A Guide For
Tree-Stability Analysis

Peter Sterken

Second and expanded edition

Exemption from liability

The author expressively emphasises that each case is unique and has to be treated as such, and that the guidance and recommendations published in the present paper should be followed in accordance with the judgement, specialised knowledge and expertise of the individual expert.

Therefore, the author is exempt from any liability for damage to persons, objects or property resulting from the use of the herein published information.

The facts and results gained in the scope of the investigations that are mentioned in this publication only relate to these cases and are not transferable to similar circumstances.

Foreword

Ever since Prof. A. L. Shigo presented his CODIT model to the world, knowledge on trees improved enormously. In stead of trying to heal a tree, a case what seemed to be rather difficult, improvement of growing conditions and preventing a tree to weaken and get infected by pathogens of any kind became the new starting point for arboriculture.

A lot of problems have been solved in the past, but still a lot of questions are to be answered, and maybe have not been asked yet. One of the main questions to be worked on is a question on the stability and safety of trees, especially in an urban environment.

This book does not claim to give all the answers. It even will give no answers that have not been given in other publications. The advantage of this book is that it will bring together the answers that are given on different aspects of tree-diagnosis.

A lot of research on different aspects of tree-stability is done, each starting from one specific point of view. Trees have been researched, on their dynamic, static and biological aspects. To get to results, it was necessary to see a tree as just a static, dynamic or living mass. All starting points to gather knowledge on trees were definitely good ones, just because there was still a lot of knowledge to be gathered and brought together.

So this book can in no way be seen as an attack to anybody who ever did any kind of research on any aspect of trees, or on any of the results they got.

But as a tree is not just a static, dynamic or biological mass, all the knowledge gathered in these different scientific fields one day should be brought together.

That is what this book tries to do: bring together all existing knowledge on tree-stability, what should lead to a better diagnosis of tree-problems. But as there is still a lot of knowledge on trees still waiting to be discovered, this book can not claim to be complete, nor to give all the answers. It is just what it claims to be: one small step upwards the knowledge and understanding of trees. Tree-diagnosis does not start with this book, neither does it stops here, it is just one step upwards, hopefully in the right direction.

Wim Peeters

Contents

1. Introduction

This guide offers a deeper understanding of how a tree fails and how to prevent it. A profound and intuitive knowledge of the inherent perversity of materials and structures, mathematics and trees, is one of the most precious qualities an arborist can have.

It is not necessary here to chew again on all types of symptoms of structural defects that can be found of a tree. The current offer of literature that deals with visual assessment is huge, and these works are good references as far as common symptoms are concerned.

This small book briefly describes the principles upon which the author's protocol is based: mycology, biology, mathematics, wind engineering, mechanical behaviours and visual assessment. But above all pleads for the integration of current methods, criteria, knowledge and common sense. The present publication can serve to the reader as a continuous thread to which the following fine works should be added:

The V.T.A. method as described in "*The Body Language Of Trees*" by Mattheck & Breloer (1995), presents tree reactions and faults leading to tree failures. The description of possible failures by fracture is a delicious and obliged literature. The VTA method agrees well with Gordon (1999) in how structures fail. Here, invasive diagnostic procedures are reserved for trees assessed with serious risks.

Currently, the SIA method (Wessolly & Erb, 1998) is a powerful tool to assess the breaking strength of a hollow tree. This method, available free of charge, calculates the diameter of a tree trunk and the necessary residual wall that a given tree needs to withstand wind gusts of 32,5 m/s. The results take into account tree height, crown form, drag factor and strength of the wood, amongst other factors.

In the Inclino-Elasto method (Wessolly & Erb, 1998), the tree is subjected to a wind simulation force by pulling and its behaviour is recorded by devices recording stem angle and fibre length changes. An inclinometer measures the inclination of the stem base in order to assess the uprooting potential of a tree. An elastometer records the longitudinal elongation or shortening of the most exterior stem fibres. This method enables a better insight in the tree it's stability. The I.B.A. method (Reinartz & Schlag, 1997) describes the interaction of mycology, vitality and stability. This visual method combines the visual detection of wood-decaying fungi, sometimes long before the first fruiting body appears, and the SIA method. The authors of the

IBA method state that not only many trees can deal easily with fungi, but also that an instrumental diagnosis is very rarely necessary.

At the current time, Prof. Dr. Francis Schwarze is investigating the interaction between the defence mechanisms of a tree and the strategies that decay fungi employ to overcome the former.

The *status quo*, i.e. the current condition of decay in a tree, can be assessed macroscopically. The above described methods can offer a static recording of this current condition. Nevertheless, the *dynamics* of the interaction, *and hence the future safety of the tree*, can only be assessed microscopically. In this way, for the first time, it is possible to incorporate a prognosis regarding the *future* development of decay, and invasiveness of different decay fungi, in the sapwood of trees.

Finally, the goal of the present publication is to blend components of the above described methods. In this way, a reasonable and carefully weighed guide is presented to assist tree-professionals during the tree-stability analysis, as *a synthesis and an integration* of these previously published assessment methods.

In-depth studies, performed by the author in Spain on Mediterranean trees and palms, were the "nursery" for the protocol. Another logical step in the development of this guide was the study of specialised literature on structures and their failure (e.g. Gordon, 1999).

The author of this current publication employs it successfully on Mediterranean tree-species like *Eucalyptus* spp., *Celtis* spp*., Brachychiton populneus, Tipuana* spp*., Cercis siliquastrum, Cupressus sempervirens, Ficus* spp. and Mediterranean pine trees*.*

For Middle-European tree-species the protocol is equally accessible.

The message is that mostly a tree can be assessed very well with the combination of a visual assessment and the estimation of its stability by wind load analysis. Even many monumental trees can be inspected very well on their stability with the help of the protocol proposed by the author of this publication.

The instrumental diagnosis seems to be seldom necessary for the assessment of the breaking safety of a tree. Should the tree in question have an extraordinary monetary value and if there are unsolved questions regarding its stability, a range of fine instrumental methods can be chosen from.

2. Prognosis of the breaking-safety of hollow trees

Introduction

This publication presents a proposal for a new method for tree-stability analysis. This proposal is *a synthesis and an integration* of previously published tree assessment methods. By integrating knowledge from different research disciplines and methods, a higher level of understanding, about how trees stand up or fall down, is achieved.

Firstly, the present proposal is basically a visual assessment combined with mathematical analysis of (wind) loads. By means of the latter, the safety reserves of the hollow tree are calculated. Also the critical wind velocity for bending fractures of the hollow trunk, the bending frequency of the stem and uprooting, failure of the anchorage roots, can be estimated.

In Sterken (2005) a proposal is formulated in order to assess whether a hollow tree is hazardous or not. It is suggested that the residual wall should have both enough safety reserves regarding wind loads and a low risk of catastrophic mechanical behaviours.

Externally visible symptoms of internal decay, like adaptive growth and growth-depressions, are to be recognised. This proposal can be a more powerful tool if combined with the mapping of decay by means of acoustic tomograms. For the interpretation of the latter, see Schwarze *et al.* (2004).

This part of the proposal enables *a momentary insight* in the tree's stability (uprooting and breakage).

Secondly, a long-term prognosis regarding the future development of decay in the sapwood, and hence the tree its safety, can be more accurately predicted when knowledge of interactions at the host-fungus are considered. According to Schwarze (2001), while trees attempt to resist the spread of decay with several defence mechanisms, in many cases fungi possess strategies by which they can overcome the host response system of the tree. The latter counteraction between host response and invasiveness of decay fungi have been studied extensively at the microscopic level by Schwarze et al.. A summary of the most important findings have been gathered in the present publication. For a more profound understanding on this subject, a review of these recent findings are recommended.

In the following lines the basic components are presented in a resumed mode:

Basis components I: momentary assessment of stability or status quo

The promising combination of opposed methods

For the first time, the present proposal situates the results of the mathematics, of which the employed formulae are offered in Sterken (2005), in the complete process of analysing tree-stability. Under mathematics is understood here, for example, calculating safety factors and the necessary thickness of the residual wall by wind load analysis. Real trees and real winds usually do not fit themselves to the mathematics.

Instead of the proposed mathematical model, the more accessible SIA method (Wessolly and Erb, 1998) can be employed by the practitioner, which might give information about the breaking safety of the individual hollow tree. According to the SIA method, in the case of many old trees, the trunk, if undamaged, can be many times thicker and safer than necessary to withstand a hurricane. The stress, induced by the hurricane load, would remain far below the compression strength of the marginal wood-fibres. Theoretically, and according to the bending theory of the hollow beam, these old trees only require very small residual wall thickness to withstand gusts of 117km/h.

Nevertheless, this can only be meant as an *orientation* for the assessment, since very low t/R ratios can lead to different types of collapse/failure due to the flexibility of the hollow shell. In this context the analysis of catastrophic mechanical behaviours, according to "The Body Language of Trees" (Mattheck & Breloer, 1995) is introduced. According to these authors, very common mechanical behaviours cannot be predicted by means of the bending theory of a hollow beam and its mathematics (main point of criticism in regards to the pulling-test or elastomethod of Wessolly and Erb (1998)). The most important failure types are shell-buckling, shearing fractures, torsion fractures and splitting due to transverse stresses. In the present proposal these behaviours have to be analysed, by which the mathematics are tempered.

The combination of the SIA method and the VTA method is very accessible and proves to be highly efficient in the field.

Visual assessment

Visual assessment is the most important component of the proposal presented here for assessing the stability analysis of trees.

The ring of sapwood is what gives the tree its main structural strength, regarding for example torsion and bending, to a tree. Therefore, if symptoms are detected that point towards damages in the sapwood, e.g. due to wood decay fungi, then it is possible that the cross-section suffers an important loss of its load bearing capacity.

If the sapwood is damaged, then the water conducting capacity can be diminished. This can lead to a loss of vitality. This loss of vitality usually produces symptoms in the upper crown structures and the bark. Other symptoms, like growth depressions or dead areas in the bark also may indicate serious structural damages in the ring of sapwood.

Therefore, it is possible during tree hazard assessment to take as a starting point *the state of the crown and bark*, before attempting to apply more technical resources. This method can be a very good orientation, in order to assess visually if there is an important loss of structural strength, caused by fungi, in the wooden body.

If there are still unsolved questions in regards to internal decay, acoustic tomography can be introduced, facilitating more accurate assessments of the fracture-safety of trees. According to Schwarze *et al.* (2004), a zone of decay can be determined accurately for its size and moderately accurately for its position by means of acoustic tomograms.

Basis components II: What residual wall thickness is required by a tree?

The safety assessment of hollow trees has always fascinated arborists, and the criteria to be employed have led to severe public discussions in the professional scene in Europe.

Based on Mattheck & Breloer (1995), many tree-consultants state that the required thickness of the residual wall should not be below a t/R ratio of 0,3 to prevent shell-buckling, cross-sectional flattening and hose pipe-kinking.

On the other hand Wessolly & Erb (1998) published an opposite theory by which often *much* lower thickness are calculated and accepted. Their methods are based on the bending theory of the hollow beam.

A complete study was made on a 17,1m high eucalyptus tree (*Eucalyptus camaldulensis*) in Spain. In accordance to the above mentioned theory, which is also employed by Wessolly. For this purpose the necessary trunk diameter and residual wall thickness where calculated for different tree-heights.

Afterwards, the results were contrasted throughout with criteria regarding torsion, shear, stress peaks, cross-sectional flattening and shell-buckling.

A literature review suggests that the different types of failure of the residual wall depend mainly on parameters like stiffness and strength of the wood in different anatomical directions (wood is anisotropic), geometry of the cross-section and different loads.
Hence, fixed t/R assessment limits should be approached carefully.
But:
Neither should the residual wall always be as thin in a real tree as predicted mathematically with the formula employed in accordance with the bending theory of the hollow beam.

The analysis by Sterken (2005) suggest that the truth lies somewhat in the middle instead of in both extremes.

Basis components III: wind loads and bending frequency
Within the scope of the present publication, the author worked out a mathematical model for the analysis of stability and breakage of trees.
The *goal of the model* is to enable tree-specialists appreciate better the interaction between wind, tree-stability, biology, wood-decaying fungi and mechanical behaviours.
The *goal of the present proposal* is to offer criteria that both situate the results of the model in the tree-diagnosis process and temper the mathematical calculations on which this model and similar methods are based.
The critical wind velocity -"V" – can be estimated with this model. "V" is the wind velocity that would cause the stress in the outer fibres to exceed the maximum compression strength and would hence produce failure of those fibres. This computerised model calculates the critical wind velocity for several types of failures (uprooting, bending fractures of the sound or hollow trunk and torsion fractures of closed and concentric cavities). Safety factors obtained by analysis

of the wind loads are incorporated as well, while the theoretical necessary residual wall thickness for each tree can be calculated.
With these analysis, a basic idea of the safety of a tree can be obtained although they can only be a small part of the stability assessment, since real trees and real winds do not always fit in mathematical models. Both the possibilities, as well as the limits of these assessment methods for trees are discussed in depth in Sterken (2005).

Assessing the wind load in the crown
In accordance with the Eurocode 1 (AENOR, 1998), which recommends equations for predicting wind loads of structures, the wind load in the tree-crown is analysed. For trees, the following formula is a logical adaptation of the equations:

$$F = \tfrac{1}{2} * Cd * p * A * u^{(z)2}$$

Where:
F = the force that a gust exerts in the crown
Cd = the aerodynamic coefficient describes the flexibility that the tree employs in order to diminish the force of the wind
p = density of the air, which depends on the pressure and humidity of the air, temperature and height above sea-level.
$A_{(z)}$ = the exposed area of the crown to the wind.
$u^{(z)}$ = wind speed "u" at a certain height "z" above ground level.

Dynamics
In this model, the bending-frequency of the bare trunk is represented by the following equation (AENOR, 1998):

$$n = (el * d)/(h^2) * v(Ws / Wt)$$

Where:
n = the bending-frequency of the trunk, expressed in Hz
el = the factor of frequency
d = the diameter of the trunk
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
The natural bending-frequency of the trunk is compared to its safety factor (regarding static wind loads), allowing a better orientation for the tree its stability.

Basic components IV: prognosis of the future development of decay

Defence mechanisms of the tree
In Schwarze (2001) an excellent description can be found regarding the current state of knowledge on compartmentalisation.

- **Barrier zone**

The barrier zone, which is very efficient regarding the delimitation of decayed wood and healthy wood, is only formed after the cambium has been injured. The latter can occur both after an injury is inflicted from the outside (e.g. collision and pruning wounds) and/or when the fungus parasitizes the cambium , from the inside towards the outside (e.g. *Inonotus hispidus*).

The barrier zone (wall 4) has been demonstrated to be very efficient, for example, in *Tilia platyphyllos* regarding *Kretzschmaria deusta*, whereas the reaction zones are much weaker. Several authors highlight the importance of the barrier zone (Wall 4) regarding the assessment of the fracture-safety of a hollow tree.

- **Reaction zones**

An intact reaction zone can provide the tree with a natural defence, often over a long period, against the spread of decay and the resulting increase of probable fracture. While possibly being primarily a means of maintaining the hydraulic integrity of the functional xylem. Reaction zones are being formed exclusively in the sapwood. In a tree, the formation of reaction zones is closely associated with the enhancement of the moisture content, living parenchyma cells and its energy reserves, the vitality of the tree, temperature and the season.
The reaction zone can be efficiently penetrated by several fungus species. For example, the hyphae of I. hispidus can colonise the living tissue in Platanus x hispanica during the dormant period, in which the tree cannot respond effectively.
These reaction zones, nevertheless, seem to be important in slowing down degradation processes and in preventing embolism in the water conducting system (Schwarze & Baum, 2002).
Typically, the reaction zone is three to four centimetres wide on the average when viewed in a transverse section. In some studies, a width up to eight centimetres has been reported (Schwarze et al., 2004).

According to Schwarze & Baum (2000), in beech and London plane, some fungal species are able to extend into the functional sapwood some way beyond the reaction zone, without stimulating the simultaneous migration of the zone. Instead, a new reaction zone forms later at the new colonisation front. This alternating event points towards possible interaction phases that might be seasonal (cyclic changes in carbohydrate reserves and accompanying changes in the moisture content, i.e. a supra-optimal water content at the lesion margin). Here, the reaction zone of the tree is envisaged as a *static boundary*.
This type of discontinuous host response may be recognised by the presence of reaction zone relics within decayed wood (Schwarze & Baum, 2000). *Inonotus hispidus* for example causes these relics, growing into the cell walls towards the healthy sapwood of *Platanus x hispanica*, whereby the obstructed cell lumina, which form the reaction zone, are avoided.

On the other hand, in *Tilia platyphyllos*, the reaction zone has been demonstrated to be a *dynamic boundary*, whereby the reaction zone migrates progressively into the previously healthy sapwood, ahead of the penetration of hyphae (Schwarze & Baum, 2002).

Interaction at the host-fungus interface
Examples of strategies for reaction zone-penetration and corresponding invasiveness of wood-decaying fungi.

- ***Ganoderma* spp.**

Depending on species, vitality and other factors, some trees have a relatively good ability to form compensation wood. In this case there are usually clear biomechanical signs, e.g. adaptive growth (Mattheck & Breloer, 1995) and growth-depressions (Reinartz &Schlag, 1997), of the decay caused by *Ganoderma* spp. before any increased risk of failure occurs. (Schwarze & Ferner, 2003).
Nevertheless, it is very important to distinguish the invasiveness of *Ganoderma adspersum* from that of *G. applanatum* and *G. resinaceum*. Reaction zones can be not efficient at all when *Ganoderma adspersum* colonises species of *Tilia, Fagus, Acer and Platanus*.

At the time of the assessment, the tree might have adequate residual walls of sound wood. This means that the residual wall has enough safety reserves regarding wind loads (SIA method, Wessolly & Erb, 1998) and a low risk of catastrophic mechanical behaviours (VTA method, Mattheck & Breloer, 1995). This proposal has been formulated in depth in the book "A Guide for Tree-stability Analysis". Nevertheless, the long-term prognosis might be negative, even within trees of high vitality.

In *Fagus sylvatica*, for example, the reaction zones can be used by this fungus as a nutritional substrate, by digesting preferably the polyphenols and suberized tyloses. Consequently, its invasiveness can be classified as high in a standing tree.

On the other hand, if *G. applanatum* or *G. resinaceum* are identified, and the stability assessment indicates that the tree is not a significant hazard, internal investigations may be unnecessary (Schwarze & Ferner, 2003). The decay can be delimited and kept under control over a longer time in trees of high vitality.

Finally, the prediction, regarding the progress of decay for a given fungus species, also will depend on the particular tree-species, and not necessarily on the trees vitality.

- ### *Kretzschmaria deusta*

Due to the degradation of the sparse polyphenols in the cell lumina and consequent spreading of the hyphae of *K. deusta* freely via the pits in the cell walls, the ability to compartmentalise this fungus by means of reaction zones is very low in **T. platyphyllos**. Even when the tree is very vital and the momentary assessment of the residual wall or the anchor roots points towards a "safe" tree.

Consequently, the absence of the barrier zone (Wall 4l of the CODIT-model) in this tree-species infected by *K. deusta* can pose a major problem. This situation can occur for example, due to the colonisation of the stem base through damaged major roots. During the stability-analysis, this factor should be recognised since its very high importance regarding the prediction of the tree's stability in future years..

In **Fagus sylvatica**, on the other hand, *K. deusta* can be very effectively compartmentalised when the healthy tree has a high vitality and high energy reserves. In this case the reaction zones are moderately efficient, due to the abundant occlusion of natural openings (pits) in the cell wall, the latter being the only pathway for this fungus to spread from one cell to another.

If the stability assessment indicates that the tree is safe, then the tree might be able to maintain an equilibrium between decay and stability for a longer period. A long-term prognosis as regards its stability can be formulated.

On the other hand, when the energy reserves are low (strongly diminished vitality and/or growing under unfavourable conditions), the very sparse anti-fungal occlusions in the lumina of the cells are not able to stop the spread of the decay. *Kretzschmaria. deusta* is regarded as particularly dangerous in this situation, impairing the tree its long-term stability and fracture-safety even if the its current state is satisfactory .

Conclusion

After assessing whether the existing sapwood, which gives the tree its main structural strength, is able to bear the impacting loads, a prognosis is made regarding the future development of decay in this ring of sapwood. This allows a more accurate assessments of the fracture-safety of the tree or defective branches.

During the stability assessment, it is very important to recognise whether a barrier zone has developed in a tree or not. An intact barrier zone might allow for an intact ring of sapwood, which can behave according to the bending theory of a hollow beam. For the necessary thickness of the residual wall, see Sterken (2005).

When the absence of a barrier zone is suspected in a tree, the residual wall might not behave in the simplified manner, as if it was a hollow beam under pure bending stresses. This due to the invasiveness of certain fungi as regards reaction zones in the sapwood, that can lead to an irregular geometry and a not clearly defined ring of sapwood. Both the study on relics of breached reaction zones in decayed wood (Schwarze, 2001), as the reporting of externally visible symptoms of a degraded residual wall (Reinartz & Schlag, 1997) seem to support this hypothesis.

Knowledge about the interactions in regards to host-fungus-vitality is also essential for making correct decisions on the appropriate amount of pruning and proper cabling.

Crown- or branch reductions can be necessary to reduce failure components like end-weight, wind loads, dynamics, torsion, bending and buckling. But due to the foliar loss, they can also lead to a reduction of vitality and hence diminished defence mechanisms (compartmentalisation and compensation).

Properly designed cabling installations can prevent excessive pruning and foliar loss, while still allowing the tree to compensate defective parts.

Figure 1. Prognosis of the development of decay and the fracture-safety of hollow trees

Part I of the proposal: momentary assessment of strength and stability

Visual assessment:
Vitality: Visually assessable symptoms of the state of vitality in crown and bark. Corresponding capacity of compartmentalisation and repair-growth.
Wood decay fungi: Ring of sapwood and symptoms in the bark and crown.

Geometry: the form of the cross-section and structural defects (confined vs. irregular rots) determine the behaviour of the wooden body under loads. This factor might influence in whether the fracture-safety is predictable or not by means of mathematics.

Mathematics: wind loads and safety. SIA method (Wessdly & Erb, 1998) + *Reasons of mechanical failure* and its visual assessment: The Body Language of Trees (Mattheck & Breloer, 1995)

Part II of the proposal: long term prognosis of stability

Strategies for reaction-zone /barrier zone penetration and corresponding invasiveness of wood decay fungi (Schwarze *et al.*). Knowledge on the development of decay allows for more accurate assessments of the long-term fracture-safety of the tree or defective branches.
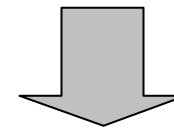
Synthesis and an integration of previously published tree assessment methods.
A reasonable and accessible method that permits a better insight in the trees safety, which proves to be highly efficient in the field.

3. A mathematical model for the prediction of the critical wind speed for the failure of trees

Introduction

Within the scope of the present publication, the author worked out a mathematical model for the analysis of stability and breakage of trees.

The *goal of the model* is only to support the analysis that are developed in this book. In this way, the model will also allow tree-specialists appreciate better the interaction between wind, tree-stability, biology, wood-decaying fungi and mechanical behaviours.

The *goal of the present publication* is to offer criteria that both situate the results of the model in the tree-diagnosis process and temper the mathematical calculations on which this model and similar methods are based.

The Critical Wind Speed -"V" – can be predicted with the V model. "V" is the wind velocity that would cause the stress in the outer fibres exceed the maximum compression strength and would hence produce failure of those fibres. This computerised model calculates the critical wind velocity "V" for several types of failures (uprooting, bending fractures of the sound or hollow trunk and torsion fractures of closed and concentric cavities). Safety factors obtained by analysis of the wind loads are incorporated as well, while the theoretical necessary residual wall thickness for each tree can be calculated.

Structure of the V model

- *Assessing the wind load in the crown*

In accordance with the Eurocode 1 (AENOR, 1998), which recommend equations for predicting wind loads in structures, the wind load in the tree-crown is analysed. For trees, the following formula is a logical adaptation of those equations:

$F = \frac{1}{2} * Cd * p * A * u^{(z)2}$

Where:

F = the force that a gust exerts in the crown
Cd = the aerodynamic coefficient describes the flexibility that the tree employs in order to diminish the force of the wind
p = density of the air, which depends on the pressure and humidity of the air, temperature and height above sea-level.
A = the exposed area of the crown to the wind.
$u^{(z)}$ = wind speed "u" at a certain height "z" above ground level.

Similar formulae are found in publications of scientists in the field of arboriculture (Mattheck & Breloer, 1995; Wessolly & Erb, 1998; Niklas, 1999; Peltola et al., 1999; Gaffrey, 2000; Spatz et al., 2000; Ezquerra et al., 2001)

The power-law model is used to predict the wind speed at a given height above ground level and is presented by the following formula (Berneiser & König, 1996; Wessolly & Erb, 1998):

$u^{(z)} = tu * u^{(g)} * (h^{(z)} / h^{(g)})^a$

Where:

$u^{(z)}$ = wind speed "u" at a certain height "z" above ground level.
$u^{(g)}$ = maximum wind speed expected, not influenced by the roughness of the terrain.
$h^{(z)}$ = height above ground level at which a certain wind speed is reached (height of the analysis)
$h^{(g)}$ = height above ground level at which the maximum wind speed is reached.
a = surface friction coefficient
tu = turbulence factor

A turbulence factor is incorporated to count with the influence of strong incoming gusts.

- *Dynamics*

In the V method, the bending-frequency of the bare trunk is represented by the following equation (AENOR, 1998):

$n = (el * d)/(h^2) * v(Ws / Wt)$

Where:

n = the bending-frequency of the trunk, expressed in Hz
el = the factor of frequency
d = the diameter of the trunk
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

In the V model, the natural bending-frequency of the trunk is compared to its safety factor (regarding static wind loads), allowing a better orientation for the tree its stability.

- *Breaking safety*

The calculation of the breaking safety of the tree is based on the bending theory of the (hollow) flexible beam. The bending stress on the surface of a hollow beam can be calculated by the following equation (Mattheck & Kubler, 1995):

$$s_{max} = (4 * M) / (pi * R^3)$$

Where:

s_{max} = the maximum bending stresses in the marginal fibres

M = the bending moment and is the sum of the forces (F) in the crown, multiplied by the distances (P). This moment is calculated with the above described wind load analysis.

R = the radius of the trunk

The geometrical moment of inertia (I) is the parameter that defines the resistance against bending of the cross-section. Hereby I can be defined, assuming the cross-section is ellipse-shaped, as:

$$I = (pi / 4) * a * b^3$$

Where:

I = the geometrical moment of inertia

b = the radius at 1 meter height parallel to the loading direction

a = the radius perpendicular to the first

The safety factor of the trunk is then found from:

$S = s/s$

Where:

S = the safety factor of the cross-section

s = the strength of the green wood

s_{max} = the maximum bending stress in the marginal fibres

By these equations, it is clear that it becomes possible to calculate the critical bending moment that would cause the stem to break, when the radii of the trunk and the strength of the wood are known. This moment is then expressed as:

$Mcrit = I * s$

Where:

$Mcrit$ = the bending moment that would cause the stress in the outer fibres of the trunk exceed the compression-strength

I = the geometrical moment of inertia

s = the strength of the green wood as published by Lavers (1983) and other publications.

In accordance with the bending theory of the hollow beam, correction factors are employed in the case of cavities. These correction factors diminish the moment of inertia, and hence the critical bending moment. Finally, the critical force of the wind in the crown ($Fcrit$) is obtained by dividing the critical bending moment ($Mcrit$) by the lever (P).

- *Uprooting safety*

The present publication treats mainly the breaking safety of trees. The safety against uprooting is a subject reserved for a future study and publication. Nevertheless, should the urban tree in question have unsolved questions regarding its root stability, the following method can be recommended:

Wessolly & Erb (1998) state that with 0,25º of inclination of the stem base, 40% of the overturning moment is reached to tip the tree over. And this regardless of the type of soil, species and possible damages. This assumption enables the prediction of the critical wind load for uprooting in a relative simple manner.

At the time of this writing, a Dutch company has developed a very interesting pulling-test for the prediction of the root-stability (www.boom-kcb.nl). Their method recognises that the tree its root plate has a rather complex behaviour, even under a static and unilateral load. Here, the angle of the root plate and stem base is recorded in *several* directions by means of inclinometers and the load exerted by a cable-winch is fully controlled with a dynamometer. The wind load is simulated in order to reach a maximum inclination of the stem base of 0,25º. Once the critical load for uprooting is known, the wind speed which would cause failure of the root system can be predicted.

The proposals of the present publication, regarding the assessment of the breaking safety, could complete very well a pulling test as proposed by these Dutch experts.

Finally, Peltola et al. (2000) describe two different models to predict the failure of the root-system by wind-load analysis for forest trees (GALES and HWIND-models).

- *Torsion safety*

The formulas employed in the V model can predict the safety against torsion of a hollow tree, provided that the residual wall is perfectly closed and concentric. Although this idealised situation might seldom occur in urban forests, in some cases it can provide good extra information (in old but vital oak trees for example where the heartwood is feasted away by *Laetiporus sulphureus* or *Daedalea quercina*).

For tree species like *Eucalyptus paniculata* for example, Lavers (1983) publishes both for maximum shearing strength parallel to grain and resistance to splitting (cleavage) approximately the same proportion of ¼ of the maximum compression strength parallel to grain. Other *Eucalyptus* species demonstrate more benign proportions, but the former value (¼) is employed here to assume the shear and torque strength of the wood.

The torsion moment is calculated assuming that an off-centred wind load can hit the crown of the tree even if the crown is very symmetric. This is in accordance with the European Standards for signpost-boards (AENOR, 1998). Hence, for symmetric crowns, the mathematical model assumes a torsion lever equal to:

$Pt = Dc/4$
Where:
Pt = torsion lever in metres
Dc = crown diameter

Nevertheless, the load centre and the resulting torsion lever in eccentric crown forms can be calculated by means of a special software and introduced afterwards as one of the parameters of the V model. The critical moment regarding torsion of the closed residual wall, is calculated in the same manner as for bending fractures (see the explained above).

- *Breaking safety of stems*

The structural strength of codominant or damaged stems (e.g. cavities or the influence of woundwood rolls) can be assessed with this mathematical model.

The safety factor of the cross-section and necessary residual wall-thickness for the stems of the tree at a given height, regarding pure bending fractures or torsion, is calculated. Correction factors can be introduced to estimate the influence of rot, cracks, included bark or cavities (see the explained above).

Also for the assessment of branch fracture, the present publication might permit to employ more efficiently advanced technical resources. The combination of visual assessment, wind load analysis, proper cabling and common sense can do miracles.

- *Critical wind velocity*

When the critical moments both for bending fractures, torsion fractures and uprooting are known, it becomes possible to predict the wind velocity that would cause these moments, provided the above exposed model parameters are known.

The formula employed for calculating "V" is a logical consequence of calculating backwards the equation that defines the wind load in the crown.

The wind speed at the height of the centre of pressure in the crown, at which the above described failures would occur, is regarded as the critical wind speed for each of those failures.

- *Necessary residual wall-thickness*

The residual wall thickness that a tree needs in order to withstand any given static wind speed can be calculated if assumed that the hollow trunk behaves like a perfectly formed hollow tube.

The equation employed here for calculating the minimum residual wall thickness, if completely concentrically and closed, is in accordance with the bending theory of the hollow beam and is the same as employed for the SIA method (Wessolly & Erb, 1998):

$t = 0,5*dm*(1-(1-(100/SF))^{(1/3)})$
Whereby:
t = minimum residual wall thickness
dm = measured net diameter
SF = safety factor of the cross-section

- *Assessing the wind load in the crown cabling*

The static wind load in the crown, cabled branches and the cables can be assessed with the V model, which enables to design tree-friendly cabling installations to prevent several types of failure.

Discussion

By these analysis, a basic idea of the safety of a tree can be obtained although they can only be a small part of the stability assessment, since real trees and real winds do not always fit in mathematical models. It should also be acknowledged that these mathematics only offer a momentary insight in the tree's stability. This means that the processes that determine for how much time the prognostic will be valid, e.g. fungal infections, compartmentalisation, compensation and others, have to be incorporated in the assessment.

In the V model, the natural bending-frequency of the trunk is compared to its safety factor (regarding static wind loads), allowing a better orientation for the tree its stability. By introducing a bending-frequency, a rough and simple overview of the dynamics effects of the wind in trees are incorporated in the V model.

For example, the trunk of a tall Cupressus sempervirens can have a high safety factor regarding a simplified static wind load but, at the same time, a bending-frequency of 5,8 Hz. This means than that the effect of sway should be considered seriously since it might lower considerably the previously predicted theoretical safety factor.

It should be noted that, due to turbulence, the real dynamic behaviour of a tree can differ from that of computer predictions. It can both sway parallel and perpendicularly to the direction of the wind and produce a rotational movement. Even when the tree is perfectly symmetrically shaped.

According to James (2003), this assumption of the natural frequency implies a simplification, which calculates only the sway period of a bare trunk. In this way, the influence of mass damping is often ignored. The latter is the dramatic influence of swaying side branches that can prevent large sway amplitudes of the bare trunk.

According to AENOR (1998), the complete wind load analysis, as presented in this publication, is a simplified model which should only be employed for structures that have a dynamic coefficient of less than 1,2. If the structure would be more susceptible than this to the dynamic effects of the wind, then the formulae presented in this section are not valid. The dynamic coefficient can higher the theoretical bending moment in the tree with a factor >1, due to the interaction of the frequency of nearby wind gusts and the frequency of the structure.

One of the questions that has been remarked repeatedly by many practitioners/ students is that it is normal to obtain deviations from the reality, since multiple parameters have to be introduced in mathematical models/ computers (e.g. strength, aerodynamic drag, wind speeds, …) which might differ slightly from the real situation in which the tree is found. For example:

- the wind force increases with the square of the wind speed. In this way, small differences in the input of the latter will lead to significantly lower or higher safety factors (both breakage and uprooting) than the real stability of the tree. Doubling the wind speed means that the calculated safety factor falls down to one fourth!
- Within species, material properties can differ in the same cross-section of the same tree, between parts of the same tree or from tree to tree, and might easily deviate from the value published in strength tables (Lavers, 1983).
- The combination of both deviations from the real situation will lead to an even greater deviation.

Therefore, at the moment of this writing, mathematical equations, and even the most refined methods, can only pretend to be an *orientation* for real-life tree-stability assessment. Safety factors of 150-200% should be introduced to make up for the natural impossibility to target precisely the chaotic interactions between tree-structure, tree-geometry, material properties and loads.

If "V" is determined for a tree and its possible ways of collapsing, e.g. 92km/h, then it can be compared to the meteorological predictions or hurricanes that would occur with a high probability. Peltola et al. (2000) describe two similar models to predict the failure of the trunk and root-system by wind load analyses (GALES and HWIND-models) for forest trees.

4. What is the necessary residual wall thickness for a tree?

Introduction

The safety assessment of hollow trees has always fascinated arborists, and the criteria to be employed have led in Europe to severe public discussions in the professional scene.

Based on Mattheck & Breloer (1995), many tree-consultants state that the necessary thickness of the residual wall should not be below a t/R ratio of 0,3 to prevent shell-buckling, cross-sectional flattening, and hose pipe-kinking.

Wessolly & Erb (1998) on the other hand publish the opposite theory by which often *much* lower thickness is calculated and accepted. Their methods are based on the bending theory of the hollow beam.

A complete study was made on a 17,1m high eucalyptus tree (*Eucalyptus camaldulensis*) in Spain. In accordance with the above mentioned theory, which is also employed by Wessolly, the necessary trunk diameter and residual wall thickness where calculated for different tree-heights.

The results are contrasted throughout the present publication with criteria regarding torsion, shear, stress peaks, cross-sectional flattening and shell-buckling.

The above and the study of scientific literature suggest that the truth lies somewhere in the middle instead of in both extremes.

An example of tree-statics
- *Wind load analysis with the V-model*

The goal is to calculate the force that a hurricane would exert on the inspected tree. Strong gusts of wind are the main reason for the structural collapsing of trees, so they should be incorporated in the stability-assessment as well.

The power-law model is used to predict the wind speed at a given height and is presented by the following formula (Berneiser & König, 1996; Wessolly & Erb, 1998):

$$u^{(z)} = tu * u^{(g)} * (h^{(z)} / h^{(g)})^a$$

Where:

$u^{(z)}$ = wind speed "u" at a certain height "z" above ground level.

$u^{(g)}$ = maximum wind speed expected, not influenced by the roughness of the terrain.

$h^{(z)}$ = height above ground level at which a certain wind speed is reached (height of the analysis)

$h^{(g)}$ = height above ground level at which the maximum wind speed is reached.

a = surface friction coefficient

tu = turbulence factor

Different terrain categories are included with their corresponding roughness parameters. The surface friction coefficient (a) can range from 0,10 to 0,40 for urban areas with tall buildings. Hence, the influence regarding wind speed of nearby constructions, other trees or even short grass on untilled ground can be incorporated.

These mathematical models are used in the wind turbine and wind-engineering industries and it is known that the wind speed can be over-estimated for heights lower than 250m.

Nevertheless, the aerodynamic drag-factor employed for each tree might provide a good equilibrium in the calculations and final result.

The force that the wind exerts in the crown is calculated with this formula (Mattheck & Breloer, 1995; Wessolly & Erb, 1998; Niklas, 1999; Peltola et al., 1999; Gaffrey, 2000; Spatz et al., 2000; Ezquerra et al., 2001):

$F = ½*Cd*p*A* u^{(z)2}$

Where:

F = the force that a gust exerts in the crown

Cd = the aerodynamic coefficient describes the flexibility that the tree employs in order to diminish the force of the wind and is adaptable for each tree in accordance to his real crown density.

p = density of the air, which depends on the pressure and humidity of the air, temperature and height above sea-level.

A = the exposed area of the crown to the wind.

$u^{(z)}$ = wind speed "u" at a certain height "z" above ground level.

For *Eucalyptus camaldulensis* a aerodynamic drag of 0,25 was chosen. The wind-exposed area of the original tree was calculated with a specialised software. An air density (p) of 1,292 kg/ m³ was used, which corresponds with an air temperature of 0ºC and a standard atmospheric pressure (Windpower, 2003). In the computer model, the impacting forces and resulting moments are derived from simulating gusts of approximately 34m/s.

- *Material properties*

As with any engineering project, the material properties of the structure (here: the wooden shell) have to be known.

For this study the important data was strength (s). The standard deviation has been discounted to stay on the safe side for the stability-calculation.

The data given by Lavers (1983) for *Eucalyptus diversicolor* (s = 3,15kN/cm² (standard deviation discounted) and MOE = 1340kN/cm²) are employed in the V-model, since there is no data available yet for the Spanish grown *Eucalyptus camaldulensis* and *Eucalyptus globulus*.

- *Geometry*

The diameter and form of the trunk and the bark thickness were kept the same, just as wind speed parameters, material properties and others. In the data-input of the mathematical model, only the height and corresponding vertical crown area varied.

Medium diameter of the trunk: 66,5cm

Medium bark thickness: 1,8cm

- *Thickness of the residual wall: bending theory of the hollow beam*

The residual wall thickness that a tree needs in order to withstand any given static wind speed can be calculated if assumed that the hollow trunk behaves like a perfectly formed hollow tube.

The equation employed here for calculating the minimum residual wall thickness, if completely concentrically and closed, is in accordance with the bending theory of the hollow beam and is the same as employed for the SIA method (Wessolly & Erb, 1998):

$t = 0,5*dm*(1-(1-(100/SF))^{(1/3)})$

Where:
t = minimum residual wall thickness
dm = measured net diameter
SF = safety factor of the tree

Results: necessary trunk diameter and residual wall thickness

With the help of the following diagram, the arborist will be able to appreciate better the analysis of the breaking safety of this *Eucalyptus camaldulensis*.

The safety factor (S) of the tree and the necessary thickness of the wooden shell is determined. This in order to be safe against gusts of 117 km/h if growing in open field and surrounded by low shrubs.

The safety factor of this eucalyptus can be calculated with the following geometrical formula (Wessolly & Erb, 1998):

$S = 100 * (dm/dreq)^3$

Where:

S = safety factor of the trunk at 1m height, if completely undamaged and sound

dm = measured net diameter of the tree (diameter without bark)

$dreq$ = required diameter of the trunk if completely sound and according to the theory of elasticity.

The required diameter and residual wall thickness at 1 meter height, for several tree-heights, can be read from the table. These results are a function of the hurricane moment, compression-strength and cross-section modulus:

height in m	required diameter in cm	required t in cm	theoretically required t/R
10	24,8	0,65	0,02
11	27,5	0,9	
12	30,3	1,22	
13	33,1	1,61	
14	35,9	2,09	
15	38,8	2,68	
16	41,7	3,41	
17	44,6	4,29	
17,1	44,9	4,39	0,14
18	47,5	5,38	
19	50,4	6,73	
20	53,3	8,48	

For example: if this eucalyptus tree has a net diameter of 62,9 cm and a height of 17,1m then the minimum required diameter is 44,9cm. The safety factor will be approximately 275%. This means that the longitudinal stress in the marginal fibres of the sound trunk, during gusts of 34 m/s, would reach a value of 1,14 kN/cm². This is slightly more than one third of the assumed compression-strength.

In this example, a value of 275% means that the tree needs a minimum residual wall thickness of 4,4cm according to the formula $t = 0,5*dm*(1-(1-(100/SF))^{(1/3)})$, if the shell would be completely closed and concentrically. Finally, a safety *margin* of 200% should be incorporated, also for the required thickness of the residual wall since the values of Lavers (1983) represent plastic failure of the wood-probes.
If the safety factor is higher than 100% the trunk can be damaged up to some extent without being unsafe. If value is lower than 100%, the tree cannot permit any structural defect. In this case, its crown should be reduced to heighten the safety. The extend to which the crown has to be pruned can also be estimated with the mathematical model.

Discussion
The study of specialised literature suggest that the different types of failure of the residual wall depend mainly on parameters like stiffness and strength of the wood in different anatomical directions (wood is orthotropic), geometry of the cross-section and different loads.
Hence, fixed t/R assessment limits should be approached carefully. But:
Neither should the residual wall always be as thin in a real tree as predicted mathematically with the formula employed in accordance with the bending theory of the hollow beam.

It is clear that the theory of the bending theory of hollow flexible beams could reach *indefinitely* low t/R ratios, since it is nothing more than just a geometrical formula. This can be observed in the table for the 10m high tree that, theoretically, would need a residual wall thickness of 0,65cm (t/R 0,02). Which is clearly unacceptable. Logically, the theoretical result obtained by this formula cannot be applied without limits in real trees! For the 17,1m high eucalyptus tree, the bending theory of the hollow beam states that the example tree needs only an t/R of 0,14 (fully exposed in open field, in the city it would be even less).

Now: *If the shell really experiments only pure bending stresses, this would be enough, but care should be taken to exclude other types of (treacherous) collapses. Amongst them are shell-buckling, torsion, cross-sectional flattening, shear or the combination of these and other mechanical behaviours!*

The reader has to be aware that mathematical models, measuring devices and methods are *only* to be used as an *aid* for determining the stability of trees. Hence, an assessment based *solely* on the results obtained by the latter is inadequate.
Given the relatively small importance that can be given to mathematics in real-life tree-assessment, they can only pretend to be a good orientation.

In the publication of Wessolly & Erb (1998), a diagram of Spatz is shown where it can be concluded that primary failure in the compression side occurs with lower loads than cross-sectional flattening *if* the t/R is higher than 0,0625 approximately.

This means that, regarding the risk of cross-sectional flattening of a *perfectly concentric and closed residual wall*, the calculations for the residual wall thickness employed in the present study could then be trusted if the tree has a higher t/R than this.

Nevertheless care should be taken, since with open or irregular cavities and cross-sections, and/ or the complex combination of (wind)loads, this ratio might not be applicable, for the tree would collapse without obeying the bending theory of the hollow beam.

It has to be said that if we focus only on the failure of the thin residual wall itself, that this might be treacherous and give a wrong view about the safety of the tree. The thin residual walls might collapse due a combination of old pruned-branch-holes and shear-stresses (Mattheck & Breloer, 1995).
And, for example, thick and heavy branches might break out of the residual wall and cause severe damage while the shell keeps up standing!

So, what is the necessary residual wall thickness of a tree?
Most of all seems to depend on: *common sense*.

5. Visual assessment

According to Gordon (1999), not only the thickness but also the composition of each component that bears the load, is dimensioned in a considerable measure by the use that it will be given and by the forces it will have to withstand during it's existence. By this, the proportions of the living structures are designed to optimise their strength. According to the author of the present publication, this statement might define beautifully one of the main components of the stability-question of trees.

The basis for the author's protocol
The SIA method (Wessolly & Erb, 1998) calculates the diameter of a tree trunk and the necessary residual wall that a given tree needs to withstand wind gusts of 32,5 m/s. The IBA method (Reinartz & Schlag, 1997) describes the interaction of mycology, vitality and stability. This visual method combines the visual detection of wood-decaying fungi, sometimes long before the first fruiting body appears, and the SIA method.

At the current time, Prof. Dr. Francis Schwarze is investigating the interaction between the defence mechanisms of a tree and the strategies that decay fungi employ to overcome the former.
The *status quo*, i.e. the current condition of decay in a tree, can be assessed macroscopically. The above described methods can offer a static recording of this current condition. Nevertheless, the *dynamics* of the interaction, *and hence the future safety of the tree*, can only be assessed microscopically. In this way, for the first time, it is possible to incorporate a prognosis regarding the *future* development of decay, and invasiveness of different decay fungi, in the sapwood of trees.

Finally, in "The Body Language Of Trees" (VTA method, Mattheck & Breloer, 1995) a description of possible failures by fracture can be found, which is a delicious and obliged literature. The description is taken by the author of the present publication as the point of departure, until the contrary can be demonstrated unquestionably.

Wood-decaying fungi

In the vast majority of current literature it is recommended to fell the tree when fruiting bodies of a certain size or certain quantity appear . But to the author of these lines, this seems to be a wrong perspective that will only lead to the wrong answer.

The presence of wood-decaying fungi like *Ganoderma sp., Meripilus giganteus, Kretzschmeria deusta, Inonotus hispidus* or *Laetiporus sulphureus*, does not mean *ipso facto* that there is a strength-loss in the wooden body. Premature conclusions should be avoided, since the presence of fruiting bodies is only an *indication* that points towards a diminished structural strength. But it is not an evidence.

A living tree is not a passive lifeless piece of wood; either it oxides as if it was a helpless old iron tube.

The fact is that many times, a vital tree can be capable of establishing an equilibrium between the formation of compensation wood and the destruction of the material caused by the fungus. Under compensation wood is understood here: laying down thicker annual rings where higher strains and stresses are detected by the cambium. According to the IBA method, the intact sapwood and cambium guarantee that the tree can grow in diameter and compensate in this way the destruction caused by the wood-decaying fungus. Externally visible symptoms in the bark usually appear when the growth of the annual rings and bark is affected. Apart from these symptoms, damages, related to the low vitality of the tree due to extended infections, will generally be seen in the crown (Reinartz & Schlag, 1997).

It is also possible that most wood-decaying fungi have serious difficulties to penetrate the sapwood and infect the cambium when the tree is vigorous, due to the highly efficient living parenchyma-cells. So vitality, growth in diameter and bark condition are critical factors when assessing the stability of a fungus-infected tree.

The wood-decaying infection, and its effects, should be understood in the global context of each tree.

Assessing the breaking safety of hollow trunks

The fact is that in many old and thick, well compartmentalising trees, the thickness of the sapwood can be estimated and that this ring of sapwood can be enough to bear the load of the wind (the necessary wall-thickness is calculable with the wind load analysis).

But how can we know in a *visual* way how much strength loss the wood-decaying fungi have caused?

The fourth wall of the CODIT-model (Shigo, 1986) can be a very good barrier making it very difficult for fungi to penetrate the sapwood. And if the tree is vigorous the parenchyma cells are very efficient to compartmentalise infections. Many wood decaying fungi, like *Laetiporus sulphureus* for example, might not be able to infect the sapwood in vital trees. This is the wood that gives the main structural strength to a tree.

So if we know the interaction between fungus, host and vitality we can estimate if that ring of wood is intact or structurally weakened.

If that area is intact, we can assess if the stem is safe against breaking, counting with this ring and by means of the calculations according to the author's protocol. The thickness of the sapwood is estimated for each species and compared with the calculated thickness that would be necessary to withstand the force of a storm in its crown. The latter can be done with the SIA method or, in this publication, with the V method. The thick wound wood-rolls around an open cavity can highten considerably the strength of the shell, not only because of the optimised geometry but also due to a stronger and stiffer, higher quality, wood.

By sounding with a hammer it is possible, with experience and practice, to determine the point where the wall is thinnest (for practising, removals of hollow trees can be very good opportunities!). Another method is to compare the sounds made in the defective area and nearby healthy cross-sections. In that way higher precision can be obtained to find the most interesting spot.

When assessing pure bending fractures, one possibility is to assume that the residual wall is equally thin all the way round the tree in order to stay on the safe side. This proposal accords beautifully with Shigo's model of compartmentalisation which assumes that the decay can, at worst, occupy all the wood that was formed before the barrier-zone was formed! For open cavities, the load-bearing capacity can be estimated with the help of correction factors. Sounding with a hammer is not always reliable, but in many old trees it is quite easy to estimate if the shell is thicker than the necessary t/R calculated.

The body language of the tree

The *body language* of the tree outdoes every instrumental diagnosis. The bark tells us about the tree's vitality and stability. Growth cracks in the phloem (inner bark) also point towards its phase of vitality. Certain anomalies in the tree's skin enable sometimes to determine the fungi-species and the extent of the infection, long before the first conk appears. This means that the tree's stability can be evaluated with still a nice time margin before it "unexpectedly" would fall over.

A vital tree can also compensate an internal weakness.
Symptoms like a swollen butt ("Elephant foot") or protuberances on the stem do not necessarily mean that the tree has a problem. They don't have to worry *ipso-facto.* Symptoms of adaptive growth like bulges, swellings or bottle-buts do not mean *persé* that the tree has a problem. True, the problem might have been countered already by this adaptive growth!
Compensation or adaptive growth is all about geometry and material. Just as in civil engineering, the tree can obtain a better structural efficiency laying down annual rings as far as possible from the "Neutral Fibre". In this way material, cost, is saved when the inner material – heartwood for example – is eliminated, since it plays a smaller role regarding stability than the outer ring.

A tree can compensate a defect if it has a good vitality and if the higher strains or stresses are to be detected by the cambium (Shigo, 1986; Mattheck & Breloer, 1995; Reinartz & Schlag, 1996; Wessolly & Erb, 1998).
Nevertheless, a tree might not always be vigorous enough to lay down this extra wood. Maybe even the wood quality – strength and stiffness – may not be as good as would be necessary if the tree lacks vitality.
Some types of structural collapsing cannot be foreseen by the tree itself. And it is possible that strong temporary gusts do not lead to compensation either, although they might be the reason for failure.

If the symptoms are correctly interpreted against the background of vitality, reaction capacity and safety factor, then a correct assessment of a damaged tree can lead to a more efficient use of apparatus.
The tree's own language has to find a hearing!

Assessment of vitality

It is suspected that a visible loss of primary growth of the twigs (upper part of the crown) are directly related to changes in the root system or wooden body (Mattheck & Breloer, 1995; Reinartz & Schlag, 1997; Wessolly & Erb, 1998; Roloff, 2001).
Therefore the assessment of the growth pattern of these twigs, and the resulting crown structures, is of vital importance when assessing the stability of a tree.
Roloff (2001) describes how the vitality of a tree (Middle-European species) can be classified in 4 phases. This author states that the growth-patterns of the last 4-14 years will draw the real biological situation of our assessed tree.
Temporary losses of vitality due to a drought-year or mild pests do not seem to have a great effect on the tree's overall biological situation. But they do lead to lesser growth or smaller or less greener leaves in that small period. Mistakenly, the tree's long-term reaction-capacity would be assessed as diminished although it isn't. A healthy tree can still catch up with life's troubles with a loss up to 30% of it's green area. So one- or two-year crown appearances might finally mislead the stability-assessment.
The assessment of the vitality by this method is generally reproducible by a third party, so objectivity and certainty is now better attainable in the vitality assessment.

This method has been transferred experimentally by the author of the present pages in Mediterranean species like *Eucalyptus* spp, *Celtis* spp*., Tipuana* spp*.,* and others.
The evaluation of the crown structures, laid down by the growth patterns of the uppermost twigs, enables to classify the tree's vitality. By this, its capacity of reaction against wood-decaying fungi can be assessed.

Conclusion about visual assessment

An expert visual assessment generally permits to recognise damages caused by wood-decaying fungi, sometimes before the first fruiting body appears, and to estimate their influence regarding tree-stability. In this way, many accidents can be prevented in time.

An expert visual assessment is the most powerful available instrument. And probably the most noble one.

6. Behaviours of the wooden body
What is the real reason that leads structures to their failure?

Introduction
In the case of many old trees, the trunk, if undamaged, can be many times thicker and safer than necessary to withstand a hurricane. The stress, induced by the hurricane load, would stay far below the compression strength of the marginal wood-fibres. Theoretically, and according to the bending theory of the hollow beam, these old trees would need a very small residual wall thickness to withstand gusts of 117km/h.

Nevertheless, this can only be meant as an *orientation* for the assessment, since very low t/R ratios can lead to different types of collapse due to the flexibility of the hollow shell.

The calculations for stem safety against breakage as employed in this publication and current tree-statics, are based on the theory of the elastic cantilever beam. A number of authors who examined stem breakage are adamant regarding the usability of stem failure calculations only under ideal circumstances. The interpretation of the trunk of a tree, as if it was a homogeneous cylinder, would allow the use of relatively simple mathematics.

But the *very common* structural problems that deal with torsion, shearing stresses, delamination or structural failure may not obey to this theory, at least in a tree, and should absolutely be taken into account.

But then, how can tree-failure due to torsion, delamination, shear, or the propagation of cracks and defects be predicted? In "The Body Language of Trees" (Mattheck & Breloer, 1995) very good orientations are offered about how a thin-walled or even a defect-free tree can fail. Some of them are mentioned here and should be taken into account to temper the mathematical calculations that are based on the bending theory of the hollow beam.

According to Mattheck & Breloer (1995), the majority of the following failure-components *cannot be predicted* by means of the pulling-test (elastomethod, Wessolly & Erb, 1998):

Fractures caused by bending stresses:
- Cross-sectional flattening
- Shell-buckling of closed cross-sections
- Local cross-sectional flattening (hose-pipe kinking)

- Shell-buckling of the walls of open cavities
- Harp-tree fractures

Fractures caused by shearing stresses:
- Basal bell fracture: shear cracks and delamination and local cross-sectional flattening
- Fractures at wound spindles and knot holes

Fractures caused by torsion:
- Opposing the direction of helical growth
- Opposing internal helical cracks (ribs!)
- Rotary fractures caused by flailing branches (complex combination of forces)

Splitting due to transverse stresses:
- The hazard beam (so many in *Pinus pinea* trees for example)
- Root-buttress delamination
- Included bark

Some criteria found in that work can be counterbalanced with the publication of Wessolly & Erb (1998).

A brief description of some common mechanical behaviours

- *Summer Branch Drop*

It is suspected that Summer Branch Drop – sudden fracture of branches on still and hot afternoons - occurs partially due to stretching and relaxing of the pre-tensioned fibres (Mattheck & Kubler, 1995; Wessolly & Erb, 1998). This pre-tensioning of the fibres can heighten the resistance against compression-loads even up to a 140% of the original compression strength (Archer, 1996).

The combination of warming up the fibres, which causes relaxation of the latter, and evaporation, which could influence pre-tensioning, might reduce the load-bearing capacity of those fibres considerably.

Also the compression loads can be quite considerable in heavy, leaning branches and, at least in dry wood, creep-rupture can occur if the duration of load is long (Wood Handbook 1999).

The stress caused by the weight of the branches would exceed the compression-strength of the wood, leading to sudden limb drop.

This phenomenon is very common in Spain in tree-species like *Eucalyptys spp., Celtis spp.,* and *Ulmus minor* in the hot and long days of august. To the best of the author's knowledge, in many cases the risk can be lowered considerably by visual assessment and specially designed cabling configurations. Maybe also by an extra addition of water in periods of drought and high temperatures.

- *Euler buckling*

Slender trees can fail by forming a large wave along the length of their stem. In reality, the tree "deviates itself" from the load and this type of failure seems to depend principally on its modulus of elasticity, height of the tree and the moment of inertia (Gordon, 1999).

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.

Usually the veteran trees do not represent this risk, as a result of having a thick trunk in comparison with their height. There are of course exceptions to this rule, e.g. slender trees and palms.

If the radius of the pipe is big and the wall thin, it can happen that the pipe is safe against Euler buckling or the large wave; but that it fails due to local folding of its skin. One of the ways in which it fails locally is called the "Brazier buckling. (Gordon, 1999).

The same might be true for trees.

- *Brazier buckling*

According to Gordon (1999), the system of escaping that the structure uses, will depend on 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 that get folded because of being too flexible. The "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).

Mattheck & Breloer (1995) seem to refer to this failure as "shell-buckling" and transfer it to a hollow tree, adding that this type of failure occurs with extraordinary thin shells under bending.

The author of this study observed similar behaviours in the open hollow trunk of a eucalyptus tree with pulling-tests (Elastomethod, Wessolly & Erb, 1998). The different deformations of the damaged structure during a wind load simulation were recorded with very sensitive measuring instruments (Young's modulus sensors).

It was astonishing to observe how the shell opened *sideways.* These *perpendicular deformations* were much higher, with the same pulling-force, than the longitudinal stretching of the marginal fibres. The pure longitudinal compression in the trunk was transformed in stresses perpendicular to the fibres due to the force-flow deviation caused by the open cavity.

This behaviour seems to suggest that this eucalyptus would fail due to shell-buckling of the wall of the open cavity and delamination. Which means that *its real structural strength* could be lower than the one predicted with the bending theory of the hollow beam.

- *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 datepalm (*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 (Elastomethod, Wessolly & Erb, 1998). With Young's Modulus sensors *extraordinary* deformations were recorded due to the sliding over each other of the two halves of the stem. 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.

- *Concentrations of stress*

According to Gordon (1999), the traditional way of calculating the safety of a structure ignores virtually stress peaks.

The force flow deflection around round holes can cause an increase of stresses by a factor of three (Mattheck & Breloer, 1995; Gordon, 1999). The effect, nevertheless, is much greater in not-so-round defects and at the end of a crack.

In this way it could be that the resistance against breaking as calculated according to the simple bending theory of a beam seems satisfying, although the stress increases dangerously in some points.

The tree-structure would start to fail from here on without worrying too much about the mathematical predictions as according to the simple bending theory, e.g. due to crack propagation and deformation energies.

"The locally thickened growth rings lead to a decrease of stresses in the edges of a wound." (Mattheck & Kubler, 1995).

A successful compensation - adaptive growth - could be the solution in this case, although it is not known if a tree can react against temporary loads (sudden gusts, not a continuous breeze). Neither does the tree notice some mechanical defects or stresses.

- *Torsion and the complex combinations of forces*

"Así mismo, no es sorprendente que [la naturaleza] evita la torsión como la peste" (Gordon, 1999).

In the case of trunks hollowed by fungi like *Laetiporus sulphureus* or *Daedalea quercina,* a concentrically closed residual wall can sometimes be found. The safety against fracture by torsion can be estimated in these cases, by means of calculating the torsion forces exerted by the wind and mathematical formulae. A closed residual wall would be a very efficient "torsion box" to resist torsion and shear stresses. But *open* shells, just as the convertible old-timers from before the Second World War (Gordon, 1999), are not as stable against this phenomenon.

The prediction of fracture by torsion or other collapses in the real life, is very difficult due to the infinite morphological variations found in trees. Several authors describe how a tree, or parts of it, can fail due to the complex combination of flexion, torsion, his own weight, natural oscillation, open cavities and so on.

This is why the failure of a tree is not always predictable, even with the absence of structural defects.

- *Basal bell fracture*

According to the SIA method (Wessolly & Erb, 1998) and the V-model, a certain tree might only need, theoretically, very thin residual walls to withstand a hurricane. Or the measurements of the fibre-elongation with elasticity-sensors during a wind simulation, might predict that the hollow buttress would be safe (Elastomethod, Wessolly & Erb, 1998). According to the theory that supports the last method, the structure would fail when the pure longitudinal deformation of the wood fibres exceeds the elastic limit.

But then the tree might fail without obeying these methodologies, simply because the latter do not contemplate torsion, shear or delamination, or, the *very common* reasons that can lead to the failure of a tree.

In the case of butt rots the tree may fail due to a combination of shear and delamination. Even with perfectly unilateral wind loads, high stresses can occur where the thin residual wall meets the root buttress.

This behaviour was observed during a pulling-test (Elastomethod, Wessolly & Erb, 1998) in Spain. There, a crack was caused unexpectedly in the hollow buttress of a plane tree under the simulated wind load. Afterwards, it was concluded that the tree it's structure failed even *before* the estimated point of material failure (Detter, 2002).

This means that the tree was *less* safer than calculated with this method and that it would have failed with a lower wind load than predicted.

When the mathematics calculate that only a low t/R is needed in a certain tree – even being a very good orientation - care should be taken to exclude the possibility of delamination of the residual wall nearby the root flares.

The basal bell fracture seems to gain importance when the ratio between residual wall and radius of the cross-section gets very small. This, again, will be true in the idealised case of perfectly closed, intact and concentrically cavities. Nevertheless, open cavities or highly curved root buttress for example might require a higher t/R.

It is possible that common sense and a good vitality – and hence a high quality repair growth - might be the key, even in the future, to solve this question.

7.   One of the secrets of current tree-stability assessment

Merely from observation during tree-pruning and tree removals, it seems to be clear that the heavy top-end weight of the crown of several tree-species probably add significantly to the swinging movements.

This is quite clear for example in tall *Cupressus sempervirens* or *Aesculus hippocastanum* when bearing their fruits. The reader can experiment the difference when swinging back and forth a branch of a *Platanus* spp. with leaves and afterwards a branch of a *Pinus pinea* with cones.

Probably also the MOE (Modulus of Elasticity) of the material from which the branch is made will influence this phenomenon, apart from its weight and centre of gravity, its form or the presence/ absence of leaves.

Naturally, and as with other methods and models, these factors do not fit easily in mathematics and should be taken into account during the visual stability assessment.

It is true that in the V-method, the bending-frequency (in Hz) of the bare trunk can be calculated from the height and circumference of the trunk and the frequency factor. But then the crown form (swinging "Lion-tails" for example), unequally positioned crown surfaces, crown weight and the centre of gravity, the form of the trunk (if it's not as straight as a pole), previous structural defects, root/soil interactions and other variables upset the calculations (Coder, 2000).

Even when leaving aside off-centred gusts and other chaotic behaviours of the wind.

Therefore, real movements of the tree under wind loads can vary highly from the ideal back-and-forth situation.

On the other hand, dangerous sway motions in trees can also be minimised due the way in which the branches counteract each other by complex swaying (James, 2003). The latter might especially be the case when the drag area is relatively evenly distributed over the whole tree.

Relatively flexible structures – structurally too damaged tree-parts for example – might not obey the mathematical calculations. This is also the case with too slender trees.

The swinging can considerably lower the safety of a tree and, to the best of the author's knowledge, it does not fit easily in mathematics.

In consequence, slender trees (some pine-trees for example) and palms, sensitive to swinging, require the contemplation of this component.

Here is an excerpt of "Structural Engineering Systems Design" (Sparling, 1997) that explains part of the mystery that involves tree-stability assessment, although it lays out about buildings:

"It is important to recognise that wind pressures, and hence wind loads, are not static in nature but fluctuate constantly. The dynamic nature of wind loads can, in fact, excite resonant motion in slender or flexible structures, generating dynamic responses that can be far larger than those that would be produced by equivalent static loads.
For low, relatively rigid buildings, on the other hand, the dynamic response is less significant and the design can be safely based on equivalent static loads."

So to the author of the present publication, one of the secrets of current tree-stability diagnosis is: a wind load analysis can safely be employed in relatively low and rigid trees.

8. Palms and stability

"En todo lo natural hay un código y cada código tiene su clave".

In the wood of a two-cotyledon tree, the fibres are well glued together, reducing the risk of the fibres sliding over each other (Mattheck and Breloer, 1995). The geometry and the material many times behave in a coherent manner, whereby one of the main components of its load bearing capacity is the pure longitudinal compression-strength in the outermost fibres. This enables the assumption that its breaking safety can be calculated by means of the simple bending theory of a hollow beam.

Mere observation of fresh cut pieces of the trunks of palms, suggests that the fibres of the palm-trunk do not seem to be glued together as good as the fibres of a (not monocotyledonous) tree.

Therefore, the mass of palm-fibres does not seem to behave as coherently as the wood of a tree. The fibres can 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 tree. Pulling-test experiments on palms in Spain lead 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 as it was a massive wooden beam.

The respectable experience of specialists in palm-care points towards the same direction.

Therefore, it is possible that the breaking safety of a palm is not predictable with the bending theory of a hollow beam and that safety factors of the trunk cannot be given. Neither the necessary residual wall thickness, as according to the last theory, could be calculated then.

At the current time, the basics of a possible solution have been developed by the author of the present pages for the stability analysis of palms.

A proposal for the stability analysis of palms

Little investigation has been performed about the structural behaviour of palms. Hence, the only fixed rules that can be given until now are intuition, experience and common sense. Nevertheless, the author of the present publication developed the here presented proposal for the stability-analysis of palms.

In this protocol, visual palm assessment is combined with mathematics for the analysis of the wind loads and *bending-frequencies of the palm trunk*. With the V model, both the bending-frequency of the palm-trunk (in Hz) and the wind load in the crown are estimated according to the Eurocode 1 (AENOR, 1998). The equations for the analysis of the wind load and bending-frequency are described in the structure of the V model. The results are combined with a rubber mallet to detect structural defects.

Within the limits of the present model, the following guidelines could be given:

- A high bending-frequency in combination with a sound structure gives a low-risk level.
- A high bending-frequency in combination with structural defects should demand attention and a closer look to the situation.
- A medium frequency cannot allow damages.
- Finally, interventions should absolutely be taken to guarantee the traffic-safety if the palm-trunk has a low frequency.

The closer the natural frequency of the palm gets to the frequency of gusts of wind (1 Hz for example), the lower its stability. For example, a sound *Phoenix canariensis* that has a bending-frequency of 13,4 Hz might present very little risk.

On the other hand, a more slender *Phoenix dactylifera* can signify a higher risk due to the combination of a half as high bending-frequency and higher wind loading. If this palm has a rot, for example, then a more detailed investigation should be undertaken.

The limits are multiples and obvious: much more investigation is required to establish acceptable levels of bending-frequency and to find the correct frequency factor for palm trunks.

The aerodynamic drag factor has to be estimated and is not published yet. Finally, independent scientific investigation is necessary to evaluate the value of the present proposal.

Within this method, the inspected palm can be cabled to other palms, trees or structures. In this case, the wind load in the crown should be estimated. The result enables a more efficient design of cabling-configurations, cable strength, cable elongation and load-transfers.

Phoenix canariensis. Casa Alegre. Terrassa, Cataluña.

(Load analysis in accordance with Eurocode 1, Part 2-4 + bending frequency of the stem.)

Height: 14,15 m

Bending-frequency: 13,4 Hz

Estimated wind load (F)
in the crown during gusts:
3,66 kN (373,32 kg)

If the bending theory of a
hollow beam would be *feasible*:

Safety factor at 1m
height: 394,8 %
t required: 2,5 cm
t/R required: 0,09

9. Protocol

Biology is one of the most important components of the protocol presented in this publication.

The ring of sapwood is what gives the main structural strength, regarding for example torsion and bending, to a tree.

Therefore, if symptoms are detected that point towards damages in the sapwood, e.g. due to wood-decaying fungi, then it is possible that the cross-section suffers an important loss of its load bearing capacity.

If the sapwood is damaged, then the transporting capacity can be diminished. This can lead to a loss of vitality. This loss of vitality usually produces symptoms in the upper crown structures and the bark. Other symptoms, like growth depressions or dead areas in the bark also can point towards serious structural damages in the ring of sapwood.

Therefore, it is possible to take as a starting point the state of the crown and bark, instead of focusing immediately on conks or hollows. This method can be a very good orientation, in order to assess visually if there is an important loss of structural strength, caused by fungi, in the wooden body.

Afterwards, the calculation of breaking safety factors might give information about the importance of this strength loss for the individual tree (V method or SIA method).

Thereby it is absolutely necessary, by means of Visual Tree Assessment (VTA method), to take in account the failure components that cannot be foreseen by mathematics.
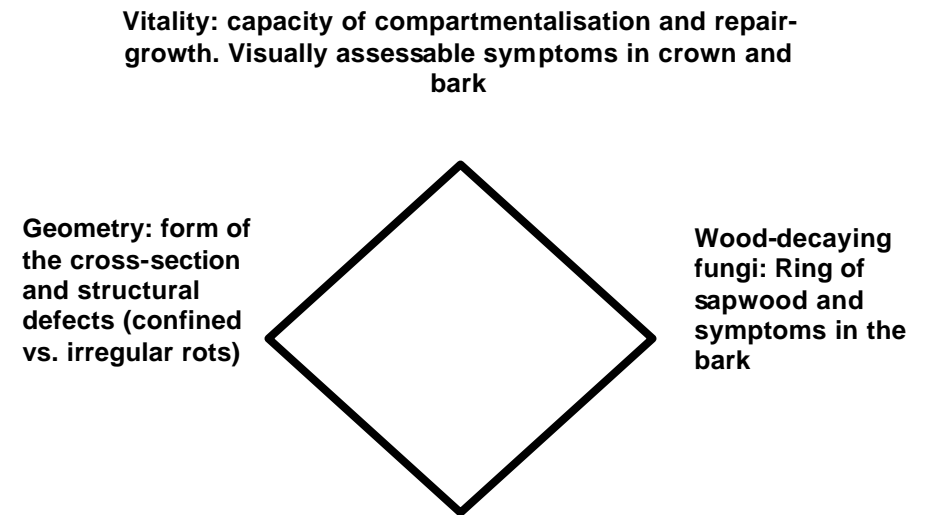
The growth pattern of the upper crown structures and growth fissures in the bark are a visible measure for the biology of the individual tree and are an orientation for:

- the transport and vessels and hence the biological and structural state of the sapwood
- the efficiency of compartmentalisation of decay
- the efficiency of compensation growth
- a long term prognosis instead of a momentary recording

The protocol offers tree-specialists a carefully designed process, including the following components:

- The wind load in a tree is analysed in accordance with international engineering standards and scientifically accepted mathematical procedures. For breaking safety, the necessary residual wall thickness and safety factor of the tree its trunk and stems is calculated.

- The reasons that cause the failure of a tree are very complex. This complex combination is broken down in its theoretical components. First the components have to be understood and their influence in the tree assessed. Amongst them, the most important seem to be: torsion, bending, shear, oscillation, crack-propagation and stress-peaks in the wooden body, fatiguing of the anchorage roots (!), architecture and stiffness of the load-bearing root system, crown clashing and real wind behaviours.

- The results of the wind load calculations are compared with the analysis of the stability-components that are relevant for the assessed tree. The usefulness of the theoretical calculations has to be tested against the real tree-behaviours.

- The interactions between host, fungi, vitality and tree-geometry have to be understood. Regarding biology, both compartmentalisation – the formation of boundaries that slow down the progress of wood-decaying fungi – and compensation – position, amount and quality of the repair growth - are directly correlated to the tree it's vitality.

- After all, the continuous thread throughout the protocol should be *common sense*.

The following components interact continuously and have to be assessed, not as solitary, but as links of a complete chain:

Vitality: capacity of compartmentalisation and repair-growth. Visually assessable symptoms in crown and bark

Geometry: form of the cross-section and structural defects (confined vs. irregular rots)

Wood-decaying fungi: Ring of sapwood and symptoms in the bark

Mathematics: V method (Sterken, 2004) and SIA method (Wessolly & Erb, 1998). + Reasons of mechanical failure and its visual assessment (VTA, Mattheck & Breloer, 1995)

Many times, when the vitality of a tree is good enough, the inner geometry of the ring of sapwood can have a clearly defined form and a coherent mechanical behaviour. This might permit to assess its breaking safety with the combination of a wind load analysis and the bending theory of a hollow beam.
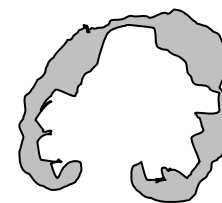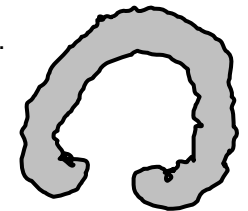
On the other hand, when the tree is not vital enough, the processes of compartmentalisation and compensation are not as efficient regarding extending rots. This can result in a irregular and treacherous geometry that might not behave as according to the bending theory of a hollow beam. Here, visual assessment will be even more important to employ more efficiently advanced technical resources.

Examples

- *Eucalyptus camaldulensis. Parc Sant Jordi, Terrassa, Cataluña.*

Vitality: excellent
Height: 17,1 m
Bending-frequency: 10,1 Hz
Safety factor for bending fractures: 275,7%
Required residual wall thickness: 4,39 cm

There are no symptoms that point towards a diminished transporting capacity. The sapwood is in a very good state and the large wound is very well limited by vigorous woundwood.
Possibly, and due to good quality compartmentalisation and compensation, the mechanical behaviour of the residual wall is very coherent. The tree its breaking safety can reliably be assessed with the theory of elasticity and visual assessment.
The excellent vitality (biology) can counter the confined cavity (stability) during several years more.

- *Eucalyptus globulus. Parc Sant Jordi, Terrassa, Cataluña.*
Vitality: very low, although the emergency-growth, stimulated by topping, provides a misleading view of the tree its vitality.
Height: 14,7 m
Bending-frequency: 16,3 Hz
Safety factor for bending fractures: 1224,03%
Required residual wall thickness: 1,09 cm

Theoretically, this tree would need only *1,09 cm* of residual wall to withstand hurricanes of 117 km/h. The bending-frequency suggests that the influence of dynamics is very low.
Hence, these mathematics predict that the tree is extremely safe.
Nevertheless, in this tree, these results cannot be taken blindly as the "happy" result. Several symptoms suggest a diminished transporting capacity. Hence, he sapwood might not be in a good state, what would lead to an important loss of structural strength. The large cavity is not clearly limited by vigorous woundwood.
Therefore, and due to the irregular and not clearly confined rots, the hollow trunk might not behave as an ideal and coherent hollow beam.

Side-ways shell buckling due to the large openings and thin shell (see Matheck and Breloer, 1995) might occur instead of obeying the bending theory of a hollow beam. Probably also with much lower wind speeds than predicted. The pulling-test experiment that was performed in this tree also suggested the latter.
Thus in this case, visual assessment, a profound knowledge of the possibilities and limits of the mathematics, a profound knowledge of mechanical reasons of failure and a good dose of common sense, will be vital to achieve the most reliable diagnosis.

- *Statics vs. dynamics*
In the V model, the natural bending-frequency of the trunk is compared to its safety factor (regarding static wind loads), allowing a better orientation for the tree its stability.

The following examples are presented here:

Eucalyptus camaldulensis	**Cupressus sempervirens**
Parc Sant Jordi	Parc Sant Jordi
Static safety: 275,7 % t required: 4,39 cm	Static safety: 217,4 % t required: 3,47 cm
Bending frequency: 10,1 Hz	Bending frequency: 5,8 Hz
= the static safety factor and theoretically residual wall thickness can be a very good orientation	= the static safety factor and theoretically residual wall thickness cannot blindly be trusted due to the high influence of natural oscillations

10. Tree-saving interventions

"…while remembering that the object is to retain the tree for as long as possible with the minimum risk." (Mattheck & Breloer, 1995)

The possibilities for keeping a tree as long as possible with a acceptable risk level are *virtually limitless*.

Amongst them, the beautiful art of cabling trees is one of the most interesting ways of lowering the risks of tree damage. Not only the theory – the contemplation of the laws of gravity, angles, mechanical energies and transfers of loads - but especially the practice is very gratifying.

The protocol of the author employs several methods for designing crown cabling configurations.

First of all the goal of the cabling has to be determined since, for example, the prevention of breakage can require a different cabling than for fall-prevention in case the branch breaks.

In the first case the static wind load in the crown or cabled main stems and cables can be assessed.

Meanwhile, the tree it's overall stability should also be evaluated.

It has no sense for example to cable a tree if the next storm would cause failure of the root-system that would make the complete tree to fall down!

The stability question has to be solved first, on all levels, before cabling can be installed!

The strength of the cabling should not exceed that of the supporting tree-part. Therefore, the critical load that would cause failure of the supporting stem, if this load would pull or push at the height of installation, can be assessed.

The maximum strength (S_{max}) that the cable should have, in order not to break the supporting branch when the fault stem would fail, can be represented by the following equation, which is derived from the formulae employed in the V-model:

$$S_{max} = ((w*s)/100)/h$$

Where:

S_{max} = the maximum strength of the cable in kN
w = the cross-section modulus of the basis of the supporting stem in cubic centimetres
s = the compression-strength of the living wood in kN/cm²
h = the height of installation in metres

Nevertheless, the above equation does not incorporates the influence of dynamics, which should absolutely been taken into account.

Also the influence of installation-angles of the cables should be incorporated. The angle of the cable is a critical factor regarding the transfer of forces. With angles also the falling distance of a failed branch can be made as short as possible.

It is very important to understand that stopping a falling branch with a cable, even a steel one, is very unlikely to be successful due to the high energy and force that grow enormously due to several reasons.

The supporting part of the tree or the cable, are usually not able to withstand the high shock when the fall is stopped.

The following equation can be offered as an evidence (free after Wessolly & Erb, 1998):

$$F = (m * g * h) / e * 2$$

Where:

F = the force in the cable at the elongation limit of the cable
m = the mass of the branch which is a product of the volume and specific density of the latter
g = acceleration due to gravity and is expressed as 9,81 m/s²
h = falling height of the branch and can be the length of the cable
e = the strain or elongation limit of the material from which the cable is made and is expressed in %

It is important to underline that cabling is only a *transfer* of forces to other parts of the tree e.g. the securing branch.

Currently, the use of flexible synthetic materials can be recommended since they can help to stimulate the formation of

repair-growth in the defective area. It is possible that in this way and with vital trees, a properly cabled branch can regain complete structural stability after some 15-20 years, after which its cabling may become unnecessary.

Damages due to perforation can be prevented by synthetic cabling systems that incorporate slings which embrace the branch or stem instead of passing trough it.

Also the risk of the so-called "karate-effect" can be lowered considerably by flexible and shock-absorbing materials. Under this effect is understood the failure of the cabled branches at the height of the installation, due to the sudden stop (caused by rigid materials like steel) of the natural swinging of the tree parts.

It is also important to study the architecture of the tree to take advantage of it multiple dimensions. It is better to connect the main stems ring-wise than to draw a star-like single cable configuration, especially regarding swinging and torsion.

The height of the installation will depend on each situation and the-one-and-only fist formula can really not be given. Profound training by experts is thus required, whereby the given information should always be contrasted with other sources.

Cabling of old trees and palms to other structures or trees has already proven to be successfully done. Thereby, the analysis of the wind load in the crown is undeniably a must to assess the loads in the cabling system and the supporting structure.

In order to stimulate the vitality of a tree, and hence its capacities of compensation and compartmentalisation, *mulching* and *deep watering* are still unbeatable, the latter especially in periods of drought. Also, in regions where summer branch drop occurs, the extra addition of water might lower the risk for this type of failure.

The reaction capacity of the tree can be heightened by administering potassium, phosphorus and magnesium during the dormant period. On the other hand, nitrogen stimulates the extension of wood-decaying fungi.

After the tree or palm has been assessed and treated (in this sequence) it is recommended to inspect it several times a year visually. Broken branches, symptoms of structural defects or fungal fruiting bodies can appear afterwards and sometimes depending on the season. Symptoms of root stability loss can appear in the soil and near the stem base after events of rain or wind. The morpho-physiology of the tree should absolutely be considered when a tree is pruned, e.g. a crown reduction for reducing its sail-area. And the works of Alex Shigo should still be considered as the basis for all our actions upon trees. The author of the present study recommends his reader to consult specialised literature, to contrast information and to build up his own baggage of tree- and human life saving knowledge.

11. Conclusion

In this publication the author only restricts himself to describing the basics of the puzzle. To him, his personal idea of tree-assessment is what the "Philosophical Stone" is to the alchemists, an idea by which the stability of a tree can be deciphered.

No attempt was made to write what others have already written better prior to this study.

The case is that the body language of the tree, its life expectancy and monetary value, many times require only an expert visual diagnosis. Many old trees can be assessed with the present proposals.

Should the tree in question have an extraordinary monetary value and if there are unsolved questions regarding its stability, a range of exquisite instrumental methods can be chosen from.

And as Mattheck & Breloer (1995) state: *"… do not trust technology alone – it can only measure what you have seen."*

12. End notes

Gordon (1999) describes how several historical disasters occurred to boats, bridges and other structures and which led to the loss of many human lives. They were mainly the result of the application of just the theory of elasticity.

Hence, we cannot rely solely on mathematics.

Tree- and human lifesaving assessment should incorporate biology, mycology, the experience and intuition of professional colleagues and everything that we are capable to integrate.

After all, we should listen to our common sense.

And something to think about:

Real trees do not fit mathematical expressions perfectly. There are differences in the growing conditions and loads on different trees and palms under different conditions over time (Horacek, 2003).

A profound and intuitive knowledge of the inherent perversity of materials, loads and geometry's - mathematics and trees - is one of the most precious qualities an arborist can have (free after Gordon, 1999).

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