SENSIBILITY OF PALMS TO HURRICANES

Peter Sterken

Summary
The safety of trees and palms is of great concern during events of strong wind. A simple model is presented which enables to assess the swinging potential of the palm during events of wind. Besides, it is suggested that the critical wind speed for failure of the palm depends on the relationship between the modulus of elasticity, the form of the cross-section, the slenderness of the palm and mechanical behaviours.

Key words: Critical wind speed · Hurricanes · Modulus of elasticity · Palms · Resonance · Safety · Wind load

1. Introduction

There is no information or method available yet for assessing the structural strength and safety of palms during hurricanes. Hence, a proposal for the assessment of the swinging potential of palms has been formulated. Natural bending sways of the palm can be excited by wind gusts with the same frequency, potentially leading to large deflections and unexpected failure. The critical wind speed, at which the frequency of vortex shedding equals this natural swinging frequency, is predicted in accordance with Eurocode 1 (AENOR 1998). Several authors (Baker 1995, Blackburn & Petty 1988, Kerzenmacher & Gardiner 1998) also suggested that trees and plants often uproot or break when they are forced by wind gusts at their natural frequency in transverse vibration. Oscillations in wheat stalks were also found to be at largest during wind gusts at the plant's natural frequencies (Finnigan 1979). In this context the present model has been developed.

A hypothesis on stem failure of palms has been formulated, based on the observation of broken palms and controlled breakage experiments (Fig. 1).

Figure 1. Controlled breakage of *Phoenix dactylifera*.

Here is suggested that the "critical wind speed for failure" of the palm depends on the relationship between the modulus of elasticity, the form of the cross-section, the slenderness of the palm and mechanical behaviours.

These mechanical behaviours, e.g. shear, splitting and Brazier buckling, can cause failure of the stem while these are not predictable by means of current methods.

With the necessary caution, the principles of this model can be incorporated in risk-assessments for palms. These principles are wind load, natural frequency, critical wind speed v_{crit} and the visual assessment of mechanical behaviours.

Correspondance: Haringstraat 15, Blankenberge (Postalcode: 8370), Belgium.
e-mail: petersterken@hotmail.com web: www.sterken.be

2. **Structure of the model**

- *Natural frequency and critical wind speed*

The palm is modelled as a fixed end cantilever. If an aero-elastic behaviour of a slender beam is assumed, then the critical wind speed v_{crit} for oscillation of this beam can be described as (AENOR 1998):

$$v_{crit} = \frac{\left(\frac{\varepsilon_l d}{h^2} \sqrt{\frac{Ws}{Wt}} \right) d}{St}$$

Where:

v_{crit} = the wind speed at which the frequency of vortex shedding equals the natural bending frequency of the stem if undamaged

ε_l = the factor of frequency

d = the diameter of the stem

h = the height of the palm or tree

Ws = the weight of the structural parts that contribute to the stiffness of the trunk

Wt = the total weight of the trunk

St = the Strouhal number which for round beams is recommended to be the same for all Reynold numbers (AENOR 1998)

In this equation, the natural frequency of the palm is calculated, which is a function of the slenderness, mass and stiffness of the palm. The natural frequency of a structure expresses the amount of vibration cycles per second. A frequency of e.g. 13,35 Hz means that the stem needs 0,07 seconds to swing forward and then return to its original position (one complete cycle).

If a periodic force is applied to a system, at or near its natural frequency, it may resonate. This can happen with palms and wind. The latter will depend on how closely the frequency matches and possible damping, which may limit this resonance. The palm will only deflect with the force, if the frequency of the wind does not matches the palm its natural frequency, without entering in resonance.

The critical wind speed v_{crit}, at which the frequency of vortex shedding equals the natural frequency of the stem, is predicted in accordance with Eurocode 1 (AENOR 1998). This is the wind speed at which the palm oscillates perfectly with the minor effort, but is not necessarily the wind speed that would cause failure.

A slender beam under wind loading can behave in the same manner as a stick that wobbles sideways when dragged through water. Vortices shed sideways from the stick cause a fluctuating load perpendicular to the dragging direction. v_{crit} is a measure for the palm its sensibility to this dynamic interaction with the wind, to assess the swinging potential of the palm. Natural bending sways of the palm can be excited by wind gusts with the same frequency, potentially leading to large deflections and unexpected failure. In this context the present model has been developed.

In this model, the positive influence of damping caused by the crown and dry leaves is not incorporated directly. This damping is a function of friction due to air resistance i.e. aerodynamic damping and natural frequencies of the leaves that differ from that of the stem. Damping can decrease the amplitude of deflection, but the crown area heightens the loaded area of the palm.

This model starts from the case where the stem can oscillate freely adopting the typical aero-elastic behaviour of slender beams. Afterwards, the equivalent wind load F_{eq} in the complete area of the palm varies with the square of v_{crit}.

- *Wind load analysis*

In accordance with the Eurocode 1 (AENOR 1998), the equivalent wind load F_{eq} in the palm is analysed with the following formula:

$$F_{eq} = 0{,}5 C_w \left[\frac{T_o}{T} 10^{\left(\frac{-z}{z_o}\right)} \rho_o \right] A v_{crit}^2$$

Where:

F_{eq}	= the equivalent wind load due to the critical wind speed v_{crit}
C_w	= the aerodynamic coefficient describes the flexibility that the palm employs in order to diminish the force of the wind
T_o	= the specific gas constant in degrees Kelvin
T	= the expected air temperature in degrees Kelvin
z	= altitude above sea level
z_o	= sea level
ρ_o	= air density at 0ºC and at sea level
A	= the exposed area of the palm to the wind estimated according to Eurocode 1
v_{crit}	= the wind speed at which the frequency of vortex shedding equals the natural bending frequency of the stem if undamaged

The safety of palms stands partially in function of the temperature and altitude, since the density of the air influences directly the force that hurricanes exert in the palm. The equation represents the air density as a function of temperature and altitude. The following examples evidence how the safety is related partially to the temperature T and to the altitude z at which the palm grows (Table 1 and 2).

Table1. An example of the influence of the temperature and altitude on the wind load F in a *Phoenix canariensis,* where all the other parameters were kept the same:

T = 35ºC	**z = 900m**	**F = 5,89kN**
T = - 5ºC	**z = 0m**	**F = 7,59kN**

Table 2. Wind load analysis in a *Phoenix canariensis*. Terrassa, Spain.

Data input				***Results wind load analysis for palms***			
Height palm	=	14,15	m	Corresponding air density ρ	=	1,32	kg/m³
Stem diameter	=	60,48	cm	Wind speed (crown height) $u^{(z)}$	=	35,05	m/s
Height crown	=	7,08	m	Wind force in the crown F	=	7,59	kN
Diameter crown	=	7,67	m	Natural bending frequency n	=	13,35	Hz
C_w chosen	=	0,20		v_{crit}	=	40,37	m/s
Weight fruits	=	0,00	kg	Equivalent wind load F_{eq}	=	10,07	kN
Maximum expected wind speed for the area	=	34,72	m/s (125 km/h)				
T	=	-5,00	ºC				
z	=	0,00	m				

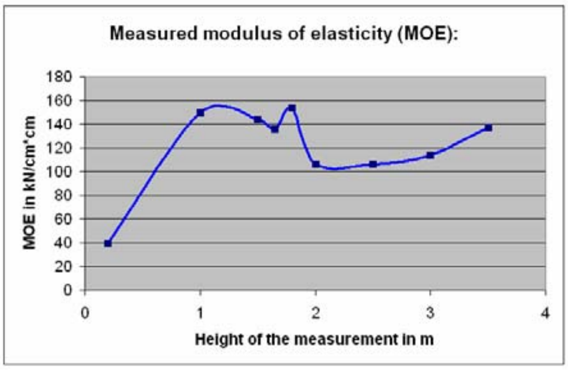
The expected wind speed for the area, at the height of the crown centre, $u^{(z)}$ can also be employed instead of the critical wind speed v_{crit}. This enables to estimate the wind load in the palm during storms.
As can be observed in this table, the critical wind speed for resonance v_{crit} is higher than the expected wind speed for the area $u^{(z)}$. This means that the risk of dynamic loading is very low and that the pure static force of the wind would be the important factor in the safety of this palm.
In a more slender *Washingtonia filifera* on the other hand, v_{crit} might be lower than $u^{(z)}$. This would mean a higher risk for dynamic interactions with the wind, which might lead to large deflections due to resonance.

3. Breaking safety of palms

In palms, mere observation of fresh cut pieces of the stem suggests that the vascular and fibre bundles of the palm-trunk do not seem to be glued together as stiff as the fibres of a dicot tree. The mass of bundles does not seem to behave as coherently as the wood of a tree. The bundles can sometimes be torn apart easily with the hands. Therefore, it is possible that the trunk of a palm is more sensitive to splitting (shear- and perpendicular stresses) than the sapwood of a dicot tree. Pulling-test experiments on palms in Spain led by the author of this publication also seem to suggest this structural behaviour. The fibrous structure might behave more as the hairs of a broom – especially with small residual walls – instead of a massive wooden beam.

A hypothesis on stem failure of palms has been formulated here, based on the observation of broken palms and controlled breakage experiments: The bending of the palm stem is assumed to be proportional to the wind force in the crown and inversely proportional to the stiffness of the stem. It is suggested that the “critical wind speed for failure” of the palm depends on the relationship between the modulus of elasticity, the form of the cross-section, the slenderness of the palm and mechanical behaviours. These mechanical behaviours, e.g. shear, splitting and Brazier buckling, can cause failure of the stem while these seem not predictable by means of current methods.

In this context, 98 measurements of modulus of elasticity E were divided over seven palms. The modulus of elasticity was measured on the stem of the palms, both on damaged and sound (control) cross-sections (Table 3). The highly variable stiffness of these cross-sections was registered with Young's modulus sensors and gently pulling the palm with a winch. The fibre elongation in between the two measuring points, caused by wind load simulation, is a measure for the stiffness of this 20cm wide cross-section. The measured E can be combined mathematically with the geometrical moment of inertia of the cross-section. Theoretically, this would enable to estimate the critical force that would cause the stem to buckle. For a detailed description of measurements of the modulus of elasticity in trees, see Peltola et al. (2000).
Table 3. *Phoenix canariensis* # 2. Parc Sant Jordi, Terrassa, Spain. An example of the different E obtained by measurements in standing palms.



Some structural behaviours of structures under loading have been described in this paper, referring to palm stems. The formulae that describe these behaviours suggest good agreement with this hypothesis, where the safety of a palm might depend considerably on the modulus of elasticity.

4. Examples of common mechanical behaviours

- *Shearing stresses*

Shearing stresses measure the tendency that one part of a body has to slide over an adjacent part. This phenomenon can be visualised by bending a book. The pages slide over each other due to the bending of the whole. The strain due to shear obeys Hooke's Law with moderate stresses.

In depth studies were performed by the author of this work on a *Phoenix dactylifera* which presented a very hollow and open trunk. The deformations of the marginal fibres in different orientations were recorded in the area of the open cavity during a wind-simulation with a cable winch. With Young's Modulus sensors *extraordinary* deformations were recorded due to the sliding over each other of the two halves of the stem (Fig. 3). And they were *many times higher* than the longitudinal deformations on which the theory of the Neutral Fibre is based. This behaviour suggests that failure would occur due to shear, splitting of the hollow stem in half, without obeying the bending theory of a hollow beam.

Figure 3. Extraordinary shearing deformations (in 1/1000 mm), in comparison with pure longitudinal fibre elongations, suggest sliding over each other of the two halves of the stem

- *Euler buckling*

Slender beams can fail by forming a large wave along their length. In reality, the beam "deviates itself" from the load and this type of failure seems to depend principally on its modulus of elasticity, height of the beam and the moment of inertia (Gordon 1999). The following equation evidences the latter:

$$F_{crit} = \pi^2 \frac{EI}{4h^2}$$

Where:

F_{crit} = the critical force that would lead to Euler buckling of the trunk or stem
E = the modulus of elasticity
I = the geometrical moment of inertia
h = the height of the tree

This phenomenon could be visualised by leaning on a thin walking stick which bends aside because of our weight. When we take away the pressure, the stick turns back to its original shape. But if we force it to bend too much – the stick escapes sideways - it breaks and we fall on the floor. Its slenderness and capacity to deform elastically determine how much of our weight the stick can take before it buckles (!). The development of similar calculations could enable to incorporate the assessment of the smaller cross-sections (constrictions) caused by post transplantation stress.

- *Shell buckling*

According to Gordon (1999) the manner in which a structure escapes from the load, will depend on th structure its form and proportions and the material from which it is composed.
A wall made of bricks (masonry) usually does not fail because of primary failure – the blocks do not get crushed by the weight of the wall – but the wall *folds away* and the whole comes down.
The same thing can happen with very hollow trees or palms that get folded because of being too flexible. This “Brazier buckling” is similar to crushing an empty drink can under pure compression. The empty can fails due to the formation of small waves, folding itself. The very thin “residual wall” of the can crumples. It seems that a possible failure of this type depends on the modulus of elasticity, thickness of the residual wall and radius of the cross-section (Gordon 1999). The critical stress for shell buckling is calculated with the following equation:

$$\sigma_{crit} = \frac{1}{4} E \frac{t}{R_{cav}}$$

Where:

σ_{crit} = the critical stress in the wood fibres that would lead to Brazier buckling of the residual wall
E = the modulus of elasticity
t = the thickness of the residual wall
R_{cav} = the radius of the cavity

The visually observed sensibility of the fibre bundles to split apart in e.g. *Phoenix dactylifera* might even heighten the risk of shell-buckling in very hollow stems.

5. Elastic energy

According to BSV (1997), the modulus of elasticity E influences directly the elastic energy W that the wind provokes in a beam. For a distributed wind load, the energy added to the oscillating beam is estimated by the following equation:

$$W = \int_{O}^{H} \left(\frac{(M_b(x))^2}{2EI(x)} \right) dx$$

Where:

W = the beam elastic energy, in Nm
H = the height of the beam, in m
$M_b(x)$ = the bending moment at height x loaded by a distributed wind load, in Nm
dx = the integration segment, in m
E = the modulus of elasticity, in kN/cm²
$I(x)$ = the geometrical moment of inertia at height x, in cm^4

It is suspected here, that this elastic energy might influence in the stability and breaking safety of a palm. This energy diminishes as the stiffness heightens. The latter is a function of the modulus of elasticity and the diameter of the stem. Possible structural damages can lower this stiffness, which means that more elastic energy can occur in the damaged cross-section. Also a thicker stem, compared to the height, signifies less elastic energy added, i.e. a higher safety, and vice versa.

The swinging energy, caused by dynamic oscillations, could be an important factor in the failure process of a palm.

6. Deflection

If a static force is applied to a beam it will deflect as a function of its modulus of elasticity and slenderness. In palms, the similar is expected. The deflection during events of wind reaches a critical point where the palm may uproot or break.

For beams and static loads the deflection is represented by the following equation (Tyler & Hicks, 2005):

$$D = \frac{F}{3EI} L^3$$

Where:

D = the deflection of the beam
F = the static load
E = the modulus of elasticity
I = the geometrical moment of inertia
L = the length of the beam

Nevertheless, oscillations of the palm can be excited by wind gusts with the same frequency, which is called resonance. This resonance may cause the palm to deflect much more as predicted, which can lead to unexpected failure.

7. Adjustment of the parameters to the real situation

The following simple experiment enables to adjust the parameters of the model, by which the latter becomes more precise. A broader quantity of measurements in different palms will give more useful data. After a broad amount of data has been recorded, the model can be employed as a solid orientation for the sensibility of palms to events of wind. The results for each palm species could enable to generalise the model for other individuals of that species, without having to perform each time the same experiment. The natural frequency n of a palm can actually be measured. The palm is deflected by pulling it with a rope, which is loosened abruptly, causing the palm to oscillate freely. The oscillations are recorded and plotted over time. This enables to record the time it takes to complete one full cycle of swinging forward and back. The natural frequency can then be calculated with the following equation:

$$n = \frac{1}{T}$$

Where:

n = the bending-frequency of the trunk, expressed in Hz
T = the time it takes to complete one complete cycle of swinging forward and back, in seconds

In this way, the factor of frequency ε_l can be adjusted for the palm stem. This permits to fine tune the calculation of the critical wind speed v_{crit} (see corresponding equation).

8. Conclusion

Although the model is in accordance with international engineering standards, it is acknowledged that there is no statistical evidence yet to show a comparison between predicted results from the model against real outcomes. Hence, v_{crit} cannot be seen yet as an exact value since some parameters have to be estimated. Nevertheless, the relative results (in m/s) show good agreement with visual observations of slenderness in palms. The above described experiments can fine-tune these calculations. Cabling the assessed palm to other palms or structures is a very efficient solution for reducing oscillations caused by vortex shedding and turbulent gusts. This has also proved to be efficient for diminishing the risk for uprooting or breakage. Therefore, the wind load in the palm has to be known. With the necessary caution, the principles of this model, i.e. wind load, bending frequency, critical wind speed v_{crit} and the visual assessment of mechanical behaviours, can be incorporated in risk-assessments for palms. According to field observations, the formulated hypothesis on stem failure might target precisely the essence of the breaking safety of palms.
Finally, the goal of this model and paper, is to set the stage for the future development of the herein briefly proposed visual palm assessment.

This paper is dedicated to *Mufi.*

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