Structural and torsional properties of the *Trachycarpus fortunei* palm petiole

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Abstract

The *Trachycarpus fortunei* palm is a good example of a palm with a large leaf blade supported by a correspondingly large petiole. The way in which the material and functional properties of the petiole interact is analysed using engineering and botanical methods with a view to understanding how the petiole functions from a structural standpoint. Initially, the histological aspects of the petiole are analysed at a microscopic level from sections of the petiole taken at regular intervals along its axis, in order to determine the density and location of the *vascular bundles*. A modified *torsion* rig was used to measure the *torsion* and *shear stress* variation along petiole sample lengths. Knowledge of *vascular bundle* placement within the petiole sections and their torsional loading characteristics contribute to understanding the petiole function.
Keywords: palm petiole, vascular bundle, axial torque, geometry, rigidity modulus, composite, material properties, Trachycarpus fortunei, torsion, shear stress.

1 Introduction

The largest blades in the plant kingdom may be found in *Arecaceae* (the palm family) providing a reason for exploration into their structure and engineering properties. The palm *Trachycarpus fortunei* was chosen because of its overall large size (up to about 12m high), and its correspondingly large leaves of up to one metre in diameter [1]. This palm is native to China and the Himalayas, thriving in temperate regions and is one of the world's hardiest palms. A popular name for it is the Chinese windmill palm because its leaves are stiff and fan-

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shaped. It has a slender single stem of about 250mm in diameter and is typically slightly narrower at the base than at the top. Environmental factors such as wind and rain acting on the blade generate bending and torsion loads on the petiole. How do the section properties of the petiole deal with this loading?

Work by Gibson *et al* [2] states that palms are among the most efficient materials available owing to their *composite* and cellular microstructures. The petiole of the palm *Chamaerops humilis* analysed in [2] was found to have a radially uniform distribution of *vascular bundles* within a parenchyma matrix. They modelled the petiole as a unidirectional fibre *composite*, with a uniform distribution of fibres in a honeycomb matrix of the same solid material. Such structures are common in many palms, 'petioles' and stems in other monocotyledonous species. By varying the volume fraction of fibres radially in a fibre *composite* of circular cross section they came to the conclusion that a non-uniform distribution leads to an increased flexural rigidity over a uniform distribution. They also found that further increases in rigidity were possible if the cross section is hollow like bamboo, whereas a thin walled tube gained little from a structural gradient.

Trachycarpus fortuneii however, has *vascular bundles* that are concentrated radially towards the outside of the petiole. The tensile modulus of palm *vascular bundles* is astonishing at 100GPa [3] compared to Kevlar which ranges from 83 to 186GPa (grades 29-149). *Sclerenchyma* (derived from the word 'scleros' in Greek meaning 'hard') is the lignified material that partially or entirely surrounds the *vascular bundles* which in effect forms tubes.

Ashby *et al* [4] found that wood, with its high value of $(E/\rho)^{1/2}$, is well suited to resist both bending and elastic buckling. In addition, palms, although having a simpler structure which is slightly less efficient than dicotyledonous or gymnospermous woods in bending resistance and buckling is nevertheless stronger in these regards than most engineering materials.

2 Torsion and botanical analysis

2.1 Petiole histology

In order to evaluate the internal structure of the petiole, cut sections were mounted in wax and scanned at a resolution of 1200dpi. This revealed the arrangement of *vascular bundles*. Three-centimetre samples were cut at six equal intervals (of 171mm) along the petiole axis ending at where the leaf blade joined the petiole (sample P6) as shown in fig. 1.

2.2 Section scanning

Fig. 2 shows that the remainder of each section embedded in the wax after removal of some slices with the microtome, was enough to use a scanner to analyse the placement and number of *vascular bundles*.

Each section was scanned at 1200dpi and a 0.25mm grid placed over them using Adobe Photoshop® software. Samples P1 and P6 are shown in fig. 3:

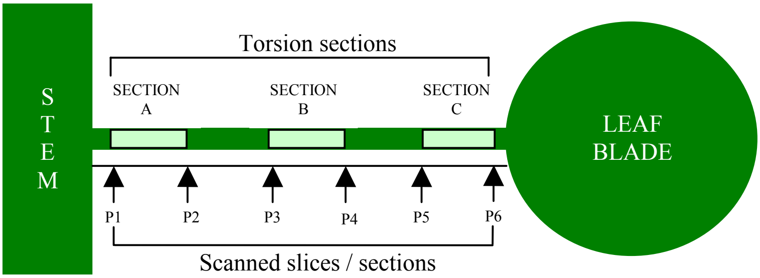

Figure 1: *Palm petiole* schematic showing the relative placement of samples for scanned slices P1 to P6 and sections A, B and C for the *torsion* experiments.

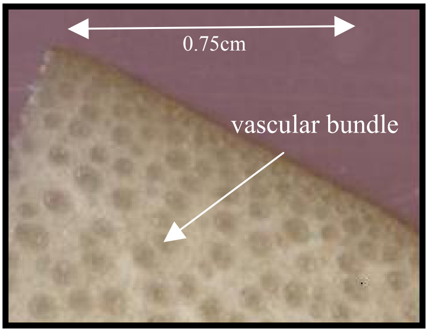

Figure 2: Part of sample P6 showing higher concentration of *vascular bundles* towards the petiole / air boundary.

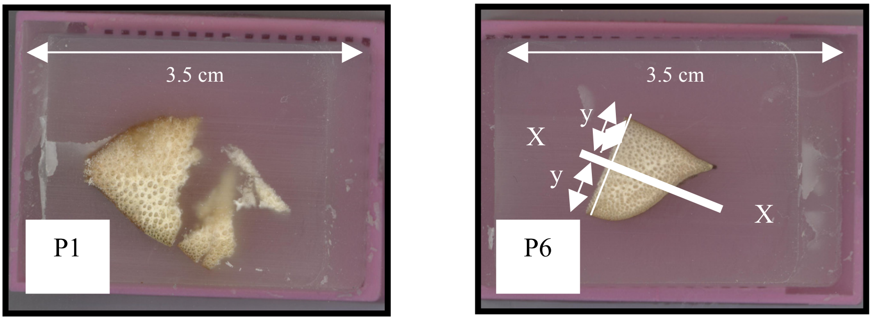

Figure 3: Sections P1 (nearest the palm stem) and P6 (nearest the blade) embedded in wax. Sample P1 was torn while cutting the hard sample using a scalpel. Line XX is a later reference when determining cross sectional area.

2.3 Vascular bundle distribution within petiole

The petiole acts as a compound cantilever and the number of *vascular bundles* in both the lower and upper halves of the petiole section P6 was counted using a graticule. The *vascular bundles* are like reinforcing rods in concrete from a structural point of view owing to the relatively high tensile strength of the *vascular bundles* within the comparatively weak surrounding parenchyma matrix. The white line shown in fig.3 sample P6 joins the adaxial and abaxial surfaces of petiole transverse section at its thickest part. Line XX also shown in the same figure bisects this line at right angles to it. It was found that there were 47% more *vascular bundles* to the adaxial side of Line XX shown on sample P6 than abaxial to it. Further to this, the 80% of the cross sectional area of the petiole in sample P6 was found to be adaxial to Line XX. The number of *vascular bundles* per 2.5mm^2 was counted using a graticule for the entire viewable area for all samples. The mean average was determined according to whether the *vascular bundles* were positioned internally or close to (within 1mm) the outer surface of the petiole. The results in fig. 4 show that the concentration of the peripheral and internal *vascular bundles* increases fairly steadily towards the leaf blade (which one would expect to some degree if number of bundles has to remain the same whilst the area of the cross section is decreasing). The gradients of the trend lines indicate that the concentration of the peripheral vascular bundles increases more per unit axial distance than that of the internal ones, correlating with the fact that the number of vascular bundles in the cross section increases distally. This is also proven as the number of vascular bundles in P4 is 330 and that in P6 is 375, an increase of 13% over a third of the petiole length.

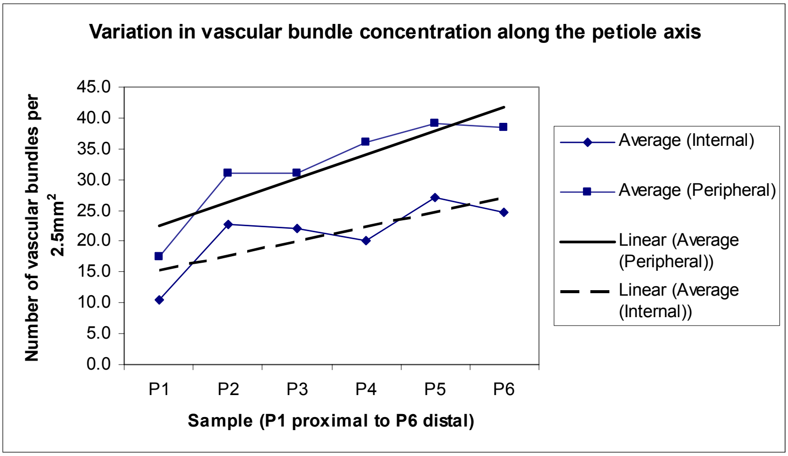

Figure 4: The variation of *vascular bundle* concentration along the petiole axis.

The external boundary (outline) of the petiole section is an irregular shape and as such is difficult to measure precisely. At the proximal end it encircles the trunk and may be an order of magnitude broader than the distal end of the petiole where it meets the leaf blade. For the purposes of the *torsion* test and aiming at straight samples as a first investigation, the most proximal part of the petiole was not tested (a distance of 100mm along the petiole axis from the trunk edge). The remainder of the petiole was tested in sections of similar cross-sectional area (not varying by more than +/- 8%) to enhance the straightness of each section and to avoid the effect of clamp ends. During *torsion* it is the outer edge of the specimen that is expected to break first, being the furthest distance away from the neutral axis. Two tests were undertaken on each of the three samples in close succession in order to check the consistency of the data and observe any hysteresis present.

2.4 Torsion test preparation and acquisition

2.4.1 Petiole preparation

A disease-free petiole of 85cm in length was sawn and the cut end of each petiole section was immediately submerged in water in order to sustain freshness and transpiration. Each petiole was divided into five equal lengths of 211mm chosen to be the same intervals as the botanical section samples. Only the first (section A), third (section B) and fifth (section C) samples were used for this experiment. The specimen length was chosen as a balance between minimising the effect of the clamp ends and minimising section variation along the petiole. As 20mm of each sample end was to be embedded in epoxy, the tested length was a 171mm sample as in fig.5. The shape of each sample end was recorded by drawing around the profile with a sharp pencil. Cellulose film was wrapped around each cut end to inhibit transpiration, enhancing the freshness of the petiole.

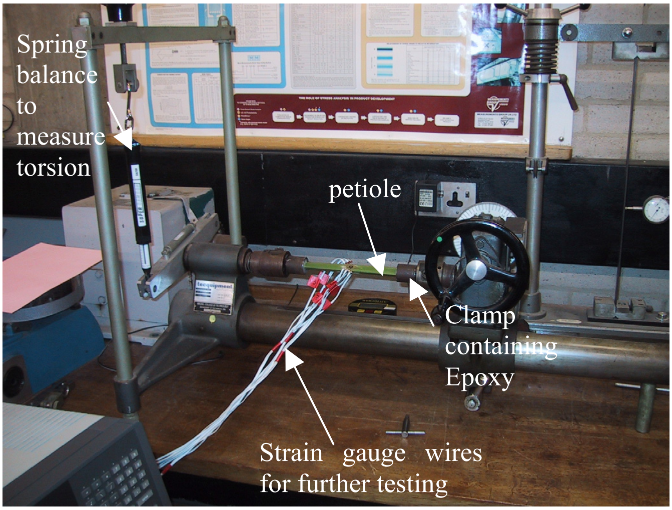

Figure 5: Torsion rig equipment showing petiole embedded in the clamps.

2.4.2 Torsion data acquisition

The sample was set up in the *torsion* rig after checking the alignment of the machine. Data for *axial torque* and angular twist was manually recorded every ten seconds after turning through one degree. This experiment was repeated to check the results albeit on already twisted sections and the time lapse noted. As the petiole is symmetrical about the central vertical plane, it was only necessary to apply torque in one sense of direction. From cutting the sample to taking the last reading, the first tests took less than two hours.

2.5 Torsion results

Fig. 6 shows that for both the first and second tests, the *torsion* values for section A are nearly twice those of the other two sections B and C when readings were taken every ten seconds and twisted through one degree. For each sample, the *torsion* values vary linearly with the angle of twist although this rate decreases slightly with increasing angles of twist (or data sample). The change in *torsion* readings per unit time would vary depending on time intervals between angular twisting increments (in this case ten seconds). The part of the petiole nearest the trunk is about twice as resistant to *torsion* as the middle and distal sections. For all of the sections, there was a time interval of ten minutes between the end of the first and the start of the second test. It can be seen from these results that section A nearest the trunk is the only one to display either strain hysteresis through plastic deformation or permanent damage.

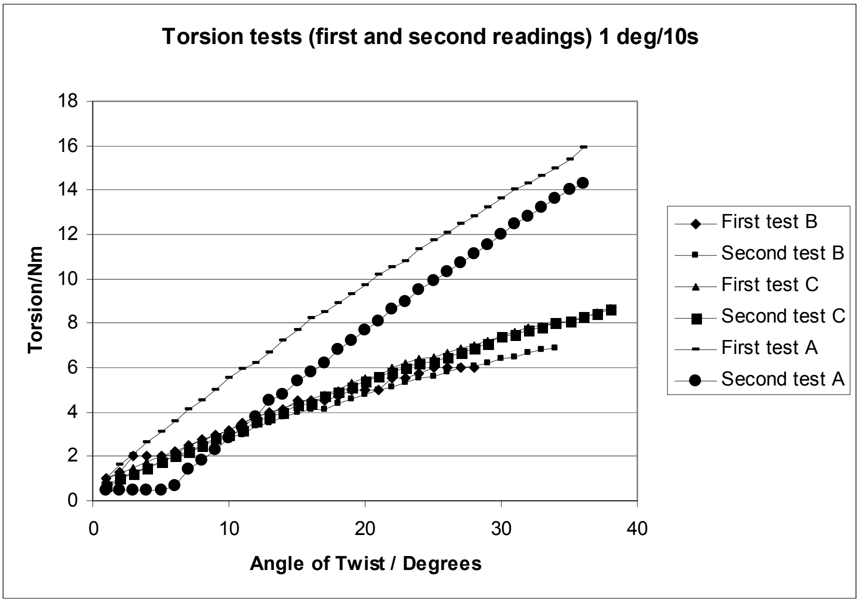

Figure 6: Results of both first and second torsion tests.

2.6 Analysis

The standard equations for *torsion* of a homogeneous section in eqn. (1) have been applied although it was found that the *vascular bundles* were not distributed evenly throughout the petiole cross section, the latter differing from the petiole analysed by Gibson et al. [2].

$$T/J = G\theta/L = \tau/r \qquad (1)$$

where T is applied *axial torque*, J is polar second moment of area, G is the *rigidity modulus*, θ is angular twist, L is the specimen length, r is the section radius and τ the *shear stress*. The *rigidity modulus* was calculated for each section by taking the gradient of the graph of *torsion* versus angle of twist. The values for G were calculated from the graph gradients as J and L where known. As the petiole cross sections were not circular, J and r were derived from the average cross sectional area of the samples being then transformed into the equivalent circular cross section. The results are shown in fig. 7.

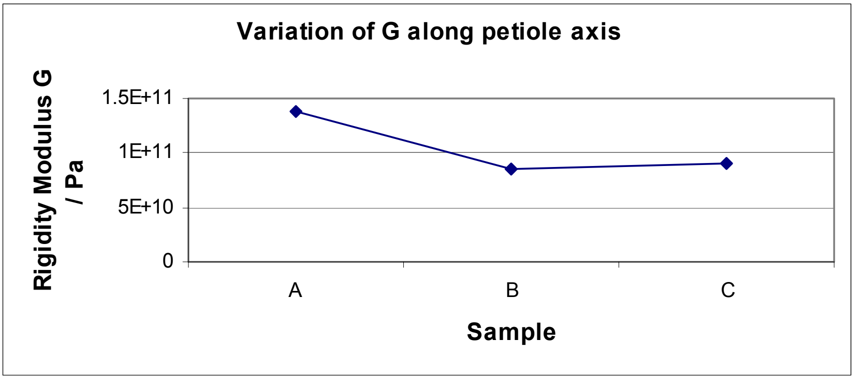

Figure 7: *Rigidity modulus* variation along the petiole axis.

J was calculated using eqn. (2) for solid cylinders using the equivalent cylindrical radius.

$$J = \pi r^4/2 \qquad (2)$$

Even though the *palm petiole* was not a homogeneous material, eqn. 1 was used to calculate the *shear stress* (τ) during *torsion* for each of the three samples as shown in fig. 8. τ was observed to range linearly for each sample and the gradient of sample A when *shear stress* was plotted vs. increased angle of twist was approximately 150% greater than those of samples B & C.

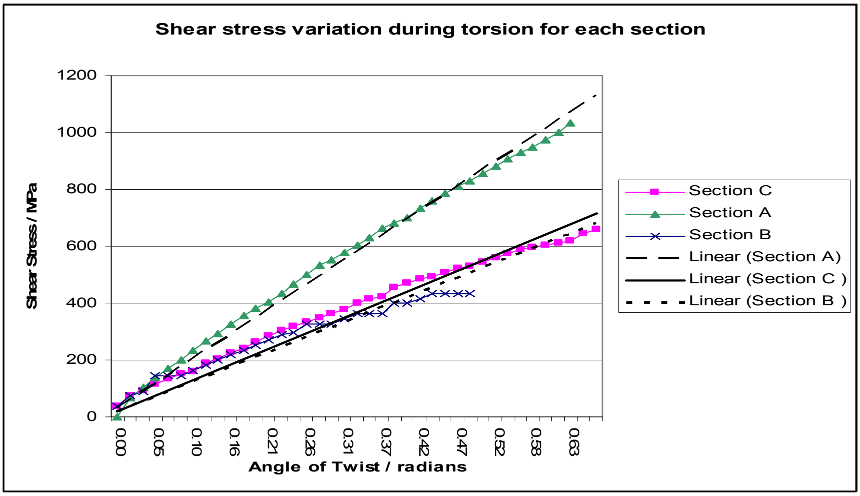

Figure 8: *Shear stress* variations during increased *torsion* derived from eqn. (1).

3 Discussion and conclusions

Using a scanner with a resolution of 1200dpi, the remainder of each sample embedded in the wax after removal of some slices with the microtome, enabled analysis of the location and number of *vascular bundles*. A higher concentration of *vascular bundles* was found towards the outer side of the petiole. In the tested sample (P6) there were 47% more *vascular bundles* in the top vertical half above line XX nearest the adaxial surface compared to the lower half nearest the abaxial surface of the petiole sample below line XX. Further to this, the area of P6 was found to be 80% more above line XX compared with below it. The concentration of both the internal and peripheral *vascular bundles* increases fairly steadily towards the leaf blade although the concentration of the peripheral vascular bundles increases more per unit axial distance than that of the internal ones. As the number of vascular bundles in P4 is 330 and that in P6 is 375, an increase of 13% over a third of the petiole length it may be the case that the vascular bundles branch distally. The increasing spatial density of *vascular bundles* towards the leaf blade should allow the petiole to twist about greater angles before any kind of overall fracture. It also shows that the *vascular bundles* have a higher bulk density than the matrix in which it is embedded – the parenchyma.

The maximum vertical distance (height) between the adaxial and abaxial surfaces of the sections decreased and the bulk density of the petiole increased towards the leaf blade end of the petiole. The cross sectional area of the petiole also decreases towards the distal end of the petiole apart from the middle Section B in our case, indicating that the *geometry* of the outer shape of the petiole requires further investigation. This would be to determine if this is a typical result and to investigate, if so, why.

The first and second torsion test data match for both sections B and C, however these tests differ for section A indicating that the properties of this section have changed. For both the first and second tests, the *torsion* values for section A are nearly twice those of the other sections B and C when readings were taken every ten seconds each time being twisted through one degree. This results in section A being twice as resistant to twisting as the other two sections, partly being caused by the greater cross sectional area. The outcome of this is that the palm trunk is isolated from many of the dynamic forces on the blade. The *torsion* values vary almost linearly with the angle of twist although this rate decreases slightly with twisting. Perhaps a different relationship would be apparent if the rate of *torsion* changed. It may be partly due to creep and the small scale elastic adjustment of the petiole material. Much research on the plant response to mechanical and *forced convection* has identified mechanosensitive ion channels which regulate the amount of calcium ions entering the cell as a result of stress. Calcium ions probably regulate the first stage in the signal transduction pathway from the first perception of the mechanical stress to the activation of genes which synthesise proteins in response to the stress [5]. For all of the sections, a time interval of ten minutes between the end of the first and the beginning of the second test was set. It is interesting to see from the results that section A nearest the petiole is the only one to display stress hysteresis. Hysteresis in this part of the material where the cross sectional area of the petiole is largest, reduces damage to it. The repeated movements of the petiole caused by the forces of a prevailing wind (*forced convection*) are reduced as a result of hysteresis enabling the petiole to temporarily re-shape to the prevailing forces.

The shear stress, τ was observed to range linearly for each of the three samples on the graph plotting τ vs. increased angle of twist. The gradient of sample A was approximately 150% greater than those of samples B & C which were similar. This shows that the shear stress per unit *axial torque* did not decrease linearly but that a reduction in stress occurred in the middle petiole sample (B). This may be so that the distal end of the petiole is more able to support the blade locally. Bending stress experiments are required to investigate this anomaly.

From this small set of experiments, we have been given an insight into the mechanical behaviour of the *Trachycarpus fortunei palm petiole*. In the course of evolution the structure found in this, and petioles of other palm species, has become ‘selected’ by pressure from environmental and functional factors. It is shown to be an efficient structure, economical in materials, well suited to its function. These results have consequential design implications for manmade cantilevers.

Acknowledgement

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