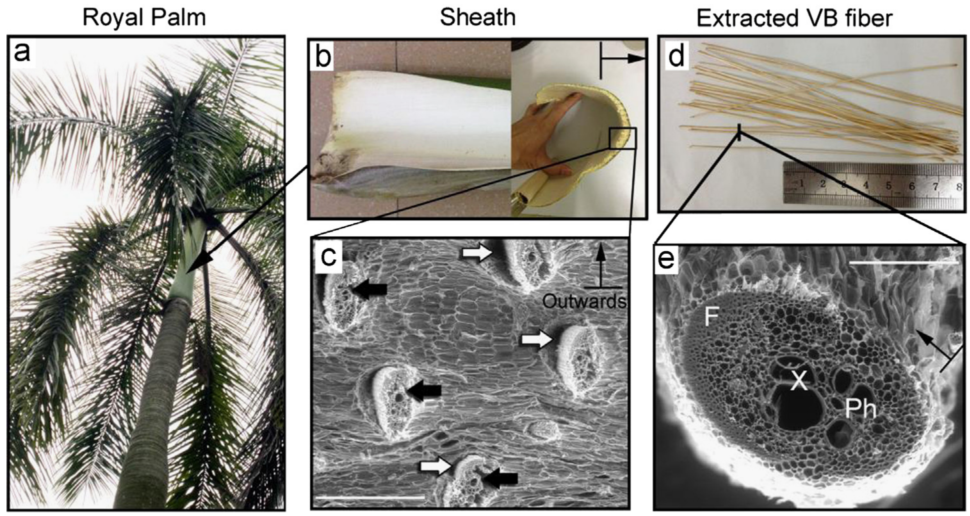

Fig. 1 – (a) Royal palm (*Roystonea regia*), (b) sheath and its cross section, (c) SEM showing damaged structure of vascular tissue in sheath, error bar = 1 mm, (d) extracted VB fibers and (e) a cross-sectional SEM image of a single VB fibers. Error bar = 0.3 mm F, fiber cap; X, xylem; Ph, phloem.

inside the palm sheath and stem are mostly cellular structures while those in the bark are often densified. During the nature growth, palm organs with different mechanical functions can be created by self-adjusting the materials composition and structure of the vascular tissue. Thus, the study of the relationship between structure and mechanical properties in the palm vascular tissue is of importance in understanding its mechanical behaviors.

Among the limited experimental studies on the palm vascular tissue, the tensile tests of the VBs were mostly performed (Zhai et al., 2012; Bachtiar et al., 2010; Sreekala et al., 2000; Shinoj et al., 2011; Ruggeberg et al., 2008). Since the extracted VBs can be used as fibers in the polymer based composites (Shinoj et al., 2011), the VB fibers from different palm species were tested (oil palm: (Sreekala et al., 2000), windmill palm: (Zhai et al., 2012), Mexican fan palm: (Ruggeberg et al., 2008)) and compared with other plant fibers (Bachtiar et al., 2010). The results have shown that the elastic modulus of the VB fiber samples along the fiber direction lies in a small level (0.6–5 GPa) compared to that of the wood (30–50 GPa). This small magnitude of the VB reduces the stiffness difference between the VB and its surrounding tissue at the tissue level. As a result, the ability of the vascular tissue to resist the interfacial crack is enhanced (Ruggeberg et al., 2008). For the study of the materials composition, the UV absorption test was conducted to measure the lignin content of the cell wall (Ruggeberg et al., 2008). A graded distribution of the lignin content from the fiber cap (F region in Fig. 1e, term "fiber" in the present paper refers to the entire vascular bundle exclusively) to the inner tissue of the VB was reported. The gradient in the lignin distribution creates a stiffness gradient, which lowers the risk of mechanical failure in the transition regions between the fiber cap and the inner tissue. The damping performance of the vascular tissue also benefits from the stiffness gradient (Ruggeberg et al., 2010). For the study of the cellular structure of the vascular tissue, Gibson (2012) and Ruggeberg et al. (2008) both linked the overall relative density of the tissue sample to its stiffness and strength based on measurements. However, the relative density is actually a macroscopic parameter for describing the complex cellular structure in the vascular tissue. The detailed structure within the vascular tissue (xylem, phloem and fiber cap) needs to be considered in the study of structure–mechanical relationship in palm vascular tissue.

The dynamic mechanical behavior of the palm tissue, which is more related to its wind resistance ability, has not been studied at the tissue level. Since the functionally graded structure has been proved to be an efficient design for energy absorption purpose (Gupta and Shunmugasamy, 2011; Ajdari et al., 2011; Cui et al., 2009; Wegst, 2011), the graded structure in the natural vascular tissue should also affect its dynamic behaviors such as the impact response and energy absorption. There exists a large volume of literature studies concerning the dynamic response of the other natural materials (Reid and Peng, 1997; Shen et al., 2012, 2013; Thielen et al., 2013). At the cell wall level, the significance of the cellulose microfibril angle (MFA) on the energy absorption capacity of wood cell wall was reported by Reiterer et al. (2001). The presence of the large MFA allows a higher level of energy dissipation efficiency for the cell wall while the samples with small MFA exhibit a much more ductile behavior. Gibson and Ashby (1988) also proposed useful theories to estimate the crushing strength of the cellular structure based on its relative densities (or porosity), and this method has been verified through many experimental studies of bones (Blaker et al., 2005; Yang et al., 2013) and woods (Gibson, 2012). However, the inelastic deformation of natural cellular materials under impact loading is also a complex process strongly influenced by the detailed geometry of the cellular structure (Reid and Peng, 1997) and the direction of loading (for anisotropic materials) (Blaker et al., 2005; Reid and Peng, 1997; Eisenacher et al., 2012). For example, a recent study proved that the small vascular bundles embedded in the pomelo peel tissue can enhance its energy dissipation efficiency (Thielen et al., 2013). Thus, it is necessary to consider