Proceedings of the 7th International Conference on Functional-Structural Plant Models, Saariselkä, Finland, 9 - 14 June 2013. Eds. Risto Sievänen, Eero Nikinmaa, Christophe Godin, Anna Lintunen & Pekka Nygren. http://www.metla.fi/fspm2013/proceedings. ISBN 978-951-651-408-9.

Biomechanical modelation of *Ravenala madagascariensis* petiole

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Highlights: The use of shape transformers methodology, local buckling Brazier model and finite elements analysisis to model the *Ravenala madagascariensis* petiole allows to discover how the relation between shape and mater gives to the plant a structural support to bear high bending and torsion loads without fail. The combination of an elliptical stiff perimeter (epidermis) reinforced with a highly ordered cellular core (aerenchyma) gives to Ravenala petiole two very efficient and secure stability mechanisms.

Keywords: *Ravenala madagascariensis*, Petiole, Structural efficiency, biomechanics modeling

INTRODUCTION

Modeling of structural behavior of plants is an important step in their biomechanical analysis. It allows identifying the relationships between the morphological and anatomical features and the mechanical behavior of the structure under analysis. The models obtained are useful for three purposes basically: to understand the physics behind biological processes (Niklas and Spatz, 2012), to support the behavior of natural materials with commercial interest like wood or bamboo (Mattheck, 1998; Niklas *et al.*, 2006; Vincent, 2012), and to bring the results of the model to the design table and translate them into objects or strategies (Vincent, 2006; Nychka and Chen, 2012).

(a) (b)

Figure 1: (a) Ravenala madagascariensis exemplar in the Botanical Garden of Medellín, Colombia and (b) cross section of the petiole.

Nowadays, one of the most innovative work areas for plants biomechanical models is the design of structures based on the structural principles observed in them (Martone *et al.*, 2010; Shimomura, 2010) in order to optimize man-made structures (Vogel, 2000). This activity, called biomimicry, uses the structural models as its main tool to mimicry the natural behavior through the design process.

Petioles can be considered like cantilever beams subjected to bending and torsion (Niklas, 1992; Vogel, 1992). The combination of shape from its cross-section perimeter and the mechanical properties and distribution of tissues, are the main variables included in most of the models.

This work approximates the mechanical behavior of the *Ravenala madagascariensis* petiole (refered as *R. mad*). *R. mad* it's a monocotiledonean plant of the Zingiberales order and Strelizciaceae (Bird of Paradise) family, endemic of Madagascar island (Kress, Schatz, Andrianifahanana, & Morland, 1994) and is planted like ornamental tree throughout the tropics. The plant presents a set of long petioles and leaves arranged sideways in a bidimensional alternate pattern like a giant hand fan (Fig. 1a). The interest for this type of study about structural morphology lies on the remarkable formal mechanisms that this petiole presents to support all the loads imposed by self weight, wind, rain and animals, and the potential to use them like patterns for the mechanical design of artificial elements. In the modeling approach the contribution of the perimetral shape of the cross-section to the overall structural performance is considered. Moreover, we link the shape with the distribution and mechanical properties of the three main tissues present in the petiole (i.e. epidermis, the combination of parenchyma and aerenchyma and sclerenchyma) (Figure 1b), with the aim to model the efficiency of the real behavior.

MATERIALS AND METHODS

To model the structural behavior of *R. mad* petiole, 9 mature petioles were collected and analyzed microscopical and macroscopically. Cross-section cuts were prepared and microscopic images were obtained with Computed Axial Tomography technique with a Toshiba Aquilion 64 CT Scanner, Motic SMZ 140 stereo zoom microscope and Jeol JSM-6490 SLV scanning electron microscope. From macroscopic images morphological and anatomical features were measure and described. Cantilever bending and torsion tests were developed to obtain the elastic load-displacement curves. To analyze and model the contribution of the perimetral shape in the overall behavior of the petiole, the shape transformers methodology -STM- was used. The STM proposes the mass minimization as optimization criteria in structural design (Pasini *et al.*, 2002). The modeling of the local buckling the cross-section under bending loads uses as reference the model proposed by Brazier (Brazier, 1927). To apply FEM, a 3-D digital model of the *R. mad* petiole cross-section was developed based on the real distribution of tissues, shapes and dimensions. Only peripheral sclerenchyma fiber bundles were taken into account, assuming that the fibers in other locations have only physiological and not a significant structural contribution to the overall petiole mechanical behavior. The model was meshed using 2D 4-node isoparametric cuadrilateral elements and 3D 8-node isoparametric hexahedrical elements with a special interpolation of the shear component for the bending test. The calculations were made by means of finite element-based code called VULCAN (Celentano, 1999).

RESULTS AND DISCUSSION

The average elliptical shape obtained from the sampled petioles has a width of 36.43mm ± 2.56mm and a height of 56.80mm ± 7.11mm with a thickness of 2.50mm ±0.16mm. This shape includes the epidermis and the first part of the parenchyma tissue which is reinforced with sclerenchyma fibers. Two models of cross-section were designed and analyzed with the STM to define comparatively its structural efficiency. Fig. 2 shows the results of the computation of structural efficiency parameters proposed by STM in bending and torsion: ψA, ψI and ψJ.

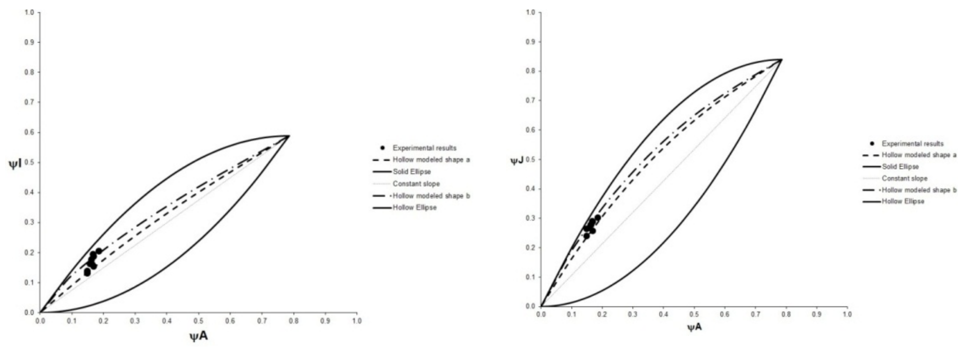

Fig. 2. a: structural efficiency maps for bending stiffness; b: structural efficiency maps for torsion stiffness.

Closed elliptical shape allows the structural modeling of the open cross-section of *R. mad* petiole. The experimental calculations for the geometrical shape transformers ψA, ψI and ψJ lie over the modeled shapes curves. It means that the supposition of the closed section is valid to analyze the structural efficiency of *R. mad* petiole. The petiole cross-section behaves as less efficient compared to a perfect elliptical shape, at bending and torsion. Nevertheless, we have to consider that real shape is an open section probably responding to structural but also to physiological and morphological requirements. Analyzing real petioles cross-sections, it was found that the theoretical circumference of thickness of 1mm (shape marked with “b” in Figure 3) that would generate an elliptical ring with the same dimensions of those observed in the petioles (shape marked with “a” in Figure 3) would have an average radius of 22.8mm ± 2.1mm. Applying the Brazier model, the ovalized ellipse generated by local buckling process from this circular cross-section has the same dimensions of the original elliptical shape but rotated 90° (shape marked with “c” in Figure 3). If both elliptical sections, the original petiole cross-section shape and the ovalized elliptical shape, are compared with the theoretical circular shape that originate them, we see that the oval cross-sectional shape of the petiole acts as a structural security factor, with a second moment of inertia 44.8%± 9.7% higher than a circular cross-section with the same area. Besides, the ovalized elliptical shape generated from the theoretical circular cross-section modeled according to the Brazier model, has a second moment of inertia 27.8%±3.1% lower than circular section. If torsion constant of the sections are compared, the average loss of torsional stiffness of the elliptical shape with respect to the circular is just 15.8%±0.8%. Thus the use of elliptical shape with the major axis oriented with the vertical direction in cantilever beams subjected to bending and torsion

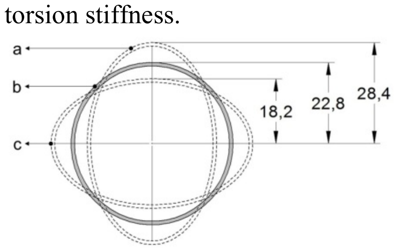

Fig. 3. Dimensional analysis of the local buckling ovalization process modeling. Dimensions in mm.

loads seems to be an evolutional structural advance of the *R. mad* petioles. The petiole rotates when the wind comes in, in order to reduce its projected area. The use of less-efficient shape in torsion, but stiffer in bending than circular section, helps the species adapting to extremely windy conditions.

FEM allows finding the normal and shear stress distribution over the cross-section. For this load the modeled petiole followed the behavior predicted for beam theory (Timoshenko and Goodier, 1969), where the maximum stresses are located on the points of the cross-section farther from the neutral axis. The shear stress distribution shows that modeled petiole exhibits a mechanical behavior which differs from the behavior predicted by elasticity theory. The values of stresses on the peripheral points over the minor axis of ellipse are very similar to the stresses on the peripheral points over the ellipse major axis, when the theory says that those values must differ proportionally to the ratio of the major and minor axis (Timoshenko and Goodier, 1969).

For bending, the Young modulus variation shows that parenchyma is the major stiffness-related tissue. A change of four orders of magnitude in the parenchyma Young modulus value, gives a bending load four orders of magnitude higher. While the same variation in the Young modulus of the epidermis and sclerenchyma fibers doesn´t respond similarly. For torsion, a variation in four orders of magnitude in the parenchyma Young modulus gives a torsional moment increase of the same magnitude order. While the same variation in the Young modulus of the other two tissues, doesn´t implies a similar magnitude variation in moment. For each load type, the level of contribution of each tissue is different. This could mean that the high level of anisotropy of each tissue affects its mechanical behavior. The change in the stiffness of the entire system is higher with the change of the Young modulus of the parenchyma for both bending and torsion, but not in same proportion. The contribution of epidermis differs in each load type. Sclerenchyma fibers appear as a tissue useful in bending but less important in torsion. FEA of modeled petiole shows that the peripheral points of the cross-section bear similar shear stresses. It could mean that the aerenchyma tissue not only helps to stabilization of the section to resist the compression stresses due bending, but redistribute the magnitude of shear stresses to decrease the warp of the elliptical section when rotation by wind, stabilizing the section to allow high angular deformations. The almost radial configuration of the aerenchyma chambers walls (Fig. 1b) suggests a mechanical based orientation. The aerenchyma anatomy shows a grid with non-circular spaces that generate almost straight lines through which the loads may be distributed. For that reason aerenchyma can be assumed as inner reinforcing mechanism.

Madagascar is an island located in the path of tropical cyclones and hurricanes with maximum wind velocity in normal weather conditions of 40km/h. This generates very complex and extreme environmental conditions to which *R. mad* seems to be properly adapted. A main conclusion is that the real contribution of each tissue to the mechanical resistance of the petiole depends more on form and organization than on individual mechanical properties.

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