Tree Biomechanics

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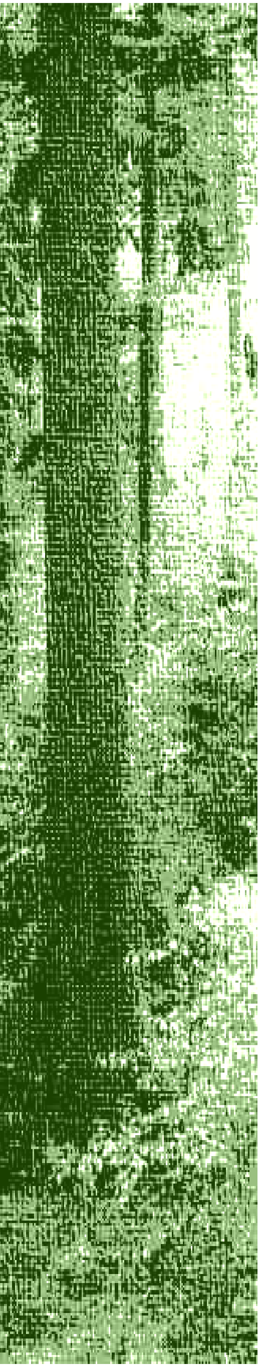
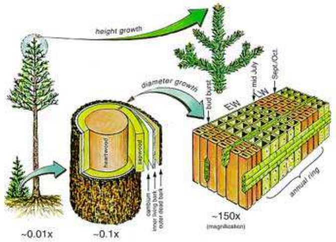
evropský
sociální
fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ,
MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání
pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

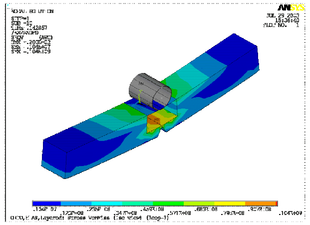
Tento projekt je spolufinancován Evropským sociálním fondem a Státním rozpočtem ČR InoBio – CZ.1.07/2.2.00/28.0018

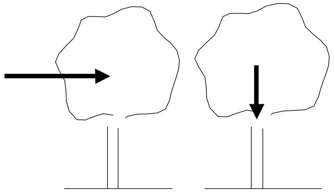
Content

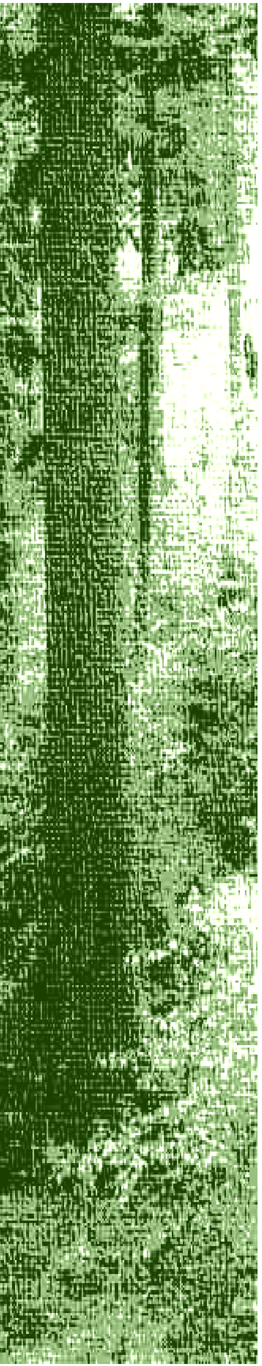




height growth
diameter growth
EW
LW
annual ring
~0.01x
~0.1x
~150x
(magnification)

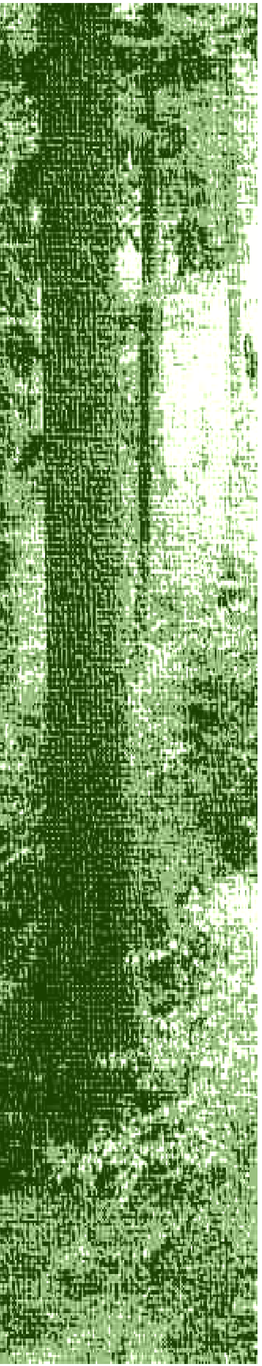






The mechanical behaviour of a tree is in the centre of interest of many forestry and arboricultural research due to damages to trees or buildings, properties or even the human life. Modelling the tree behaviour and measurement of the actual condition of the tree *in situ* is, therefore, important for the tree safety assessment. Trees adapt their stem (Telewski, 1995) and root growth (Nicoll and Ray, 1996) in response to the wind loading to which they are subjected in order to resist breakage or overturning. By understanding the behaviour of trees in strong winds (Mayer, 1987; Gardiner, 1994, 1995; Peltola, 1996; Blackburn, Blackburn, 1997; Gardiner et al., 1997) and the mechanisms of root anchorage (Deans and Ford, 1983; Coutts, 1986; Ray and Nicoll, 1998) it has become possible to develop mechanistic models that predict the critical wind speeds for damage to occur and how these are affected by the properties of the trees within the stand. Such an approach allows predictions of the impact of any arbocultural operations on tree stability and the design of arbocultural strategies for reducing wind damage.

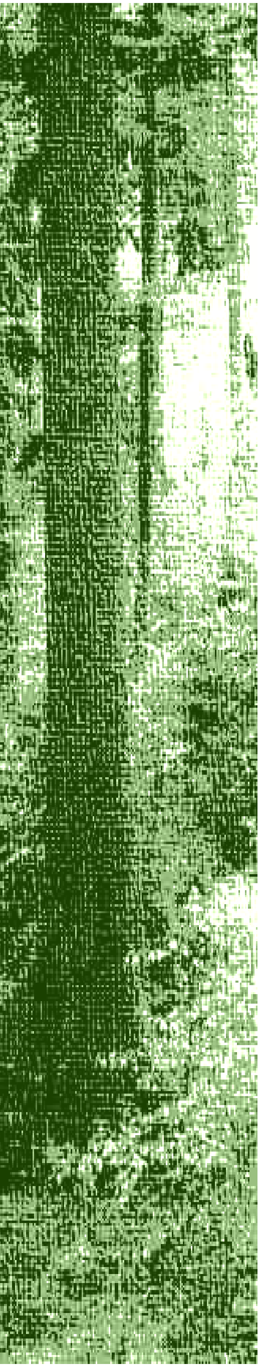
Various authors describe the mechanical behaviour of a tree in various ways. Because of large dimensions and complicated geometry of a tree, the calculations are carried out usually by the use of computers. There is a trend to utilize the finite element method (FEM) that is very powerful to describe such complicated mechanical structure as a tree (Mattheck 1995, 1998, Badel, Perré 2000, Fourcaud et al. 2000, Alhasani 1999, Daudeville 1999, Grill, Laghdir and Jullien 1997).



Other authors proceed from Timoshenko’s theory (Spatz 2000) or a tree is considered as an elastic cantilever beam accordingly to Euler theory (Wessolly 1998, Mossbruger 1986).

Consideration of the tree as a forced damped harmonic oscillator, has allowed to model its dynamic response to wind loading (Mayer, 1987; Gardiner, 1991; Gardiner, 1993), but these considerations are not going to be observed in this paper, as well as those related to growth stresses (Archer, 1986). Both Leiser and Kemper (1973), and Milne and Blackburn (1989) have found that axial stresses due to wind loading vary along the stem with a maximum occurring at a position which depends on taper. According to Mamada et al. (1984), the theoretical height of maximum stress was in good agreement with the height at which the stem breaks. However, other authors (Petty and Swain, 1985; Mattheck, 1991; Wood, 1995) suggest that the stress should be constant in the stem.

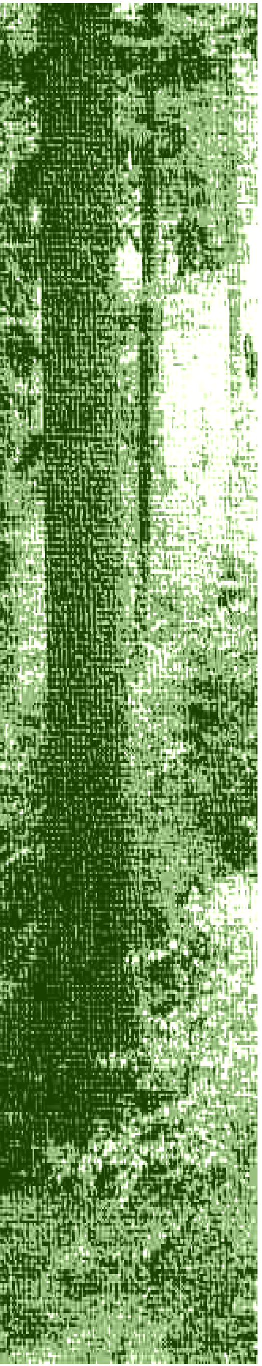
Mechanistic models (e.g. Peltola and Kelloma»ki, 1993; Peltola et al., 1999) have recently been under development for predicting the critical wind speeds at which trees are likely to be uprooted or broken; i.e. to provide tools for assessing the risk of wind and snow damage in the context of tree safety and stability. However, much basic work is still needed, especially with regard to the components of root anchorage (because of the complexity of the root-soil system), and also with regard to stem stability. These can be investigated using static loads, with the reservation that the results may need to be modified when the dynamic forces caused by wind are introduced (Coutts, 1986).



In a static system the breaking and uprooting forces, usually calculated as bending moments at the base of the stem, are treated as arising in two ways. Firstly, the force produced by wind action on the crown, simulated by pulling with a rope, causes defection of the stem. The leaning stem then assists in uprooting the tree because its centre of gravity moves over the hinge point in the root system (Ray and Nicoll, 1998). Thus, a second force is provided by the weight of the stem and crown. The uprooting moment is resisted by bending of the tree stem and various components of root anchorage: the weight of the root-soil plate, the strength of the windward roots, the strength of the root hinge and the soil strength at the base of the root-soil plate. If the uprooting moment exceeds the resistive bending moment of the tree at a particular angle of deflection, the tree will deflect further. The tree will give way if the uprooting moment exceeds its maximum resistive bending moment, with the relative strengths of the stem and roots determining the mode of failure (Petty and Worrell, 1981).

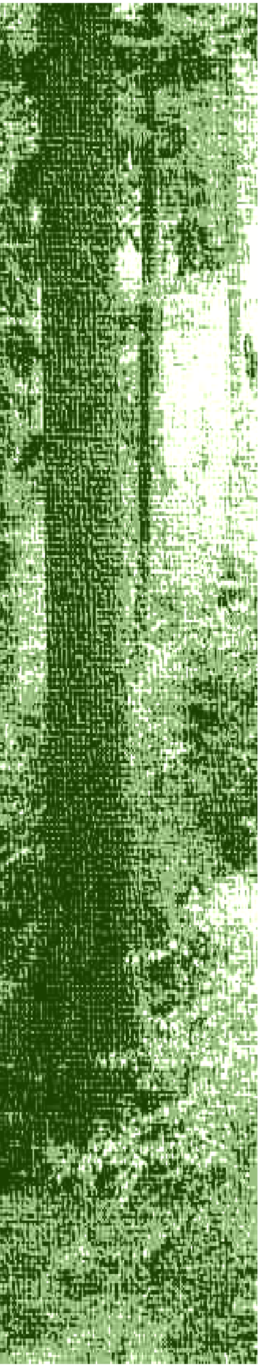
Measurement of maximum resistive bending moment is provided by the use of a winch system. It is used to pull the trees and the applied force needed to “uproot” a tree or bend its stem is measured. This technique or its principles are used relatively wide. Utilization of the pulling test is referred in Wessolly (1995a, 1996b), Stokes et al. (1995, 1997, and 2000), Brüchert and Gardiner (2000), Crook et al. (1997). In the seminar, the “Elasto- and Inclinomethods" for tree stability assessment using the pulling test (Wessolly, Erb 1998) was applied.

- Focus of interest (for forestry and arboricultural research) owing to the potential for trees to harm people or property
- Significant practical implications for tree safety assessments
- Response to wind loading – breakage or overturning of tree
- Mechanistic models that predict the critical wind speeds above which damage may occur
- It is possible to predict the influence of arboricultural operations upon tree stability



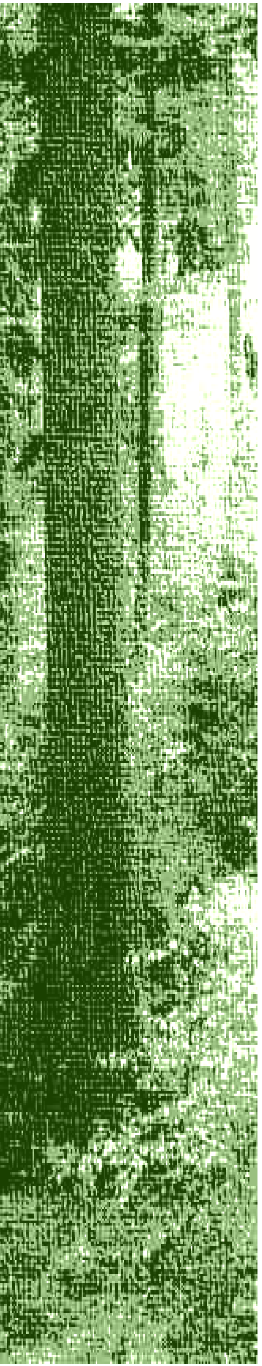
Objectives of biomechanical approach

1. Assessment of the mechanical safety of the tree as used by engineering concept with generally accepted rules
2. Identification of forces acting on tree
3. Determination as to whether the tree structure withstands these forces
4. Finding the weakest places in the tree and determination the size of the weakest place relative to the adjacent cross-sections
5. Determination of residual carrying capacity of a tree
6. Quantitative prediction of fracture safety
7. Non-destructively monitor exactly the same place for years



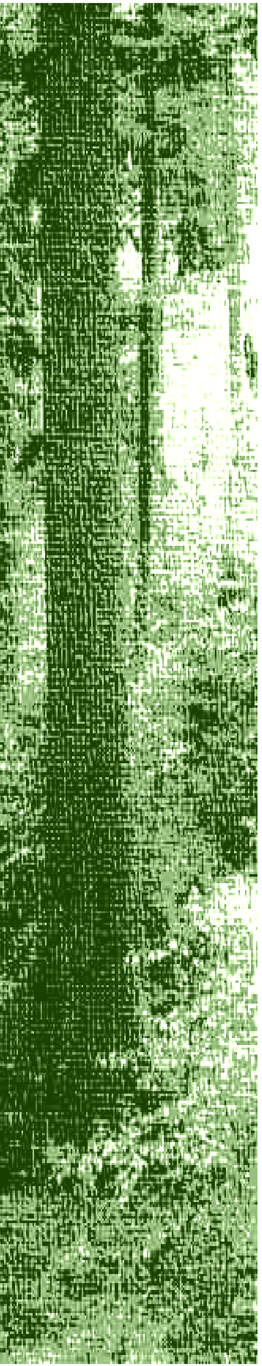
Key concepts

1. Mechanical principle of tree design
2. Principle of optimal design
3. Principle of similitude
4. Principle of adaptive growth
5. Principle of stability and flexibility strategists
6. Principle of holistic approach



Key terms

1. Adaptive growth
2. Optimal design = compromise in respect to functions
3. Safety factor
4. Tree stability = resilience (S-strategy) vs. resistence (K-strategy)
5. Tree reiteration = repeating pattern of design
6. Hollow structures



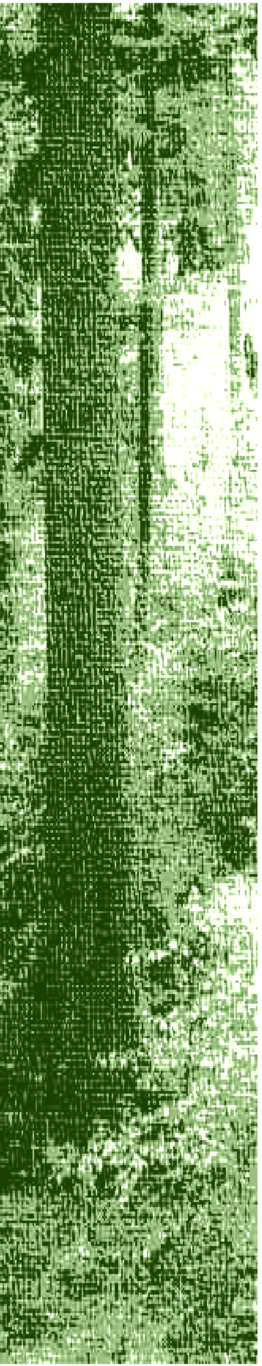
Limitations (special cases)

We are limited by very complicated interactions in tree stability concept. To take all possible potential factors into account is impossible (yet).

1. Simplifications:
   a) loads (laminar steady flow, sailing area x 3-D crown surface, Cx concept, streamlining, ...)
   b) wood properties (very complicated, spatial distribution, static x dynamic behaviour, changes in time, ...)
   c) geometry

2. Assessment of „static“ picture of tree – often without its history and future development

3. Root system – out of our reach, non-destructively tests ?



Methods of analysis (solutions steps)

1. Discovery of damage, situation, site
2. Determination of loads – wind, mass
3. Determination of tree form – basic statics structures, organ correlations, defects
4. Comparison damage stage to basic structures
5. If necessary, definition of damage more precisely (device-aided)
6. If necessary, carry out tree-care measurement (device-aided)

2.1 Hazard Tree Evaluation

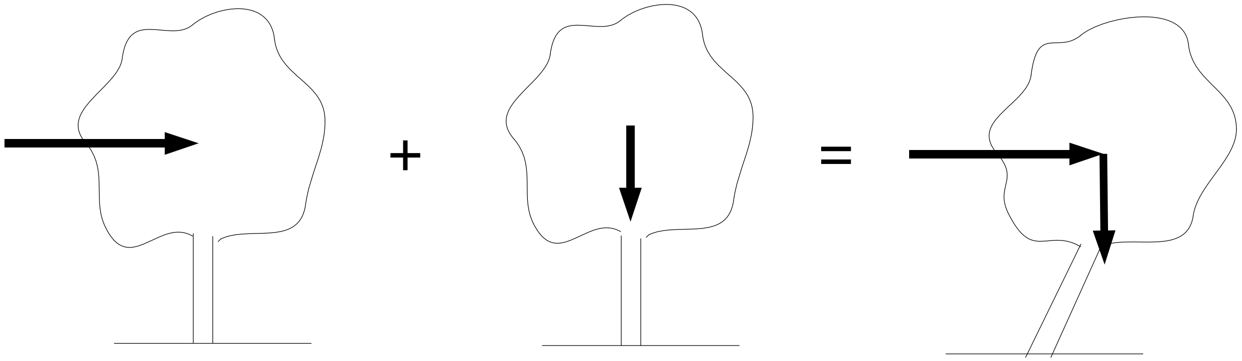
- Interest in hazard tree management has increased in recent years due to safety and liability concerns resulting from preventable accidents.

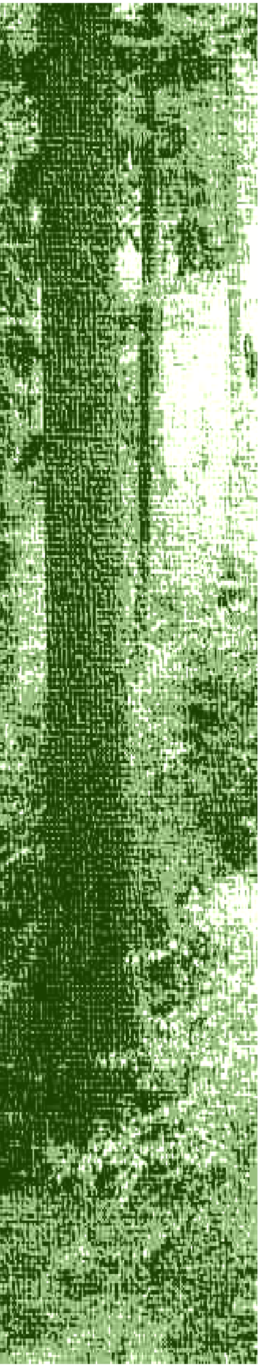
2.2 Problems (defects) identification

- Recognizing hazardous trees and taking proper corrective actions can protect property and save lives.
- A “hazard tree” is a tree with structural defects likely to cause failure of all or part of the tree, which could strike a “target.”

2.3 Biomechanical approach

The development of the approach is schematically presented.





2.1 Hazard Tree Evaluation

Components of Hazard Tree Evaluation

1. Site
    - History
    - Recent exposure to loads
    - Construction activities
    - Environmental conditions

2. Tree
    - History – toping
    - Architecture – growth habit
    - Signs of decay
    - Weak structures
    - Root system

3. Target
    - Potential to fail and injure or damage a target

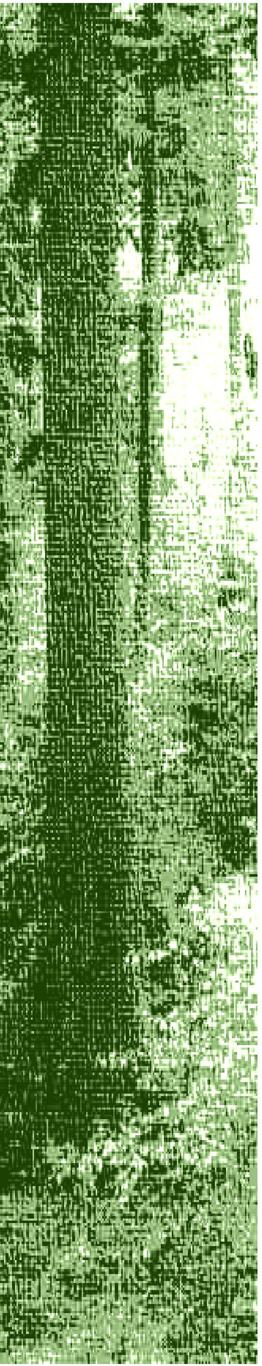
2.1 Hazard Tree Evaluation

What to Look For

- Hazardous defects are visible signs that the tree is failing.

- We recognize seven main types of tree defects:
  - dead wood,
  - cracks,
  - weak branch unions,
  - decay,
  - cankers,
  - root problems,
  - and poor tree architecture.

- A tree with defects is not hazardous, however, unless some portion of it is within striking distance of a target.



2.2 Problems (defects) identification

The key to reducing the risk with a tree is to **identify** and correct the problem.

Problems identification:

- Visual tree assessment (Body Language of Tree)
- Devices-aided assessment (Resistograph, Arbosonic, ...)
- Combination of visual and devices-aided assessment

Objectives

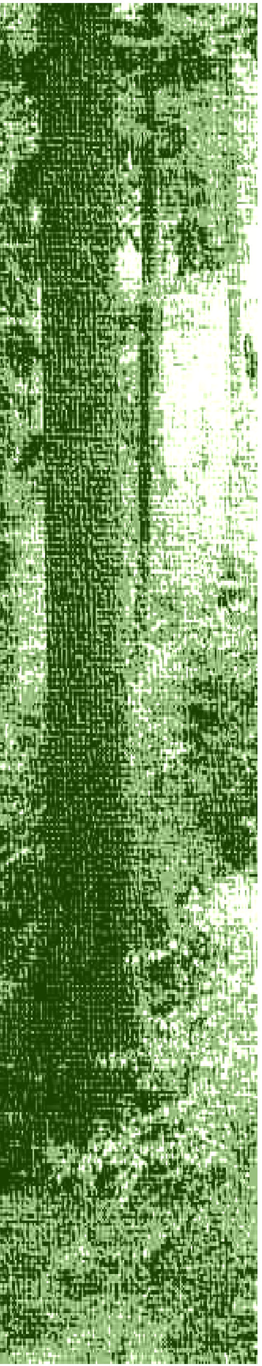
1. Determination of tree stability without injury.
2. Monitoring of stability.
3. Assessment of safety against fracture.
4. Determination of weakest places within the tree.

2.2 Problems (defects) identification

Key concepts

There are 6 current tree inspection systems in wide use:

1. The Visual Tree Assessment method (**VTA**)
2. The Evaluation of Hazard Trees in Urban Areas (**EHT**)
3. Statics-Integrated Assessment (**SIA**) and Statics-Integrated Methods (**SIM**)
4. The Forestry Commission in the United Kingdom developed a quantitative windthrow hazard classification scheme
5. The Windthrow Handbook for British Columbia Forests
6. Mechanistic approaches (**static and dynamic models**)



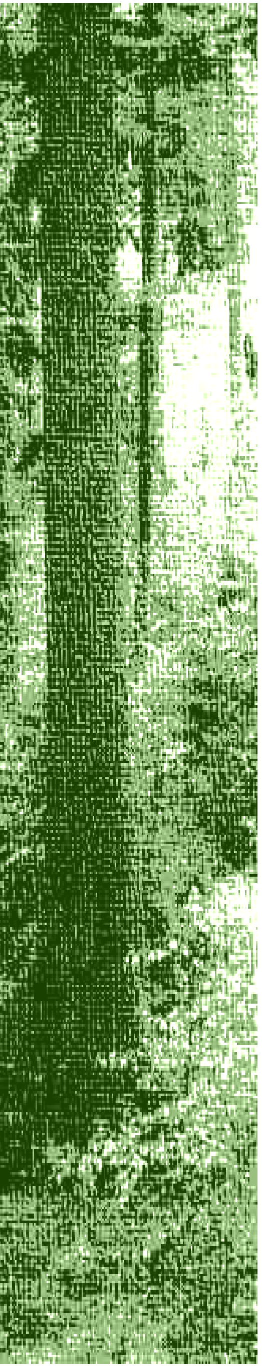
2.3 Biomechanical approach

Resistance to breakage

- Wind- and mass-induced stresses are calculated according to elastic theory.
- Stresses are calculated within the tree at any height.
- When stresses exceeds the strength of wood, the stem will break.
- The critical load is product of stem diameter and wood strength.

Resistance to overturning (uprooting)

- Tree overturns if the load (due wind) exceeds the support provided by the root soil-plate anchorage.
- Uprooting forces (bending moment) at the base of the stem are provided by the wind and weight of the stem and crown.
- The uprooting moment is resisted by bending of the tree stem and various components of root anchorage.



3.1 Tree structure and function

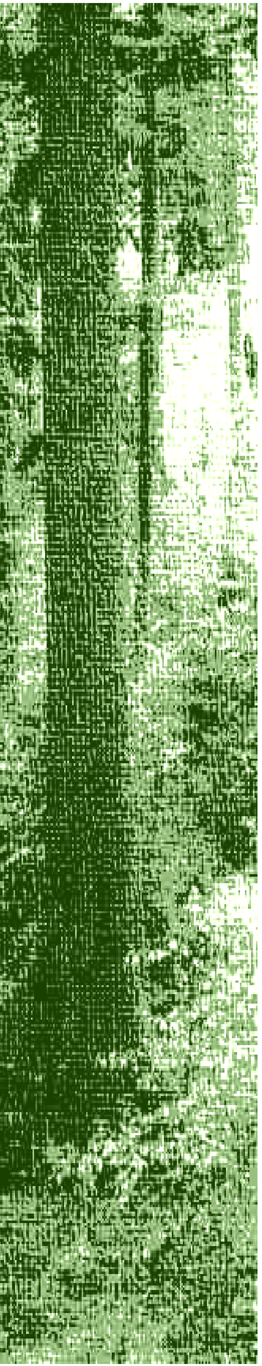
Form of tree trunk and branches is probably largely controlled by biomechanical requirements. In respect to their form, stem and branches are not simple “optimum structures” adapted to only one function, but are “good enough” or “optimum compromise” structures which perform a number of different functions.

3.2 Tree growth and ontogeny

Tree functions, and thus also the design of the tree, may vary during ontogeny of a tree.

3.3 Intro to wood science

Stability is one of the most important prerequisites of tree design. Trees are compromise structures to meet mechanical requirements.



3.1 Tree structure and function

Key terms

Tree represents open dissipative system satisfying vital requirements:

(1) must **growth**

(2) need **stability** to support the energy producing leaves

(3) water and minerals have to be **conducted** from roots

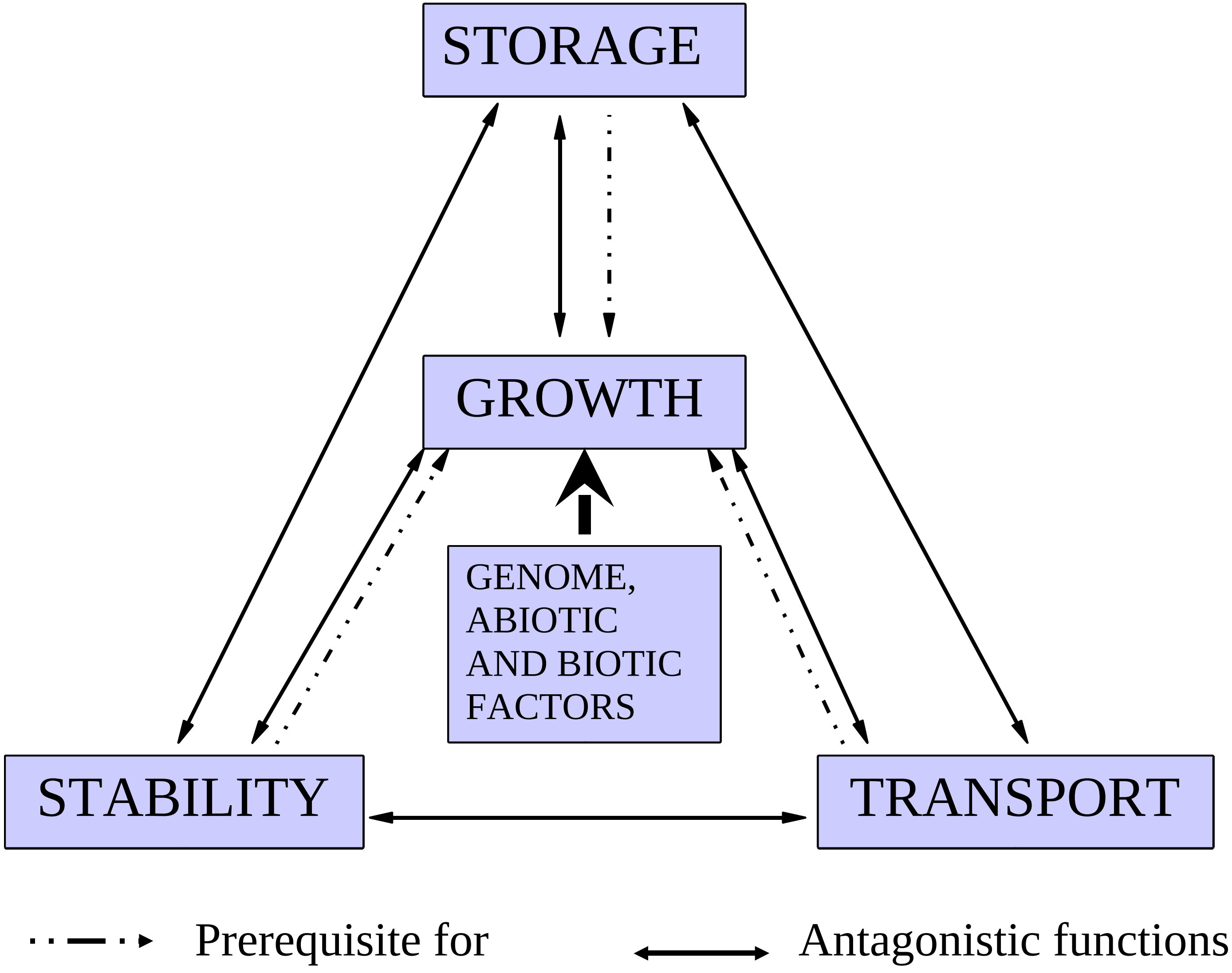
(4) nutrients and water must be **stored**

All functions are tightly **interconnected**.

Supporting, storage and conductive functions are indispensable for growth.

A complex framework of genetical, abiotic, biotic factors controls the system.

3.1 Tree structure and function



STORAGE

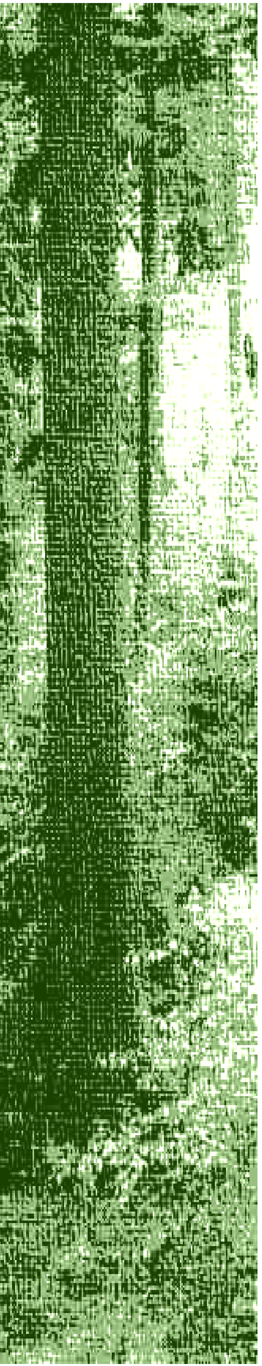
GROWTH

GENOME, ABIOTIC AND BIOTIC FACTORS

STABILITY

TRANSPORT

(Mosbrugger 1990)



3.1 Tree structure and function

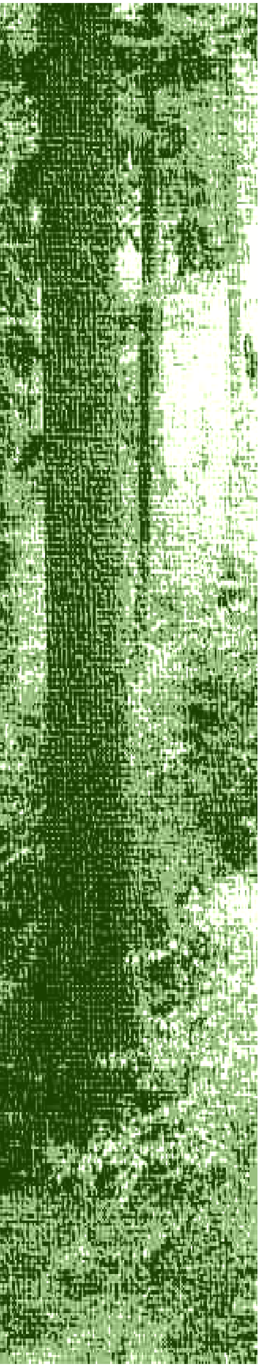
Assumptions

The tasks must be performed by **every part of a tree** (roots, stem, branches, leaves), but their relative importance varies from organ to organ.

In general, the **trunk** should represent **an energy-saving compromise structure** for stability, conduction and growth.

Wood is also measurements of **“surplus”** assimilates substances formed during growing season.

Stability ⟷ Vitality



3.1 Tree structure and function

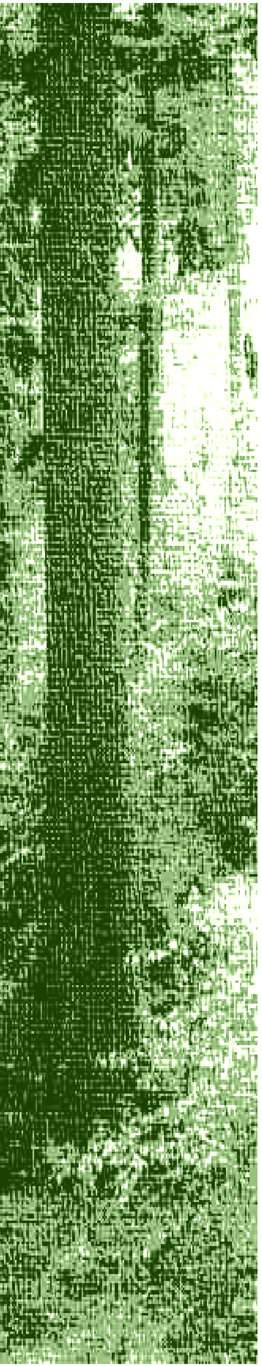
Key concept

Basic idea of constructional morphology is the principle of **optimal design** – each biological structure is optimally adapted to its natural load, which acts also as its design mechanisms.

This type of mechanism is called **adaptive growth** – trees are compromise structures that have to meet a number of different and opposing mechanical requirements.

The principle – the stem and branches of trees should have a form which functions best using a **minimum amount of material** (assimilates).

The shape of tree may be viewed as “good enough” or **optimum compromise structure**, which perform a number of different functions with (nearly) a minimum cost of energy.



3.2 Tree growth and ontogeny

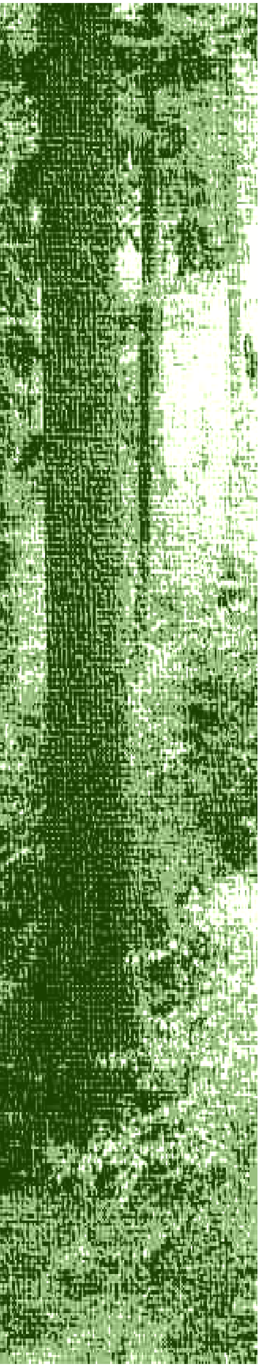
Key concept

The anatomical tree-ring structure may be compared to a display in which we can observe the resultant effects of ecological conditions.

The tree-ring structure is the result of a complex of factors that affect the site, and it is also an expression, both quantitative and qualitative as well, of these prevalent conditions on the site.

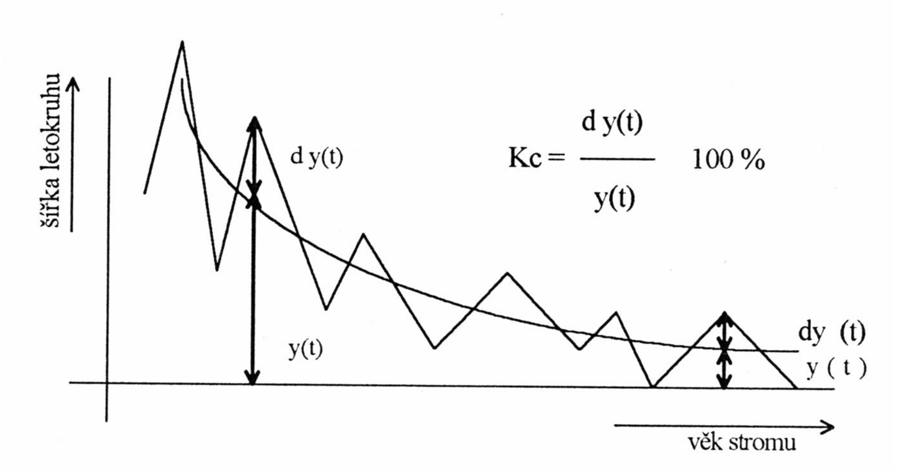
Trees are capable of responding to the effects of environmental factors in a variety of ways.

Cambial age affects the intensity and frequency of abrupt growth changes.



3.2 Tree growth and ontogeny

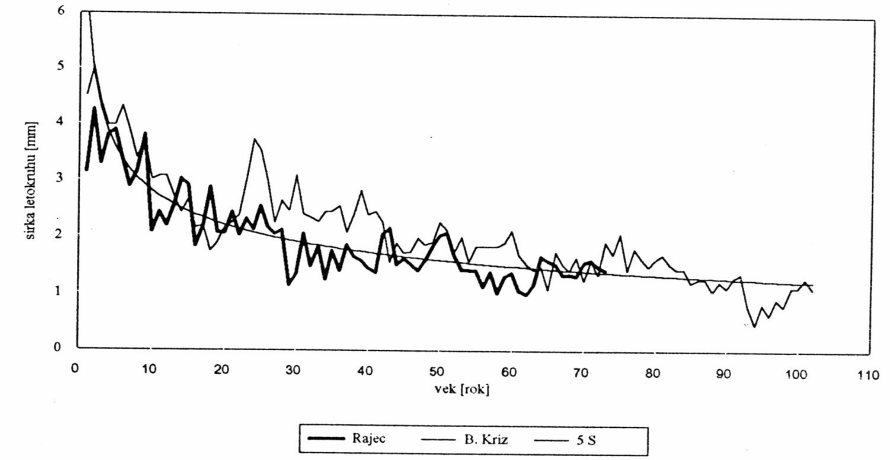
Young cambium, whether at the apex of old trees or at the base of young individuals, features fewer changes and is less susceptible than at an older age.



There are two aspects involved in plant aging:

(1) physiological aging (senescence) and

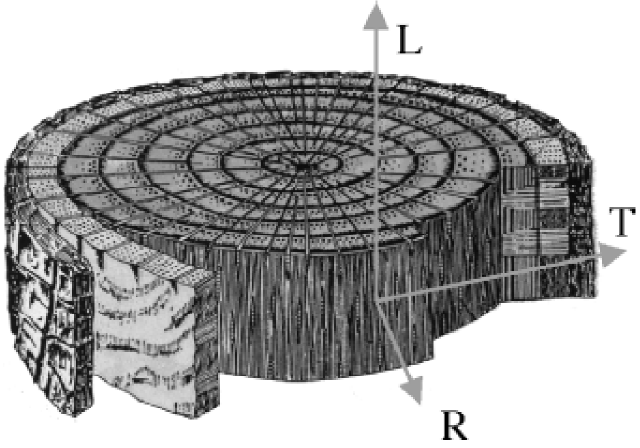
(2) ontogenetic aging. The annual growth in width (thickness) is determined in part by the maturity state of the individual



3.3 Intro to wood science

Objectives

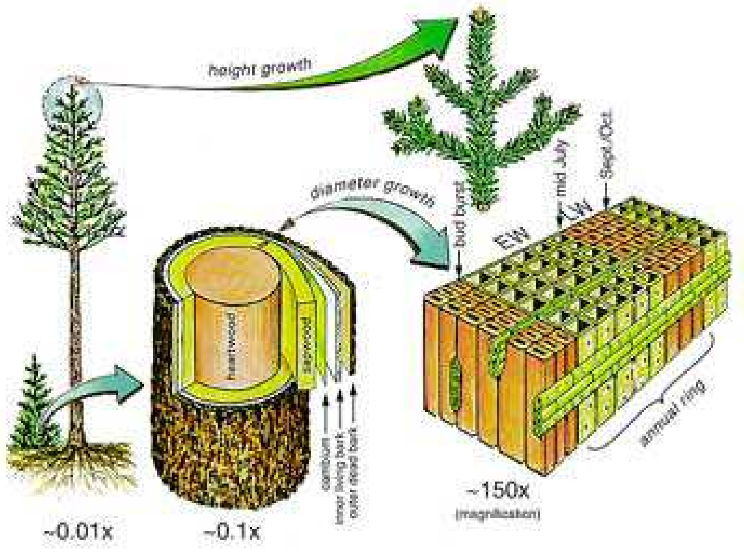
1. Wood – victory or loss ?
2. How does wood structure limit wood properties ?
3. Why mechanical properties are determined by wood structure ?
4. Wood is hierarchical structure, unfortunately very complicated – true or false ?
5. Wood is optimised compromise structure – how to apply it in tree biomechanics ?

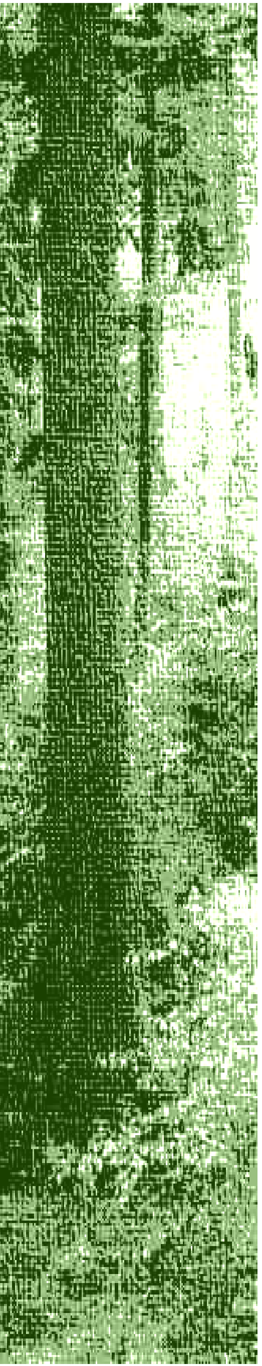


3.3 Intro to wood science

Key concept

- Wood nature
- Chemical composition
- Submicroscopic structure   X   Wood as material
- Microscopic structure
- Macroscopic structure





3.3 Intro to wood science

Key terms

1. Orthotropic nature of wood – unique and independent mechanical properties in the directions of three mutually perpendicular axes

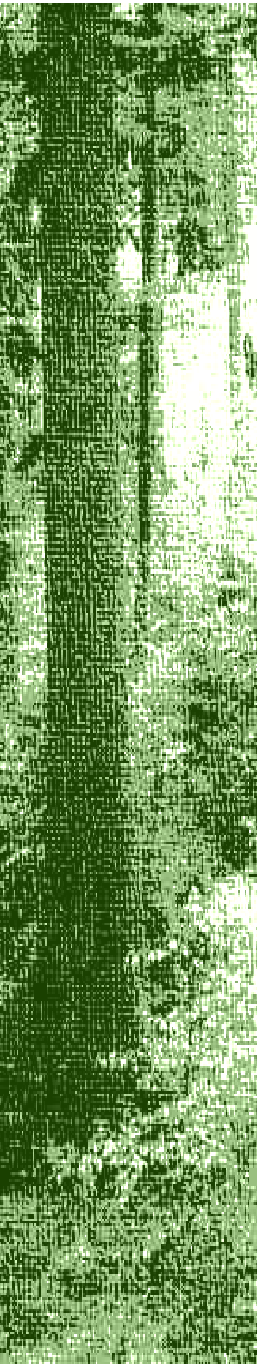
2. Mechanical properties represented as „strength“ properties – maximum (ultimate) stress = resistence to failure

3. Mechanical properties represented as „elasticity“ properties – modulus of elasticity = resistance to deformation

4. Allowable stress – the maximal stress anywhere in the structure

5. Factor of safety = the ratio of actual (calculated) stress to required strength

6. Tree design – the *desired response* of tree is given (key concept of biomechanics)



3.3 Intro to wood science

Wood as material

a) Wood is a material with **anisotropy** of all physical properties, including mechanical.

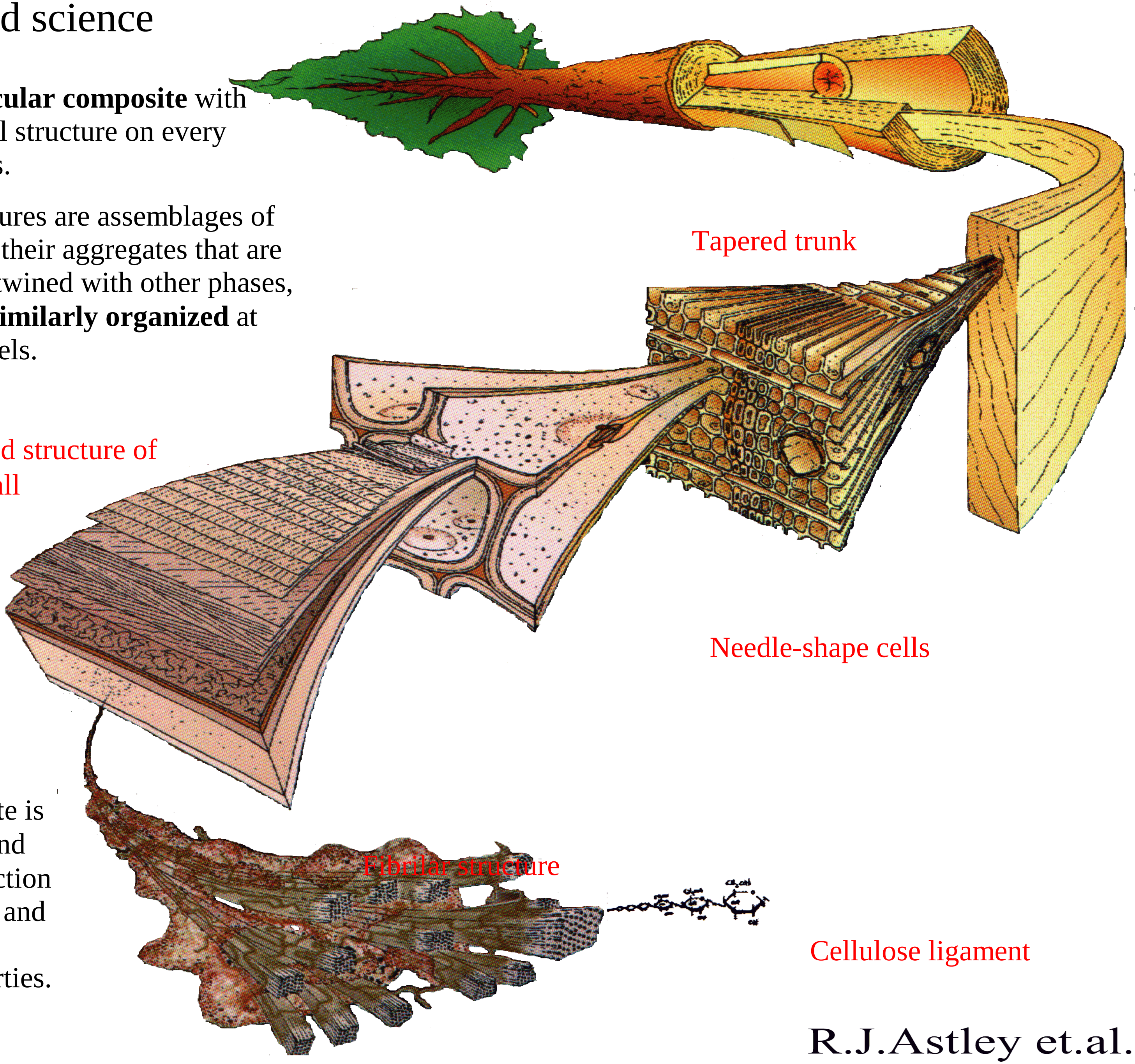
b) This anisotropy is based on the chemical composition and structure of the wood.

c) The anisotropic nature of wood is the best compromise between requisite functions (bearing, storage, conduction).

How does the wood look like… →

3.3 Intro to wood science

- Wood as **biomolecular composite** with similar hierarchical structure on every organization levels.
- Hierarchical structures are assemblages of molecular units or their aggregates that are embedded or intertwined with other phases, which in turn are **similarly organized** at increasing size levels.

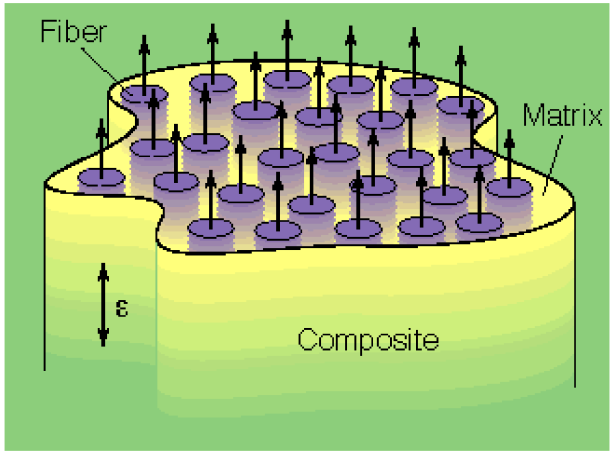


- Wood as composite is rich in **cellulose** and **lignin**. The interaction between cellulose and lignin determines mechanical properties.

R.J.Astley et.al.

3.3 Intro to wood science

Wood as bio-composite – chemical composition

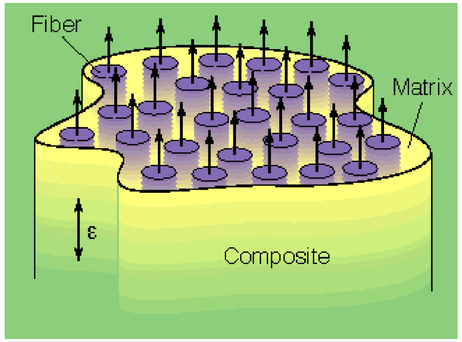


Wood = **F**iber-**R**einforced **C**omposite

Lignin forms the matrix, to which the cellulose is embedded.

3.3 Intro to wood science

Wood as bio-composite – chemical composition



Lignin forms the matrix,
to which the cellulose is embedded.

Cellulose

- is responsible for elasticity
- behaves as brittle matter
- provides stiffness and restricts deformation

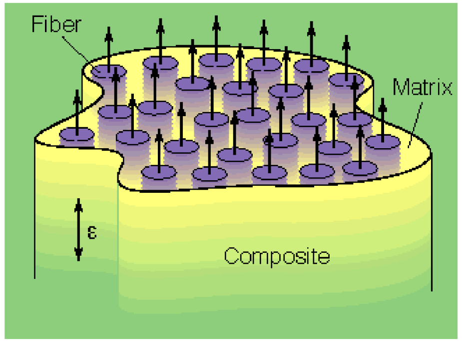
Lignin

- is responsible for plasticity
- has ductile character
- provides the strength and energy absorption

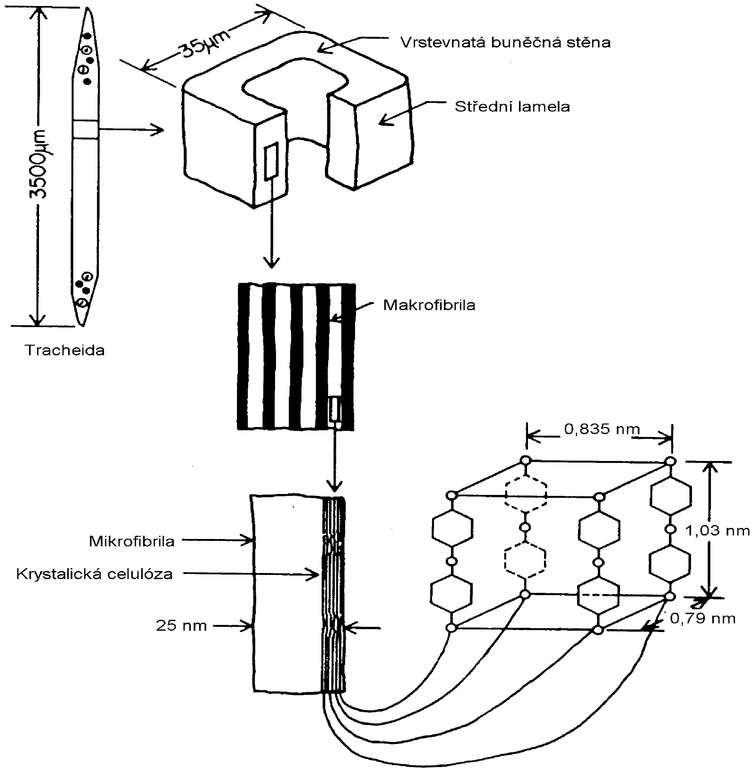
3.3 Intro to wood science

Wood as bio-composite – chemical composition

Lignin forms the matrix,
to which the cellulose is embedded.



- wood is fibrous material
- main components are cellulose, hemicelluloses and lignin
- chemical bonds provide the stress transmission
- therefore, wood properties are related to grains direction

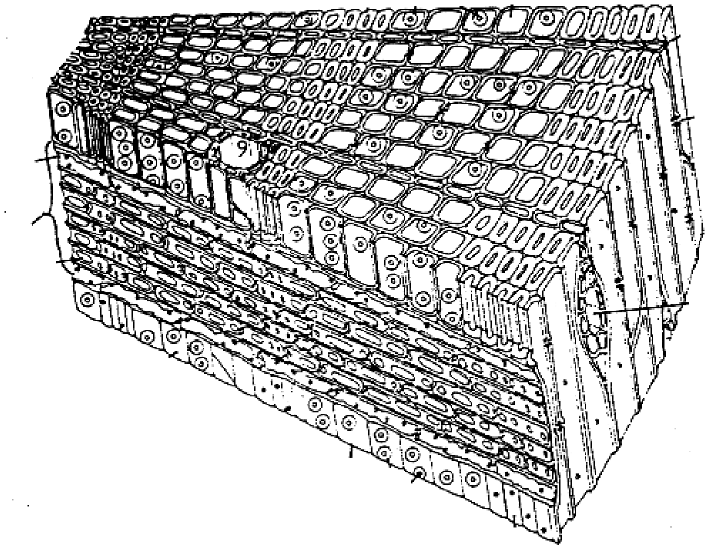


3.3 Intro to wood science

Wood as bio-composite – anatomical structure

What is important for tree biomechanics ?

Softwoods



- Simple structure
- Two types of elements only
- Regular structure
- Rare irregularities
- Universal elements

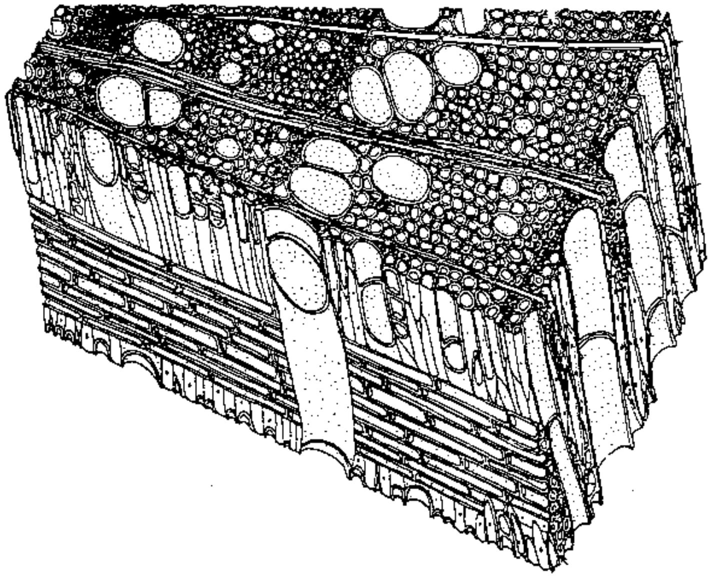
3.3 Intro to wood science

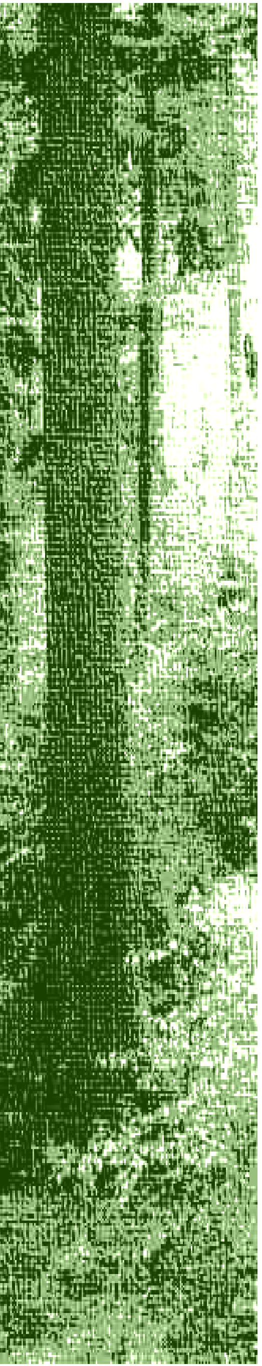
Wood as bio-composite – anatomical structure

What is important for tree biomechanics ?

Hardwoods

- Irregular, complicated structure
- Three types of elements at least
- Cells more specialized





3.3 Intro to wood science

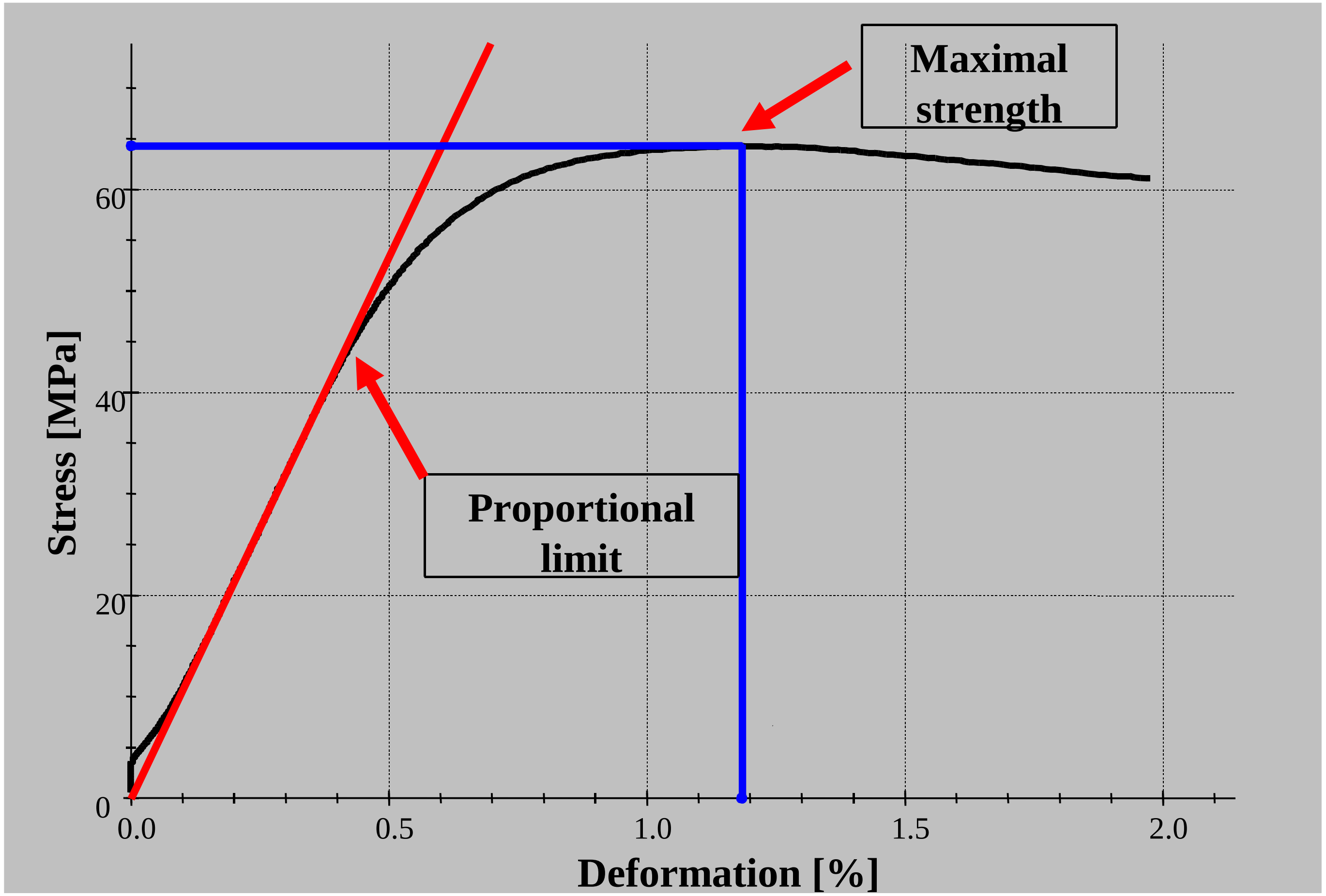
Wood as bio-composite – mechanical properties

- Stress-strain diagram
- Different wood mechanical behaviour
- Important properties
  - Density of wood
  - Modulus of elasticity
  - Strength
  - Deformation

3.3 Intro to wood science

Wood as bio-composite – mechanical properties

How get to know your material – Stress-Strain Diagram



3.3 Intro to wood science

Wood as bio-composite – mechanical properties

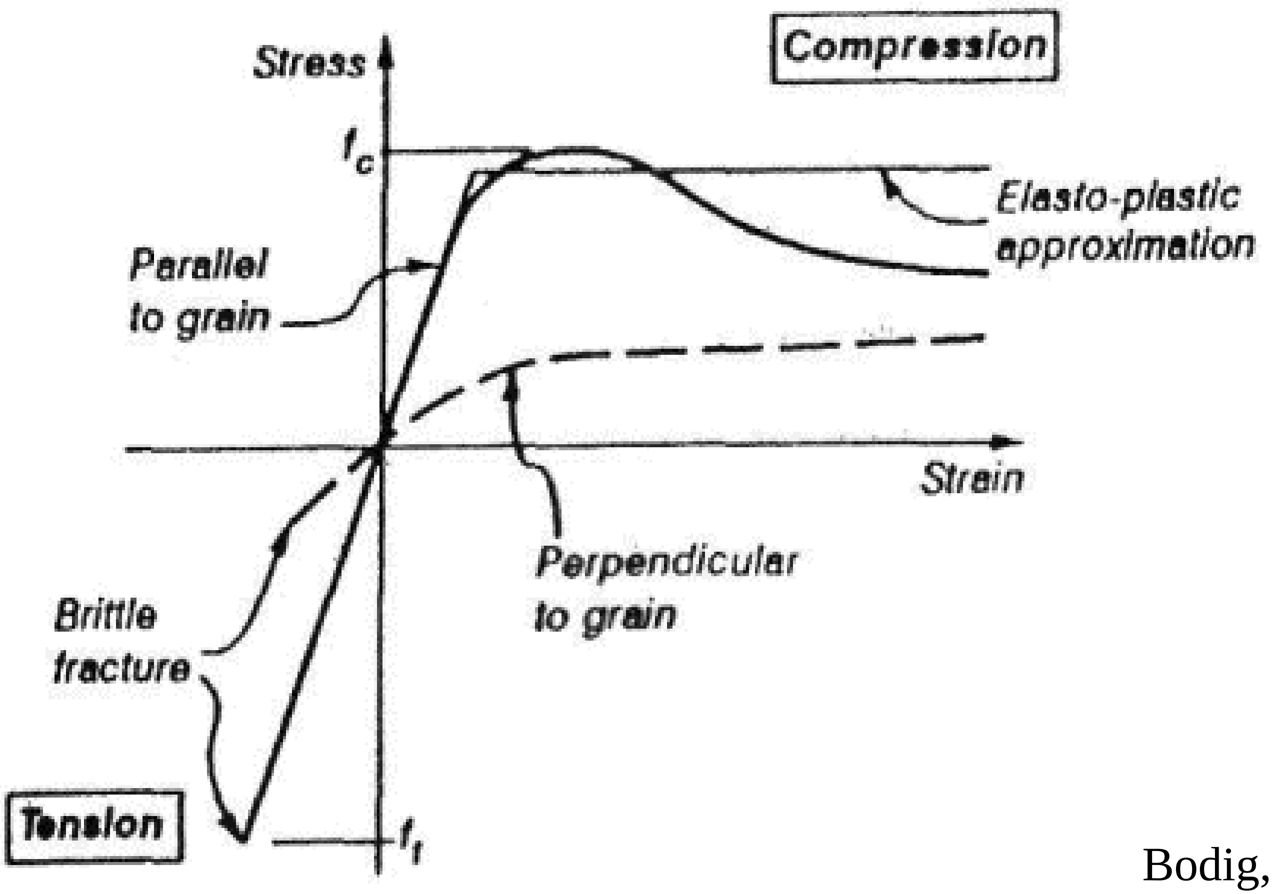
What is the stress-strain diagram providing us?

- Character of material (will be discussed immediatelly)
- Important values (could be measured only)
    - Modulus of elasticity
    - Strength
    - Proportional limit
    - Deformation
    - Energy saved

3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Stress-strain diagrams all in one

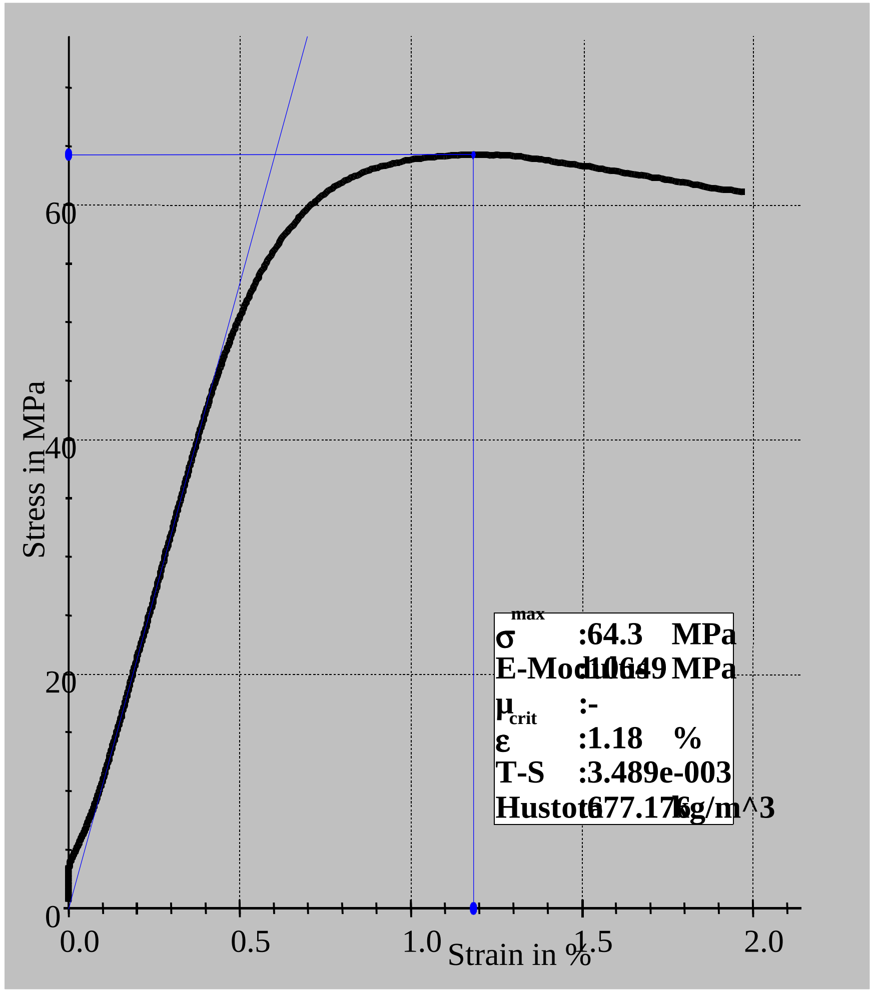


Bodig, Jayne (1983)

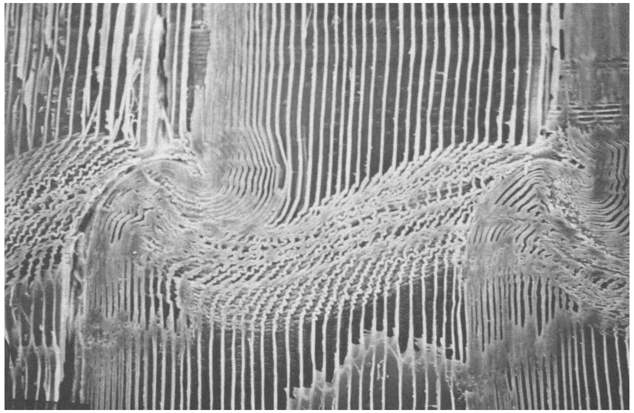
3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Compression parallel to grains



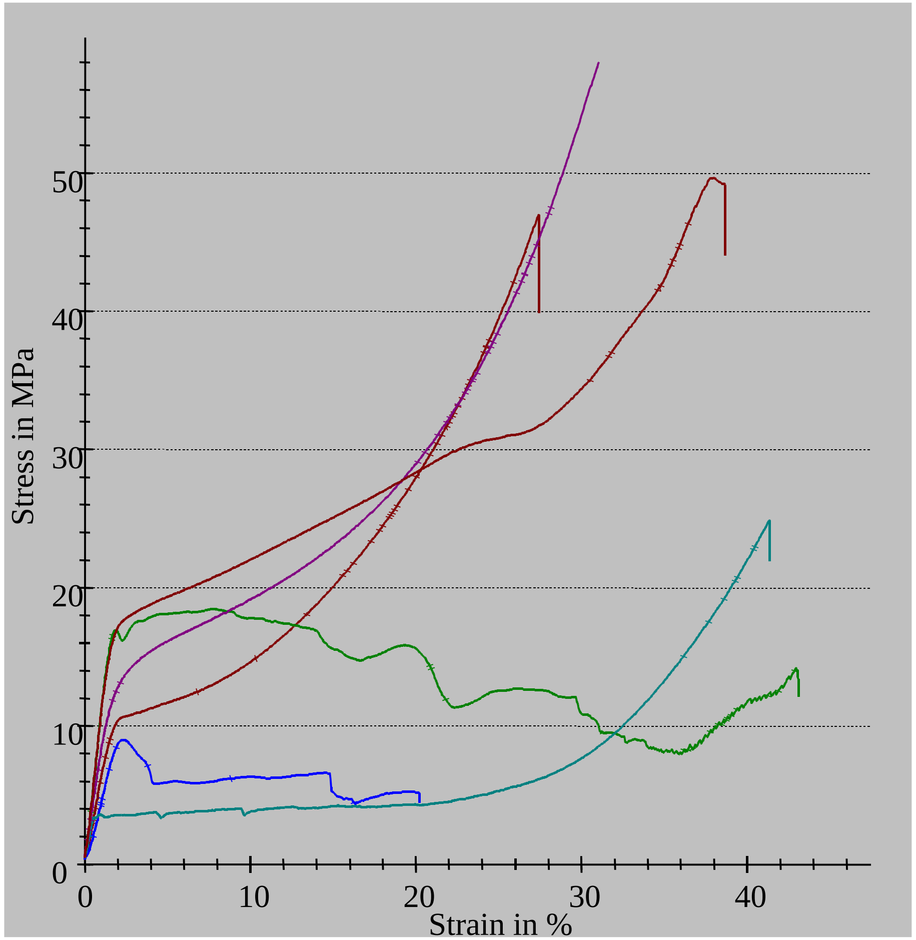
- Viscoelastic behaviour
- High stiffness
- High strength
- Deformation about 1 %
- High amount of saved energy
- “No failure”- **good** way of loading



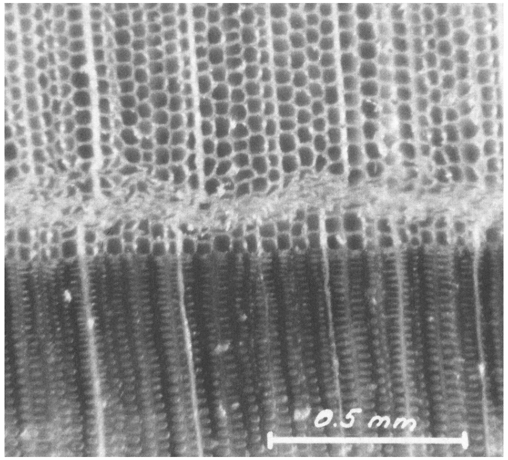
3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Compression perpendicular to grains



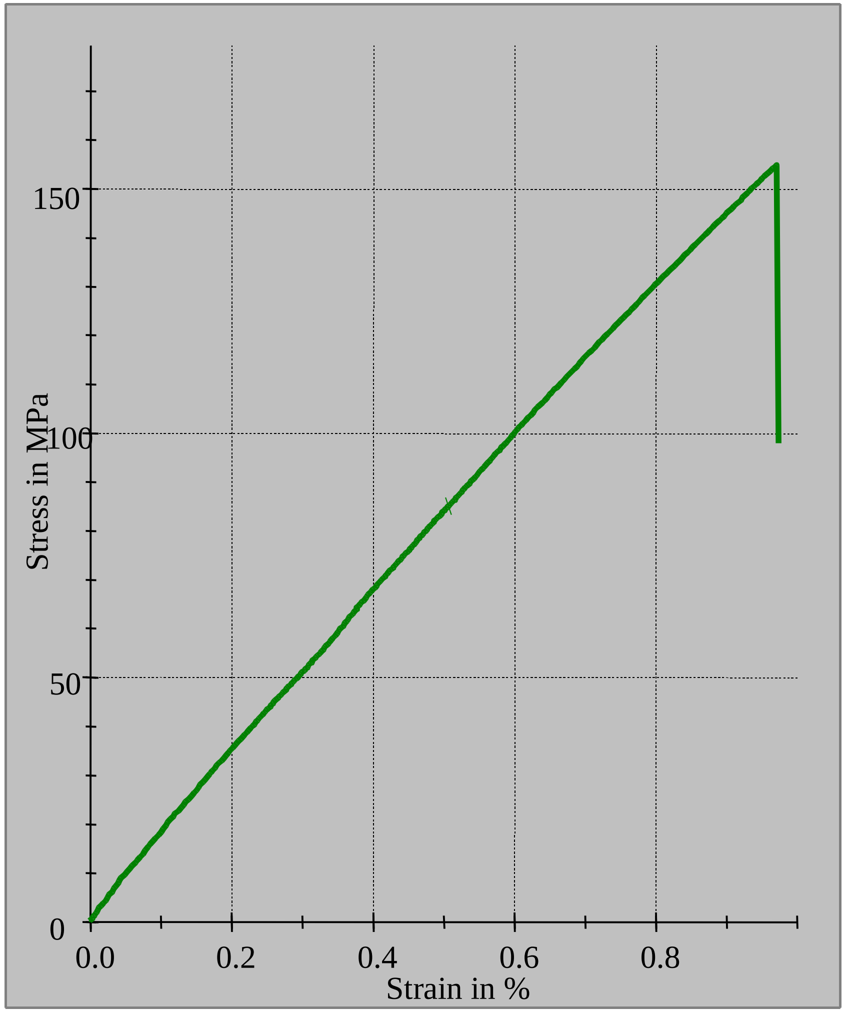
- Plastic behaviour
- High deformation
- Low strength
- Hardening
- **Bad** way of loading



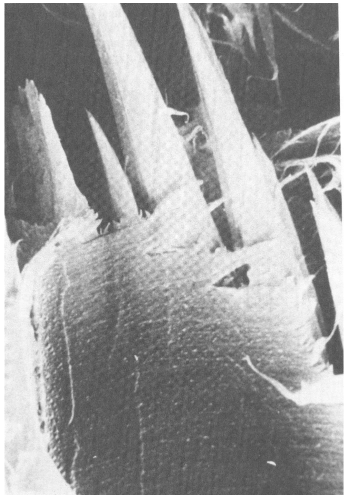
3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Tension parallel to grains



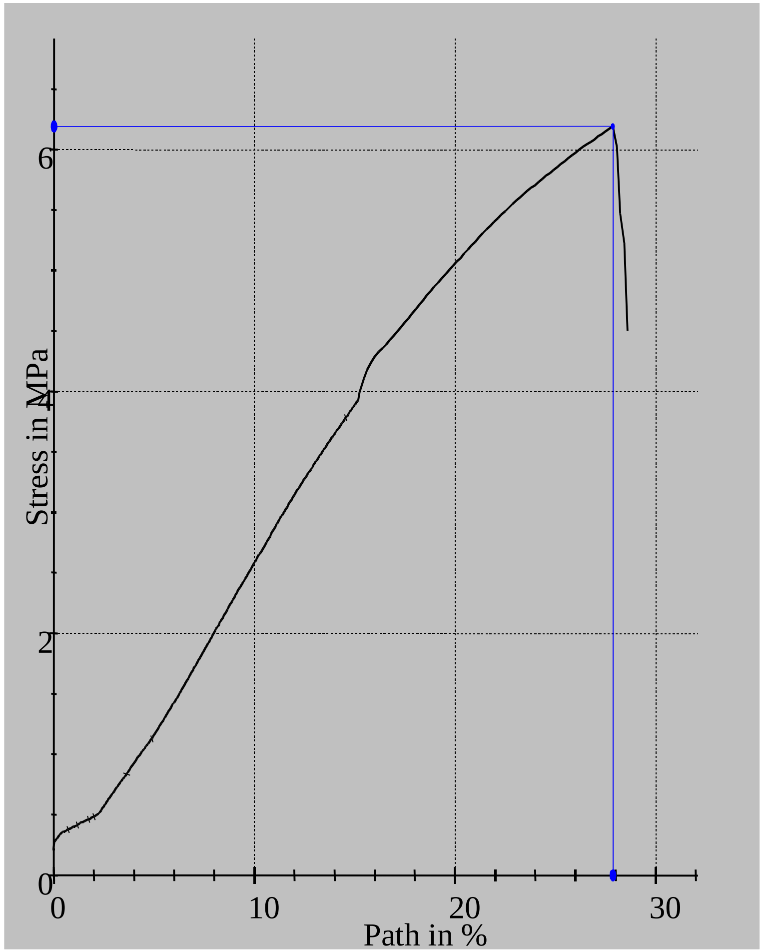
- Elastic brittle behaviour
- Fails by tearing
- High stiffness
- Very high strength
- Low deformation (1 %)
- **Good** way of loading



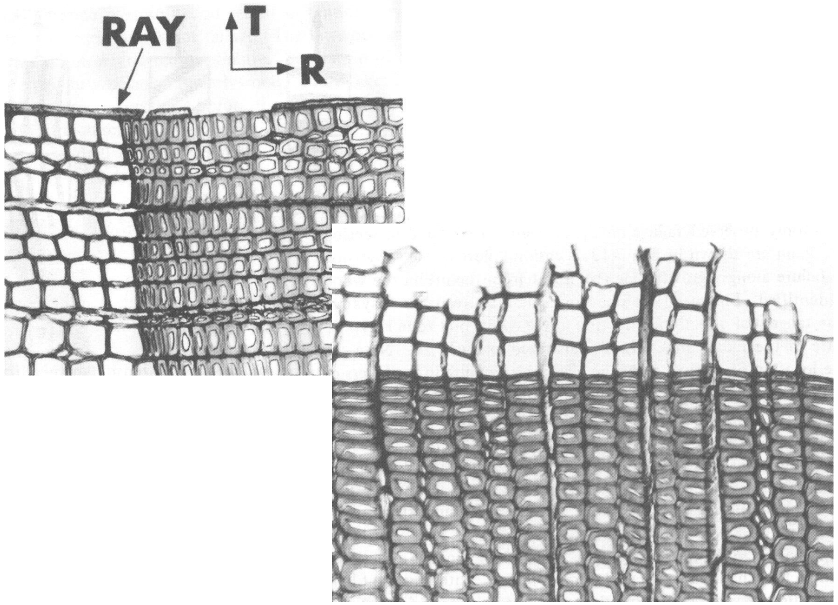
3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Tension perpendicular to grains



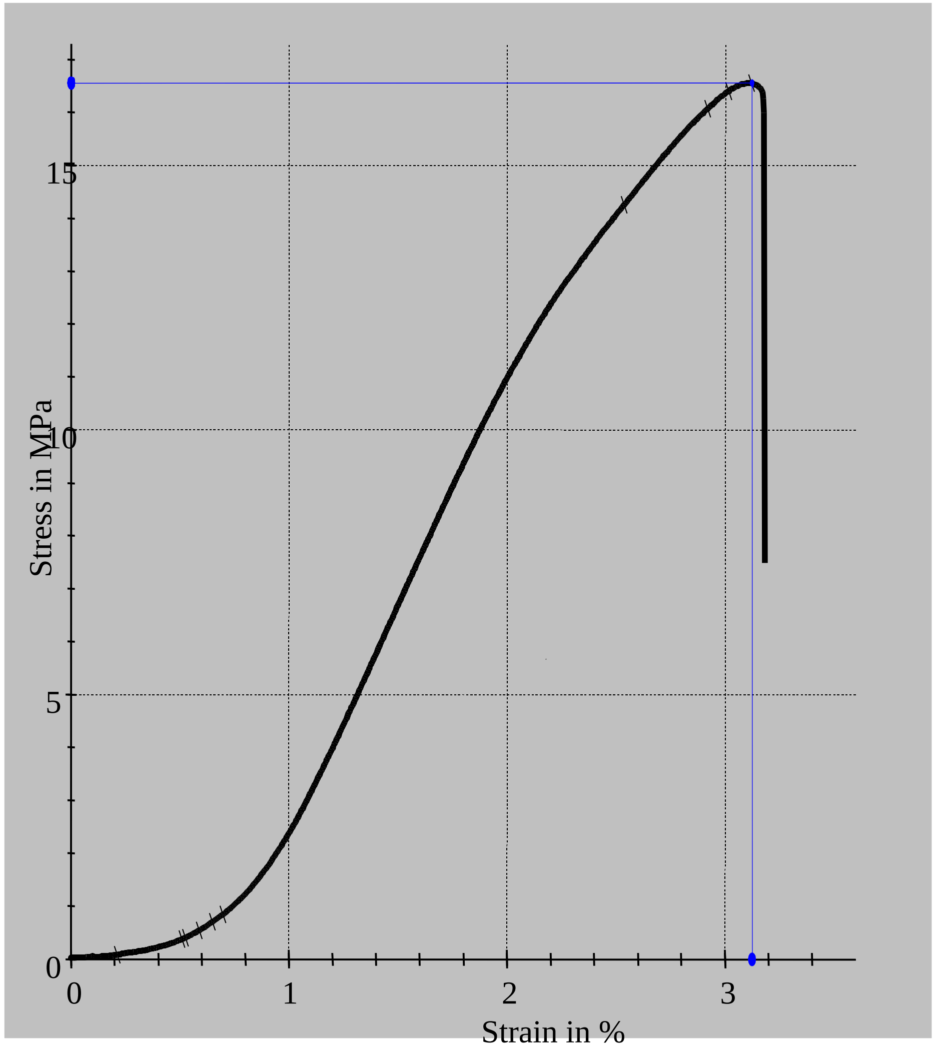
- Brittle material
- Very low strength and stiffness
- The **worst** way of loading
- Fails by tearing



3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Shear

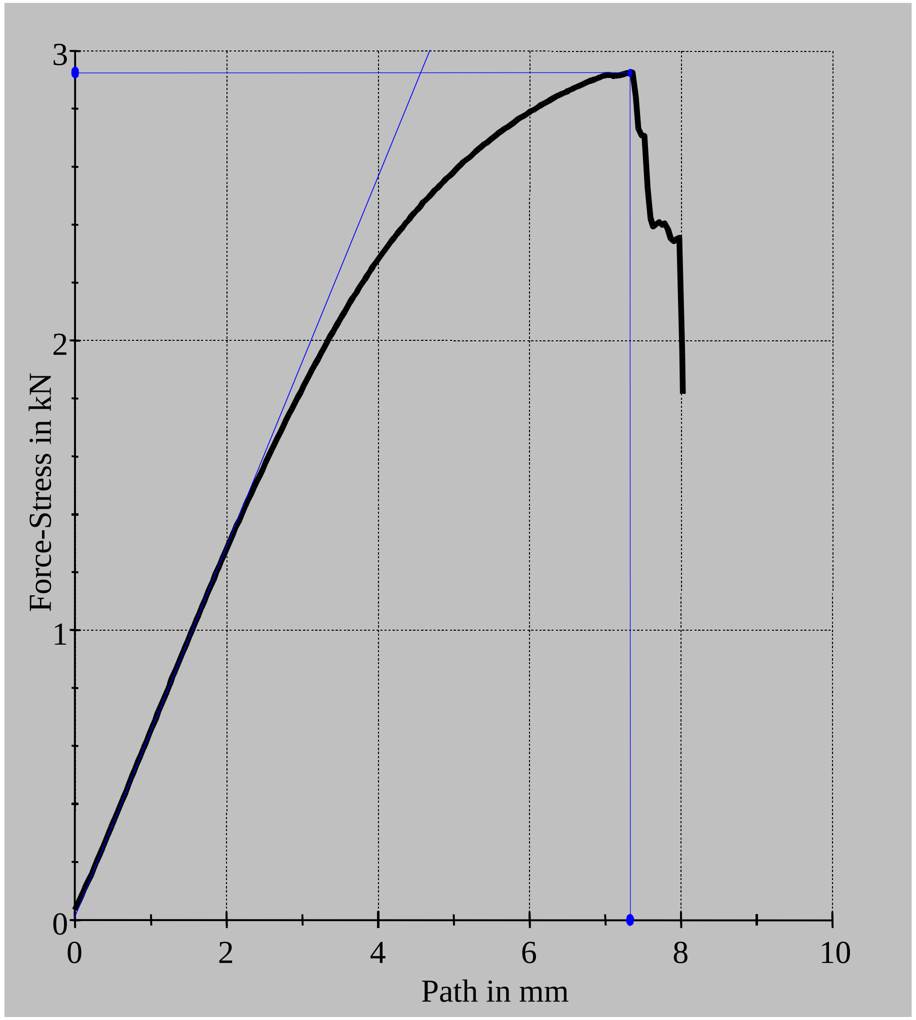


- Viscoelastic behaviour
- Low strength and stiffness (one exception)
- Fails by shearing
- **Bad** way of loading

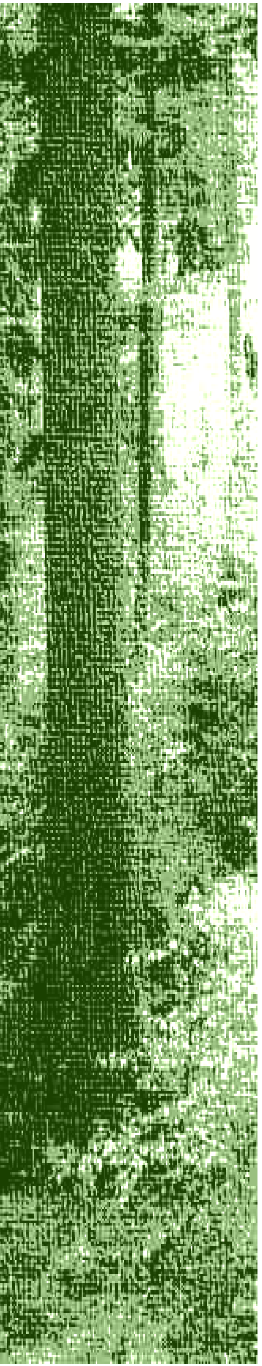
3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Bending



- Combined loading
- Viscoelastic brittle material
- Fails by breaking on the tension side
- Combines compression and tension



3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Wood – what a strange thing !

- Wood mechanical behaviour depends on:
  - Mode of loading (bending, compression, etc.)
  - Direction of loading relative to grains
  - Velocity and maintenance of loading
  - Water content
  - Temperature of wood

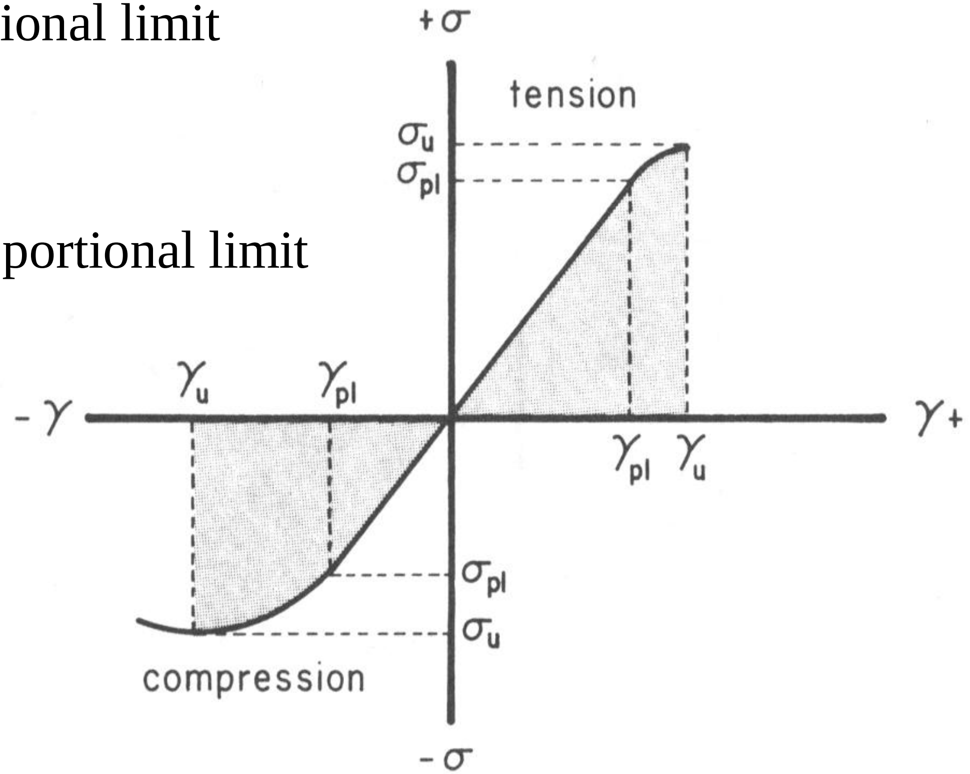
- Wood can behave like:
  - Plastic – viscoelastic – elastic matter
  - Ductile – brittle

3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Key terms

- **Modulus of elasticity** – stiffness of wood
- **Strength**
  - ultimate/maximal
  - strength at the proportional limit
- **Deformation**
  - ultimate/maximal
  - deformation at the proportional limit

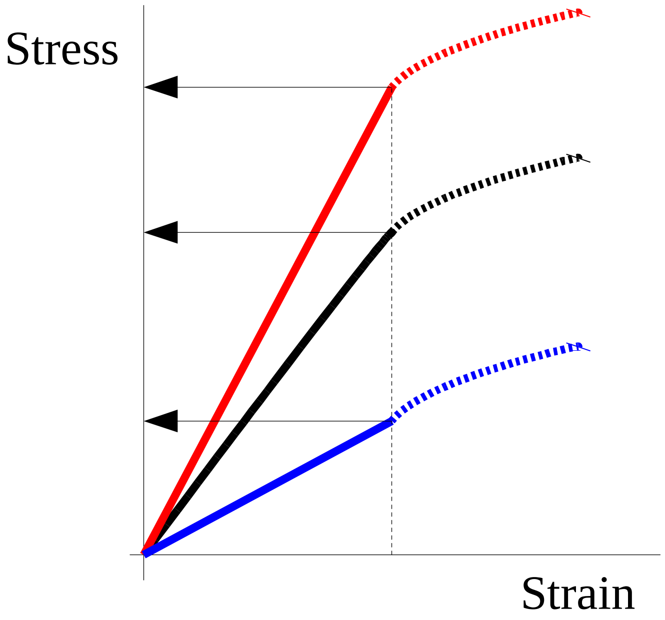


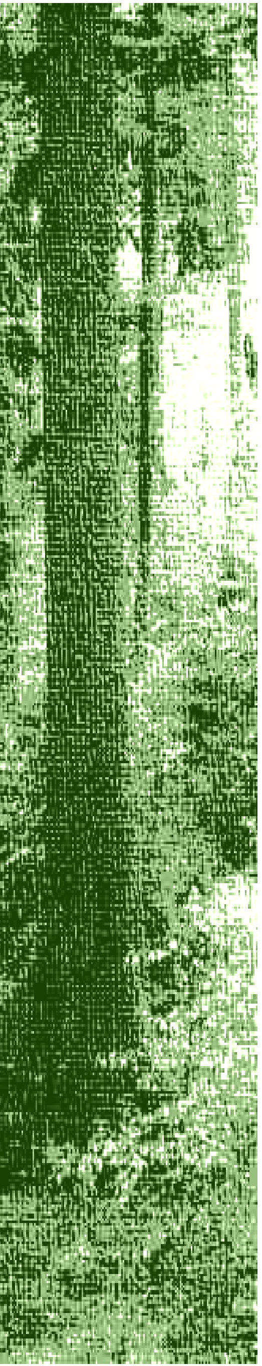
3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Modulus of elasticity (stiffness)

- Ratio between stress (strength) and relevant deformation
- Tangent of elastic part of stress-strain diagram
- Shows internal resistance of material against unit elongation
- E-modulus - describes the **stiffness** of the material. It represents the stress necessary for the unit deformation (strain) of the material [MPa, kN/cm2].



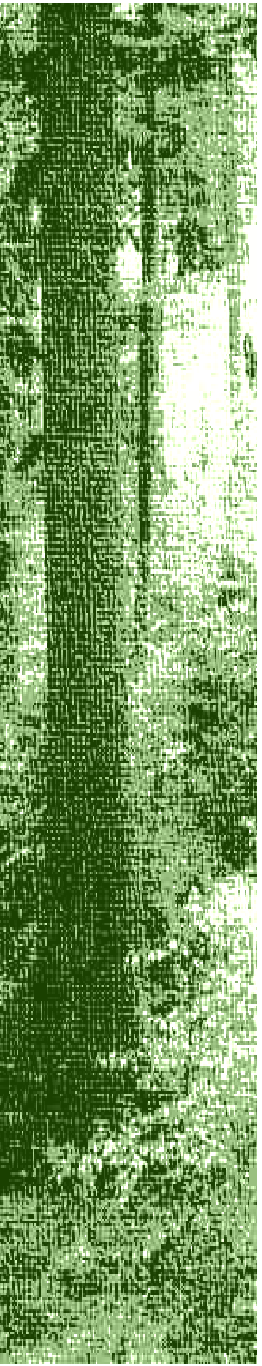


3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Modulus of elasticity (stiffness)

Taxon	Moisture (%)	Density (kg.m-3)	E (MPa)	G (MPa)
Spruce	**Green**	**497**	**7 300**	**400**
Picea abies	12	350	9 500	500
Beech	**Green**	**833**	**9 800**	**800**
Fagus sylvatica	12	600	12 600	1 100
Oak	**Green**	**833**	**8 300**	**-**

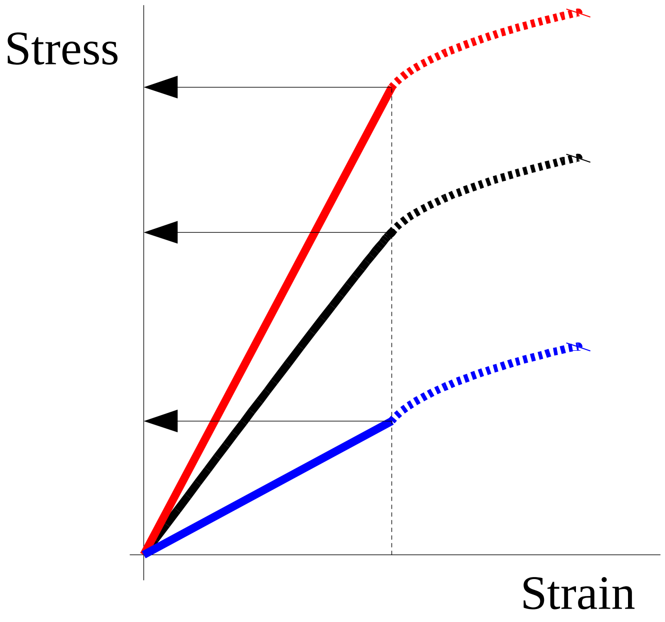


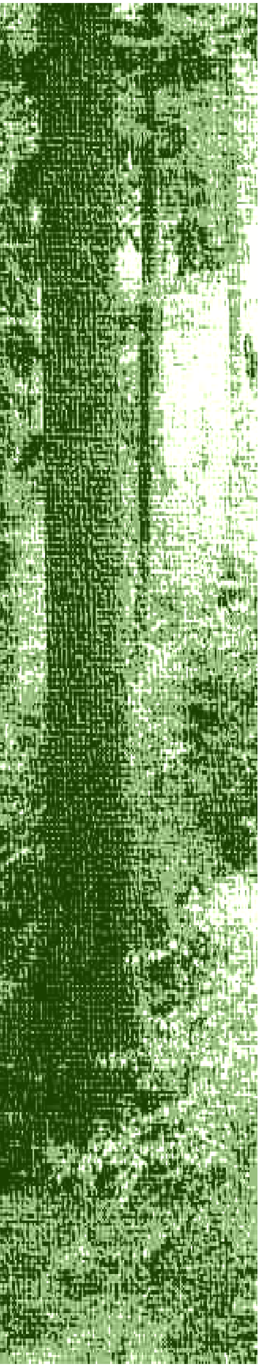
3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Strength of wood

- Force per area
- Expresses maximal bearable force of material
- Need to be distinguished from stress (it is the physical field, strength is the property)



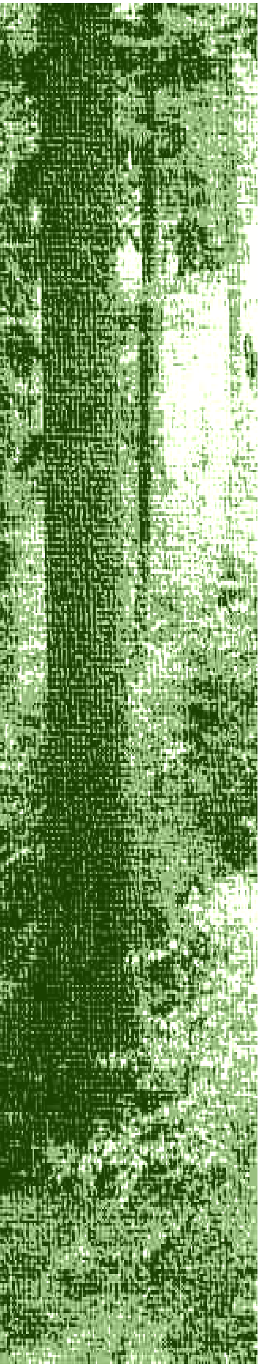


3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Strength of wood

Taxon	Moisture (%)	Density (kg.m-3)	MOR (MPa)	Comp. ‖ (MPa)	Tension ‖ (MPa)
Spruce	**Green**	**497**	**36**	**17**	
Picea abies	12	400	66	35	84
Beech	**Green**	**833**	**65**	**28**	
Fagus sylvatica	12	689	110	54	130
Oak	**Green**	**833**	**59**	**28**	

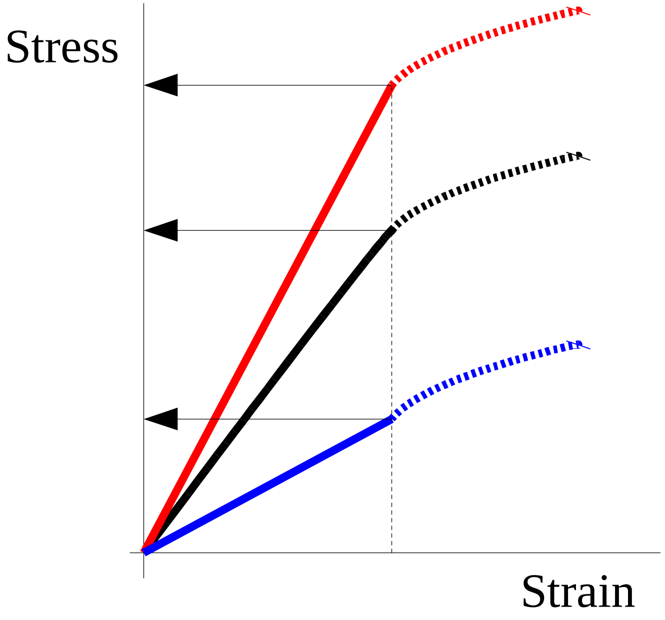


3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Deformation

- Displacement x deformation (strain)
- Deformation = relative change of dimensions
- Three types of deformation
    - elastic (reversible immediately)
    - elastic in time (reversible during certain time period)
    - plastic (irreversible)
- Transversal deformation



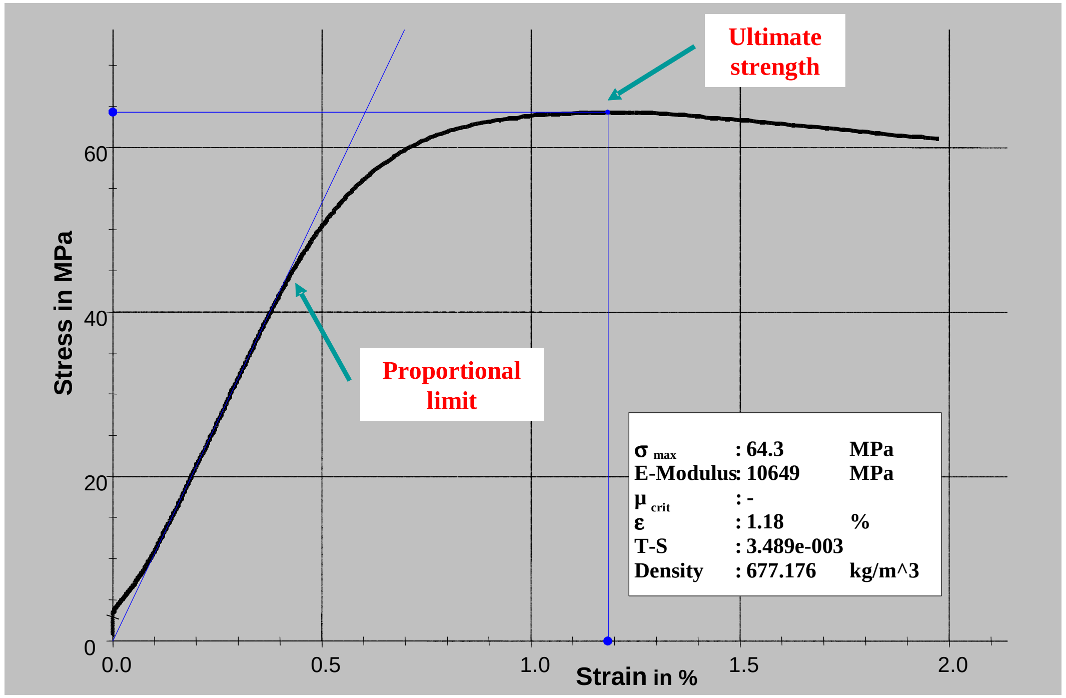
3.3 Intro to wood science

Relation between stress and strain

Strain – only quantity which could be easily measured (compared to stress)

E-modulus – only material **constatnt** ever known (the criterion of the stiffness) because of the wood nature (chemical constitution and anatomical structure)

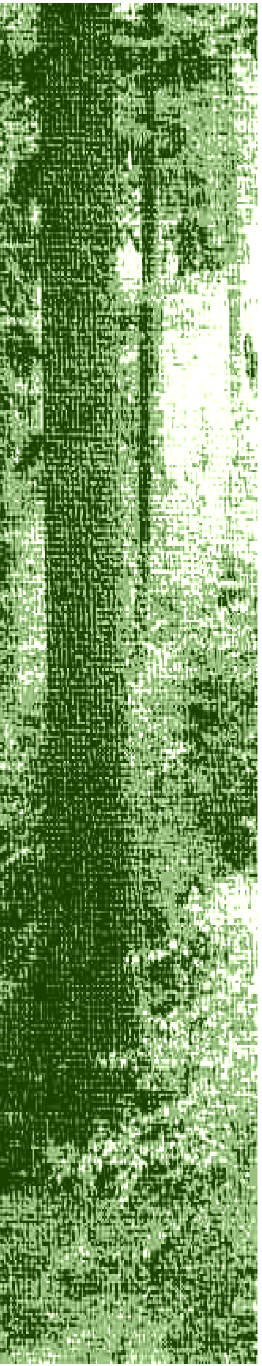
$$\sigma = E\,\varepsilon$$



Ultimate strength

Proportional limit

σ_{max}	: 64.3	MPa
E-Modulus	: 10649	MPa
μ_{crit}	: -	
ε	: 1.18	%
T-S	: 3.489e-003	
Density	: 677.176	kg/m^3



The development of the approach is schematically presented. The main limitations of the adopted approach are that it does not account for large tree deflection or for dynamic effects, and that growth stresses are not considered neither. The hypothesis on which the mechanical analysis is based are summarized in the following lines, being the ones usually adopted by several authors who have studied the bending of tree trunks and branches:

a)The stem of standing trees can be treated as an elastic cantilever beam rigidly fixed on one side and free on the other. Its section varies with height, and this non-uniform taper can be described by a mathematical function.

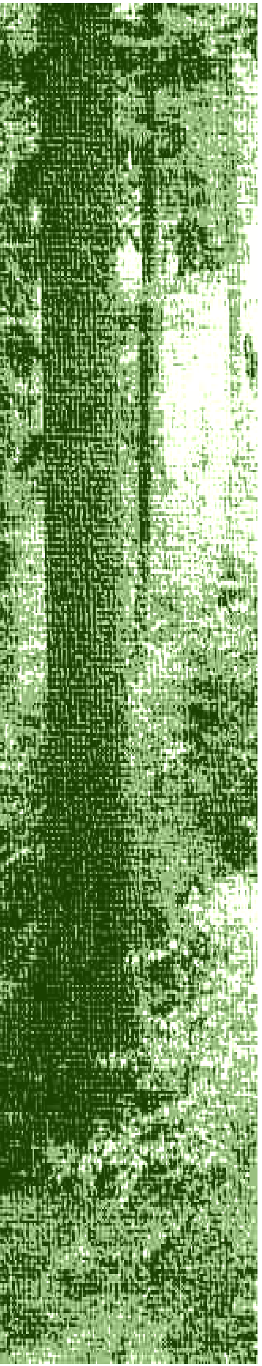
b)The transverse section of the stem is considered either circular or elliptic, with an area S and a second moment of inertia I.

c)In order to calculate the self-weight of the tree, its canopy weight can be evaluated as a point vertical force applied in its centre of gravity.

d)In order to calculate the wind load, a horizontal point load applied also in the canopy centre of gravity can substitute it.

e)When bending, trees will usually fail on the compression side first, because wood is an extremely anisotropy material whose compression strength is about half the tensile strength (Mossbrugger, 1990). In the development of the method the most unfavourable case will always be considered, searching for the point where maximal compression stress occurs.

4 Components of Tree Stability



4.1 Tree geometry

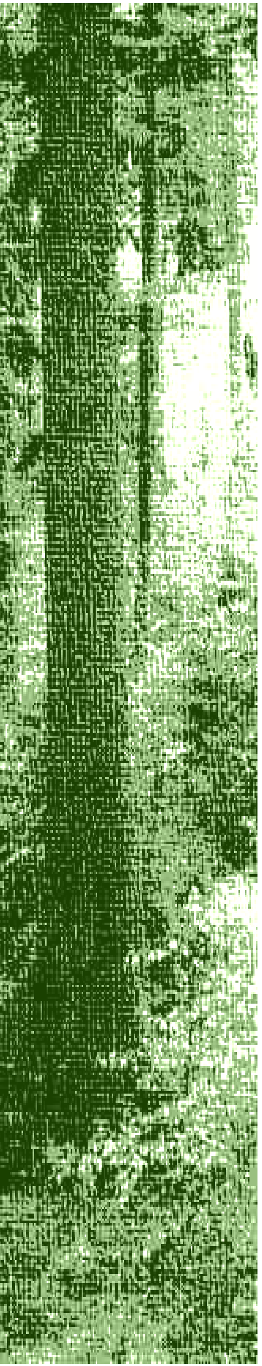
- The trunk of a tree has a specialised structure in order to support mechanical efforts, due to the self weight of the tree (crown and stem) and to the external loads (wind, snow).

4.2 Wood properties

- Wood structure, considered as a strengthening tissue, is supposed to be closely related to the stress level which affects it during the life of the tree.

4.3 Loads applied to tree

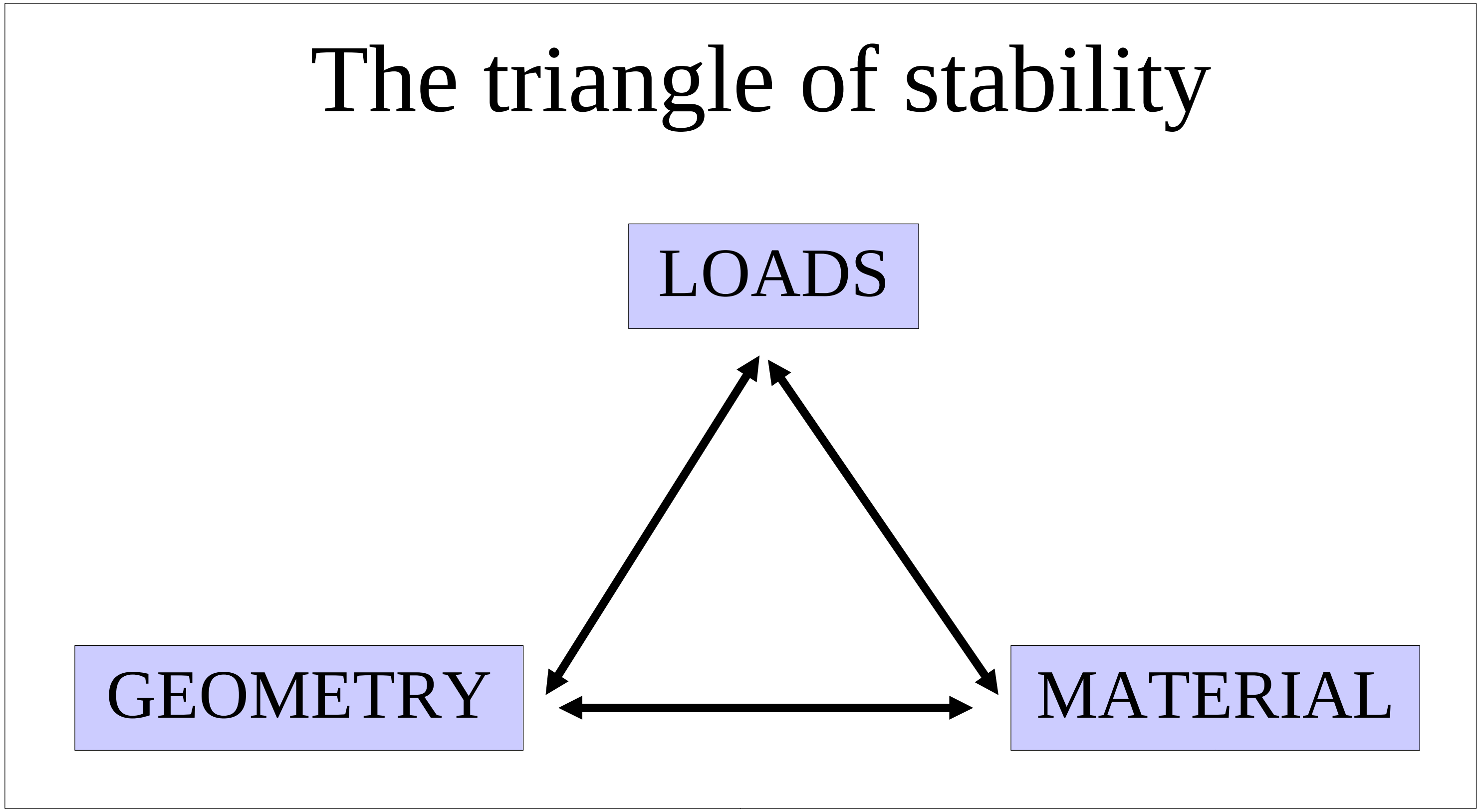
- The distribution of longitudinal stresses in the stem due to its self-weight and several wind loading is calculated using the structural theory of a cantilever beam



4.1 Tree geometry

4.2 Wood properties

4.3 Loads applied to tree

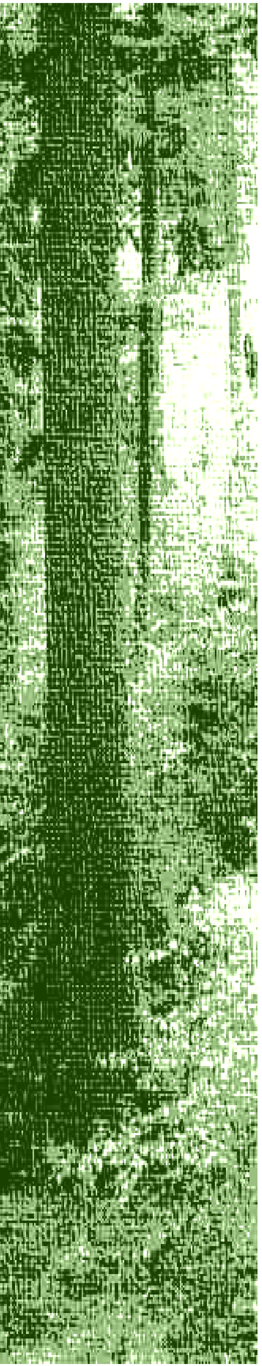


The triangle of stability

LOADS

GEOMETRY

MATERIAL



4.1 Tree geometry

Objectives

What is the optimum geometry of tree – stem, branches, crown, roots ?

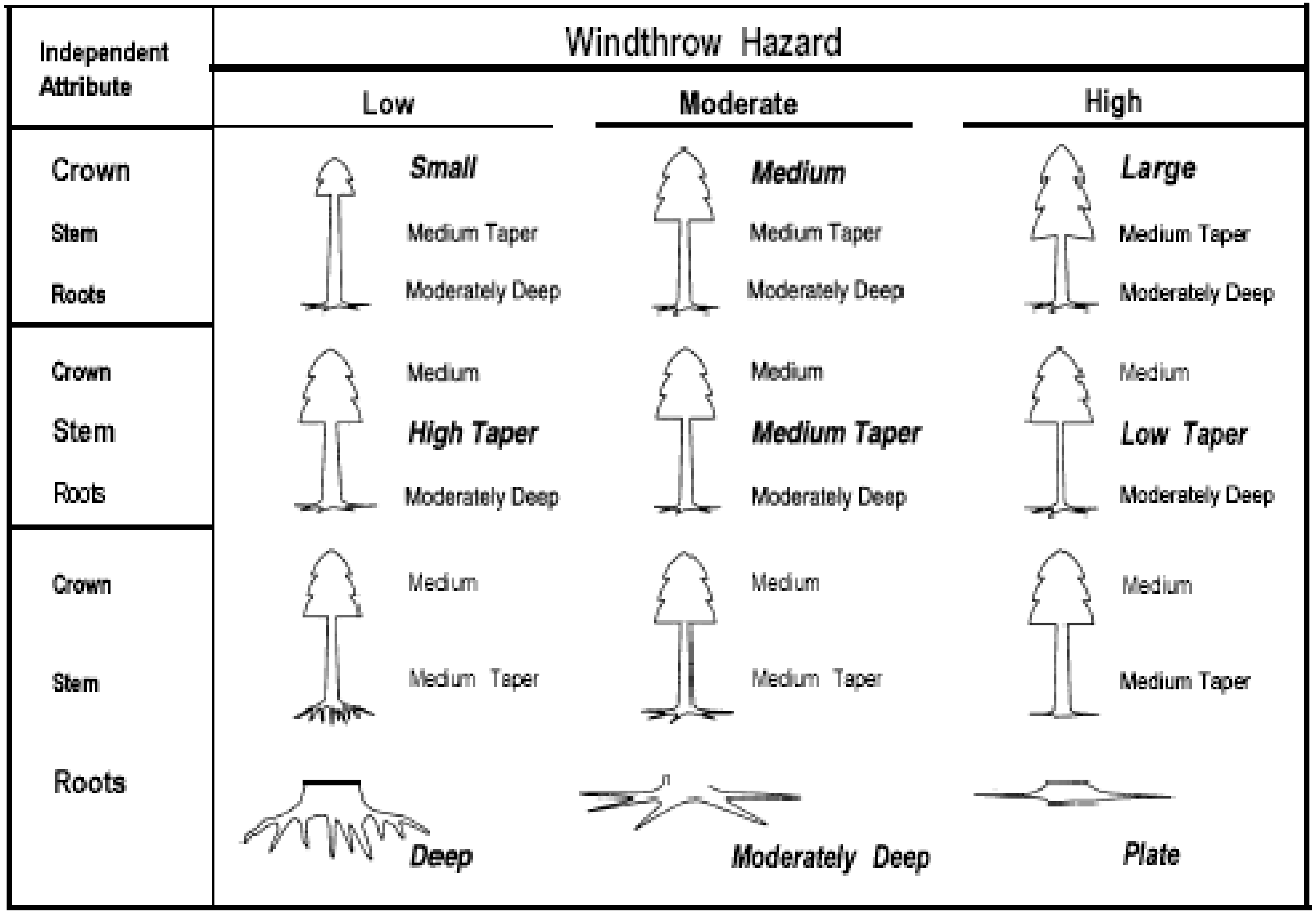
What is the optimum rate of tapering depending on the kind of loading ?

1. The geometry of tree (stem, branches and roots) is probably largely controlled by **biomechanical requirements**.

2. The taper is advantageous for tree to save structural material and not to rely on extremely high safety factors against fracture, in particular near the top of the tree.

4.1 Tree geometry

Special cases



Independent Attribute	Windthrow Hazard		
	Low	Moderate	High
Crown Stem Roots	***Small*** Medium Taper Moderately Deep	***Medium*** Medium Taper Moderately Deep	***Large*** Medium Taper Moderately Deep
Crown Stem Roots	Medium ***High Taper*** Moderately Deep	Medium ***Medium Taper*** Moderately Deep	Medium ***Low Taper*** Moderately Deep
Crown Stem Roots	Medium Medium Taper ***Deep***	Medium Medium Taper ***Moderately Deep***	Medium Medium Taper ***Plate***

4.1 Tree geometry

4.1.1 Shape of the trunk

The trunk of the tree is a **nonprismatic** tapered cantilever beam.

It is fixed in the ground (soil) due its roots.

The stem is **bearing structure** – its function is to bear the crown with leaves and fruits, to spread the active crown area above the neighbours, to occupy maximum of the roam for light.

The highest trunks are successive (the phototropic growth – is opposite to the requirement of the stability!).

Higher trunk is more advantageous for dissemination of the seeds.

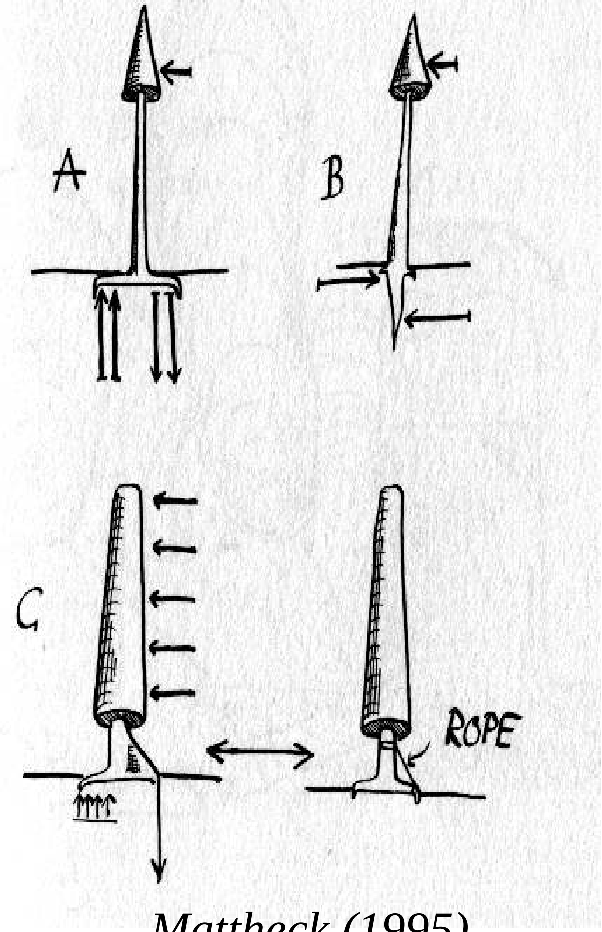
4.1 Tree geometry

4.1.1.1 Shape of the trunk – Tree height

The highest tree of the world was the *Pseudotsuga menziesii* with the height 140 m.

Note that:

- The higher the tree – the longer lever arm.
- The higher the tree – the higher wind velocities
- The higher the tree – the worst water supplementation



Mattheck (1995)

4.1 Tree geometry

4.1.1.2 Shape of the trunk – Stem cross-section

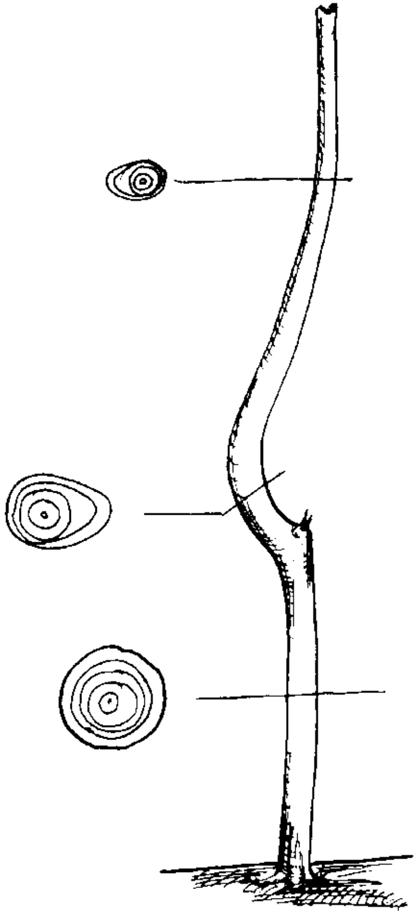
The stem have round cross-section. This is more advantageous from the mechanical point of view.

The cross-section can be hollow. It is necessary to remember, that the hollowness of the trunk is not disadvantage.

The bearing capacity of the tube-like structure does not decrease directly with the loss of the material. It results from the way of loading.

In the bending is the bearing capacity of the trunk given by the *modulus of inertia I* or *section modulus W.*

You can calculate, that the tube with the remaining residual stem-wall 0.1 of the diameter, has still 50 % bearing capacity.



Mattheck (1995)

4.1 Tree geometry

4.1.2 Shape of branches

Branches are horizontal beams, which are fixed in the stem. This connection between the trunk and the branch is very strong. Is allowed by the systematic overgrowing of the wood layers of the trunk and the branch. Resultant structure look like screw. It allows to carry branches with weight of several tons.

Permanent loading of branches (bending due their own weight) causes the cross-section deviation. Branches have oval shape, which is caused due the production of the reaction wood.

The same principle you can see on the leaning stems on the picture.

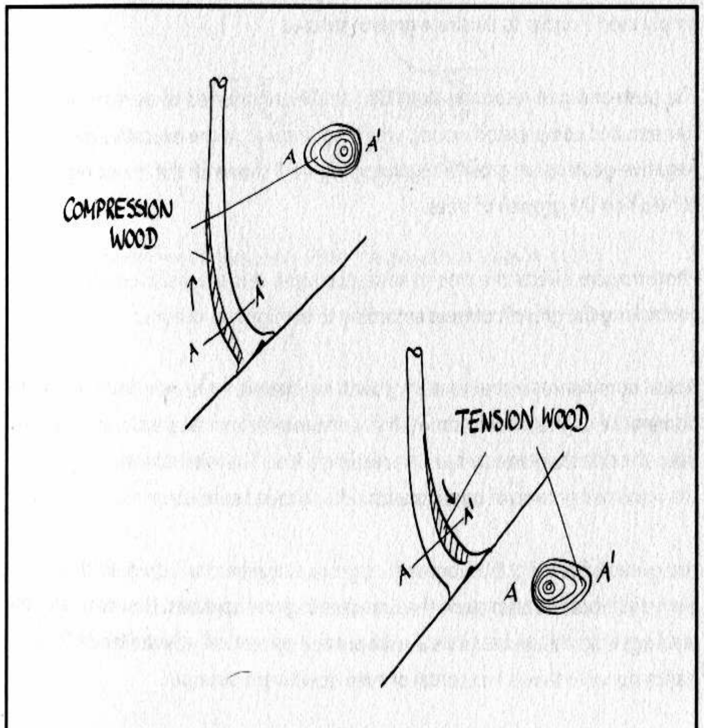


Figure 7: Gymnosperms are pushed upward into the vertical position by formation of compression wood at their lower sides facing the soil. Angiosperms are pulled into position by formation of tension wood at their upper sides facing away from the soil.

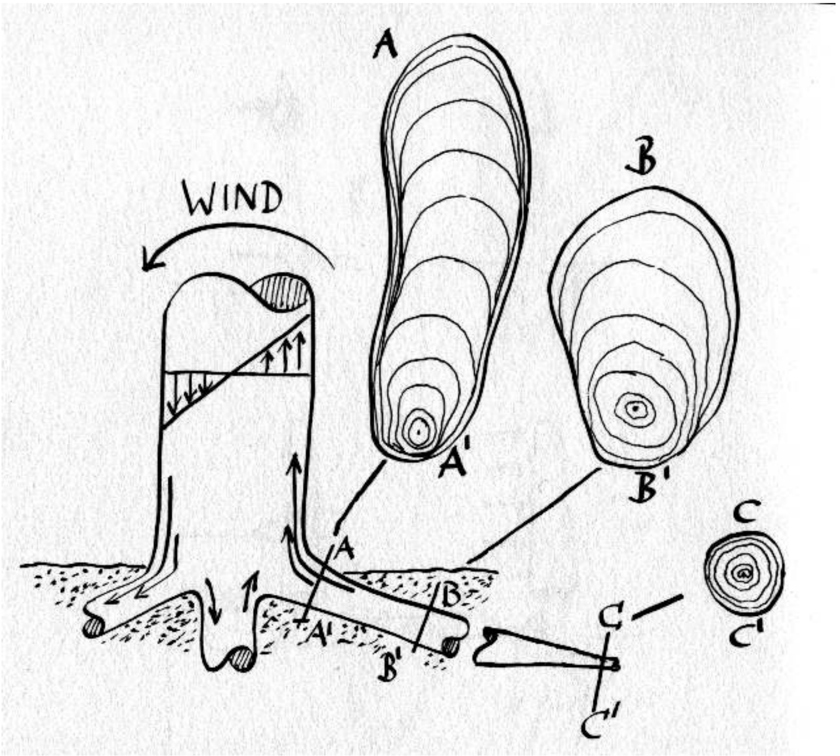
Mattheck (1995)

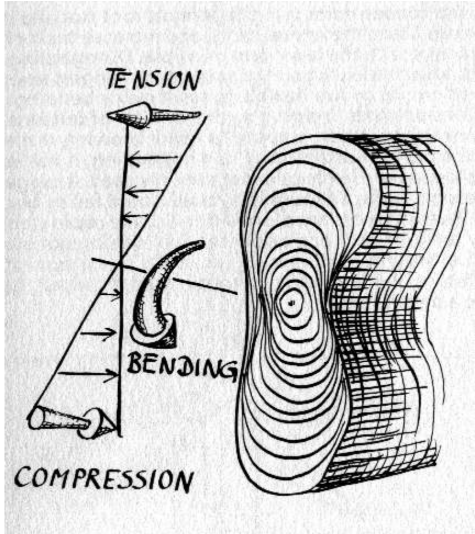
4.1 Tree geometry

4.1.3 Shape of roots

The roots have to transmit the forces and stresses arising in the crown and the trunk to the soil. There are these forces spread out by the friction between the roots and soil.

The shape of roots is also optimised to the functions, which they have to realize.





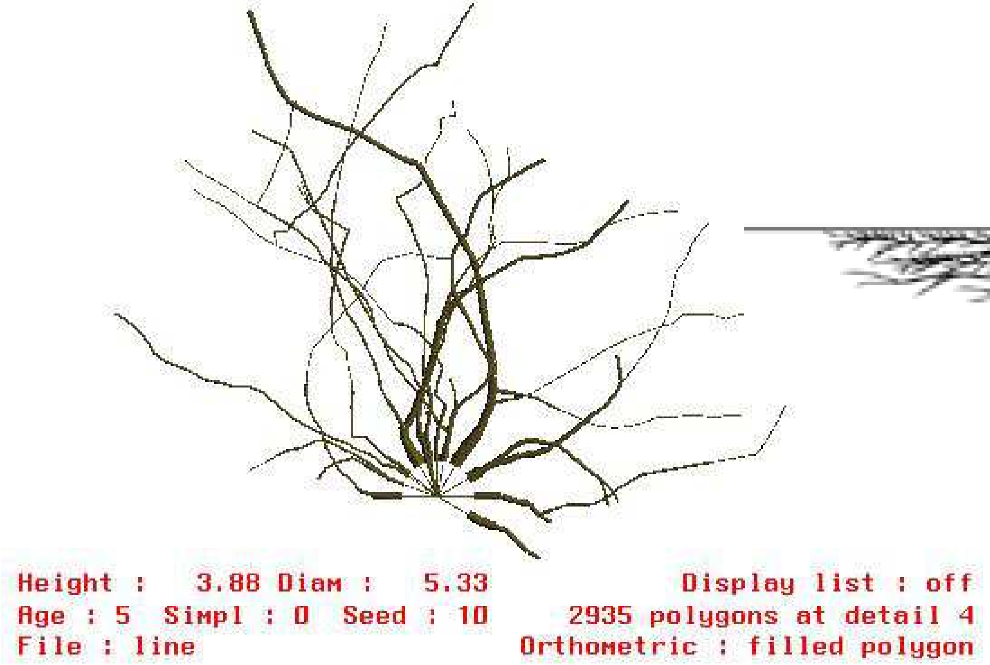
Mattheck (1995)

Wood is formed in accordance with the dominant force flow both axially and circumferentially.

4.1 Tree geometry

4.1.4 Shape of root system

The unilateral development of root system is a measure of asymmetric loads.



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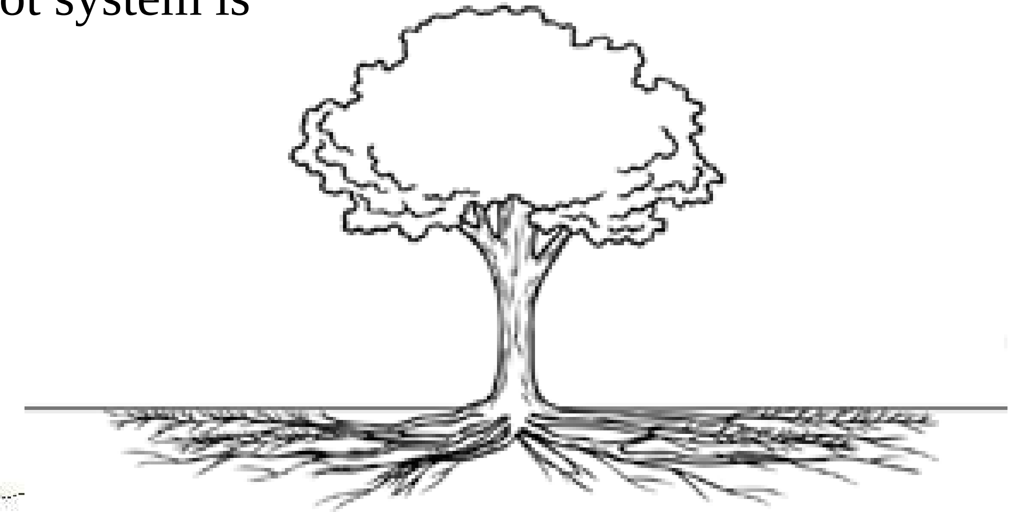


4.2 Wood properties

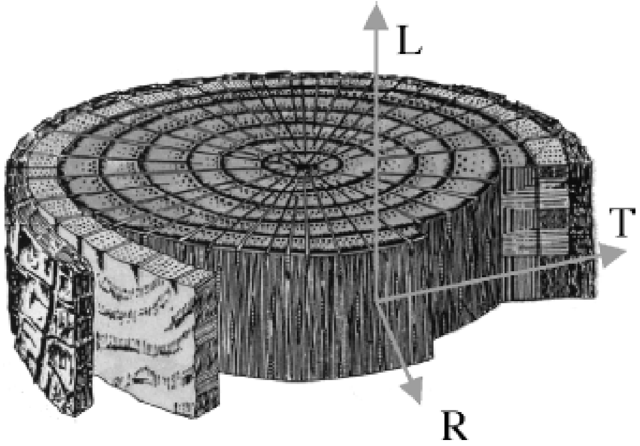
Objectives

1. Methodological issues
    - 1.1 Wood at different moisture and physiological activies
    - 1.2 Dimensions of standard specimens for determination of properties
    - 1.3 Statistical processing of data
    - 1.4 Determining of modulus of elasticity and stress at proportional limit

2. Mechanical properties of wood

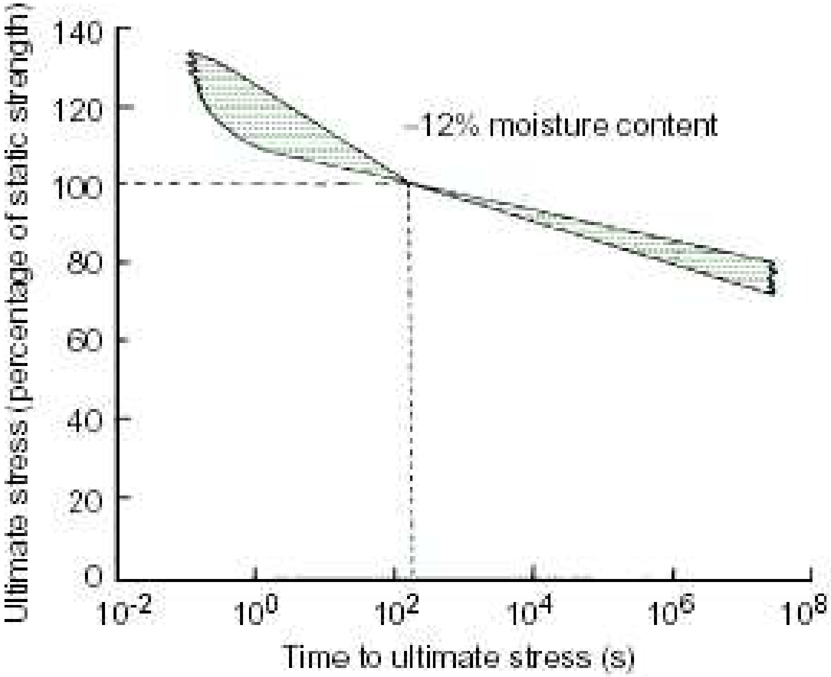
3. Relationship between properties from static and dynamic material tests

4. Items needed to be address

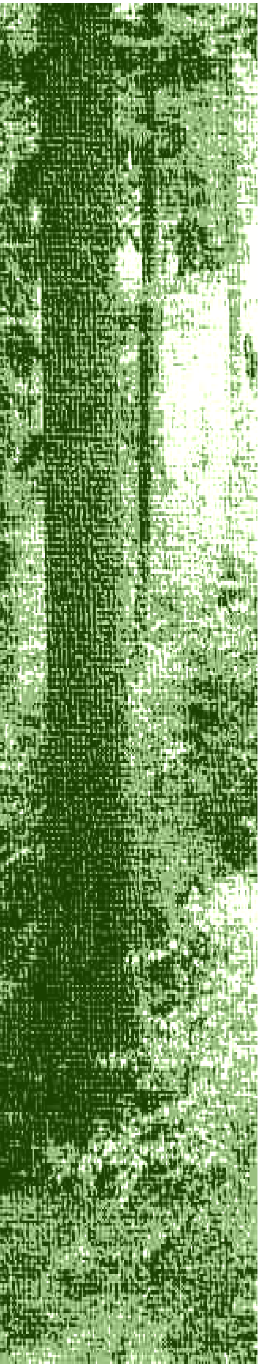


4.2 Wood properties

Relationship between properties from static and dynamic material tests



- Relationship of ultimate stress at short-time loading to that at 5 min loading, based on composite of results from rate-of-load studies on bending, compression, and shear parallel to grain.
- Variability in reported trends is indicated by width of band (Forest Products Laboratory 1999).



4.2 Wood properties

(Wessolly, Erb (1998))

Stuttgart Material Properties of Wood

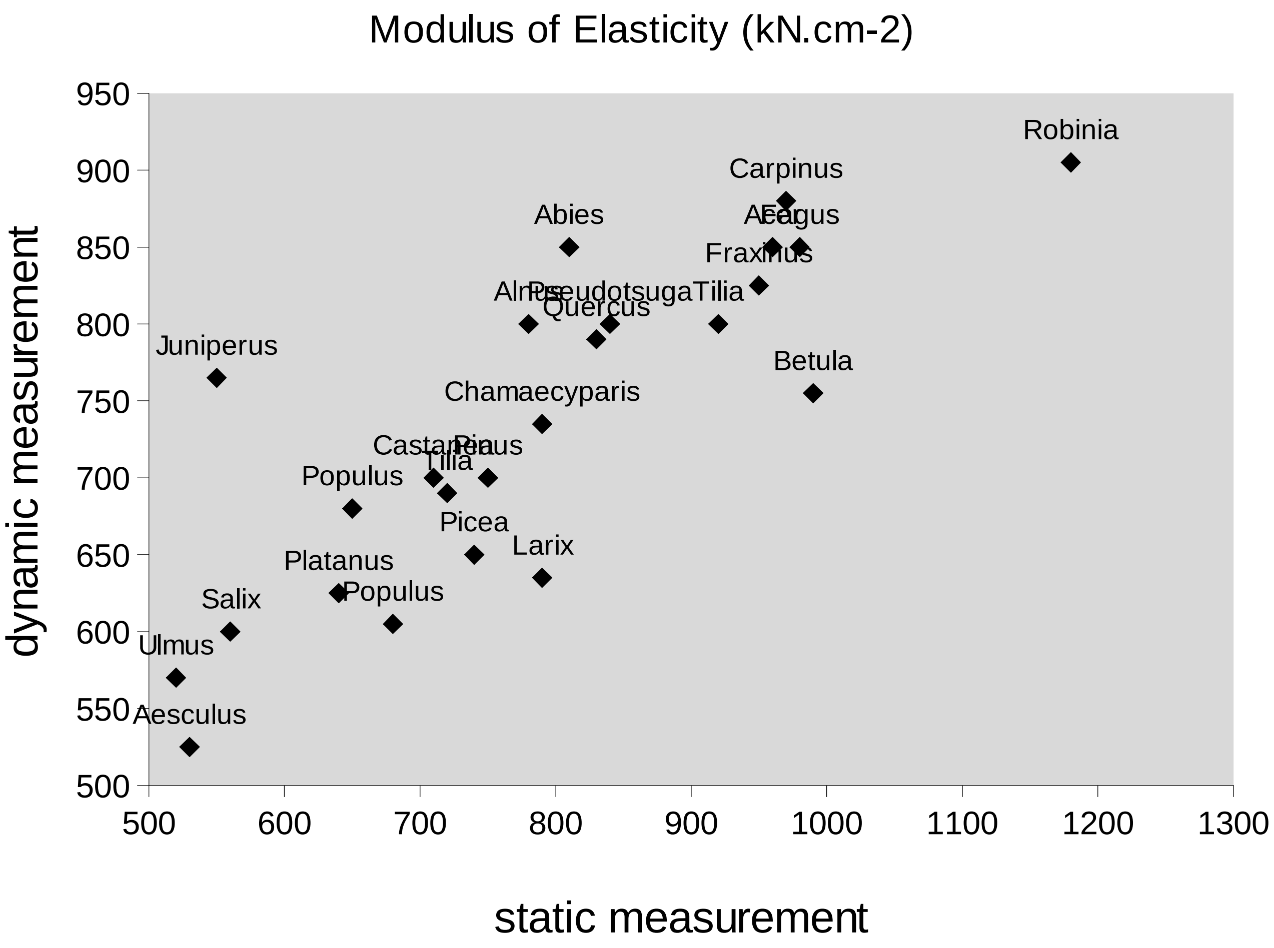
green wood, dynamic measurement (1 Hz)

green wood, static measurement

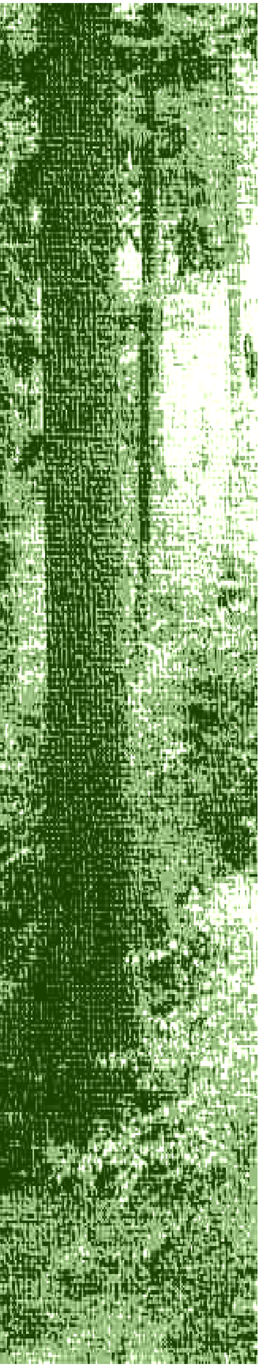
Common species names	**Specific gravity** -	**Modulus of elasticity** kN/cm2	**Deformation prop. limit** %	**Compression prop. limit** kN/cm2	**Modulus of elasticity** kN/cm2	**Compression prop. limit** kN/cm2
alder (*Alnus*)	0,86	800	0,25	2,0	780	2,2
ash (*Fraxinus*)	0,93	825	0,32	2,6	950	2,7
aspen (*Populus*)	0,76	680	0,24	1,6	650	1,6
basswood (*Tilia*)	0,84	700	0,25	1,8	720	1,5
beech (*Fagus*)	1,0	850	0,26	2,3	980	2,8
birch (*Betula*)	0,88	705	0,31	2,2	990	2,6
black locust (*Robinia*)	0,95	705	0,28	2,0	1180	4,2
cedar (*Chamaecyparis*)	0,69	735	0,27	2,0	790	2,4
cedar (*Juniperus*)	0,75	765	*0,20*	1,5	550	2,1
douglas-fir (*Pseudotsuga*)	0,63	800	*0,25*	2,0	840	2,5
elm (*Ulmus*)	1,01	570	0,35	2,0	520	1,9
fir (*Abies*)	0,63	950	0,16	1,5	810	2,2
hornbeam (*Carpinus*)	0,99	880	0,18	1,6	970	2,7
horse chestnut (*Aesculus*)	0,92	525	0,27	1,4	530	1,7
chestnut (*Castanea*)	1,06	700	0,36	2,5	710	2,4
larch (*Larix*)	0,82	535	0,32	1,7	790	2,4
limetree (*Tilia*)	0,75	450	*0,38*	1,7	920	2,6
sycamore (*Acer*)	0,89	850	0,29	2,5	960	2,3
maple Norway (*Acer*)	0,92	700	0,36	2,6		
oak english (*Quercus*)	1,1	790	0,35	2,8	830	2,8
oak pubescent (*Quercus*)	1,0	720	0,28	2,0		
pine (*Pinus*)	0,82	700	0,24	1,7	730	2,2
poplar (*Populus*)	0,89	605	0,33	2,0	680	1,9
redwood (*Sequoiadendron*)	1,05	500	0,36	1,8		
rowantree (*Sorbus*)	1,07	600	0,27	1,6		
spruce (Picea)	0,70	650	0,32	2,1	740	2,0
sycamore (*Platanus*)	0,99	625	0,43	2,7	640	2,4
tree-of-heaven (*Ailanthus*)	-	560	0,36	2,0		

4.2 Wood properties

Relationship between properties from static and dynamic material tests

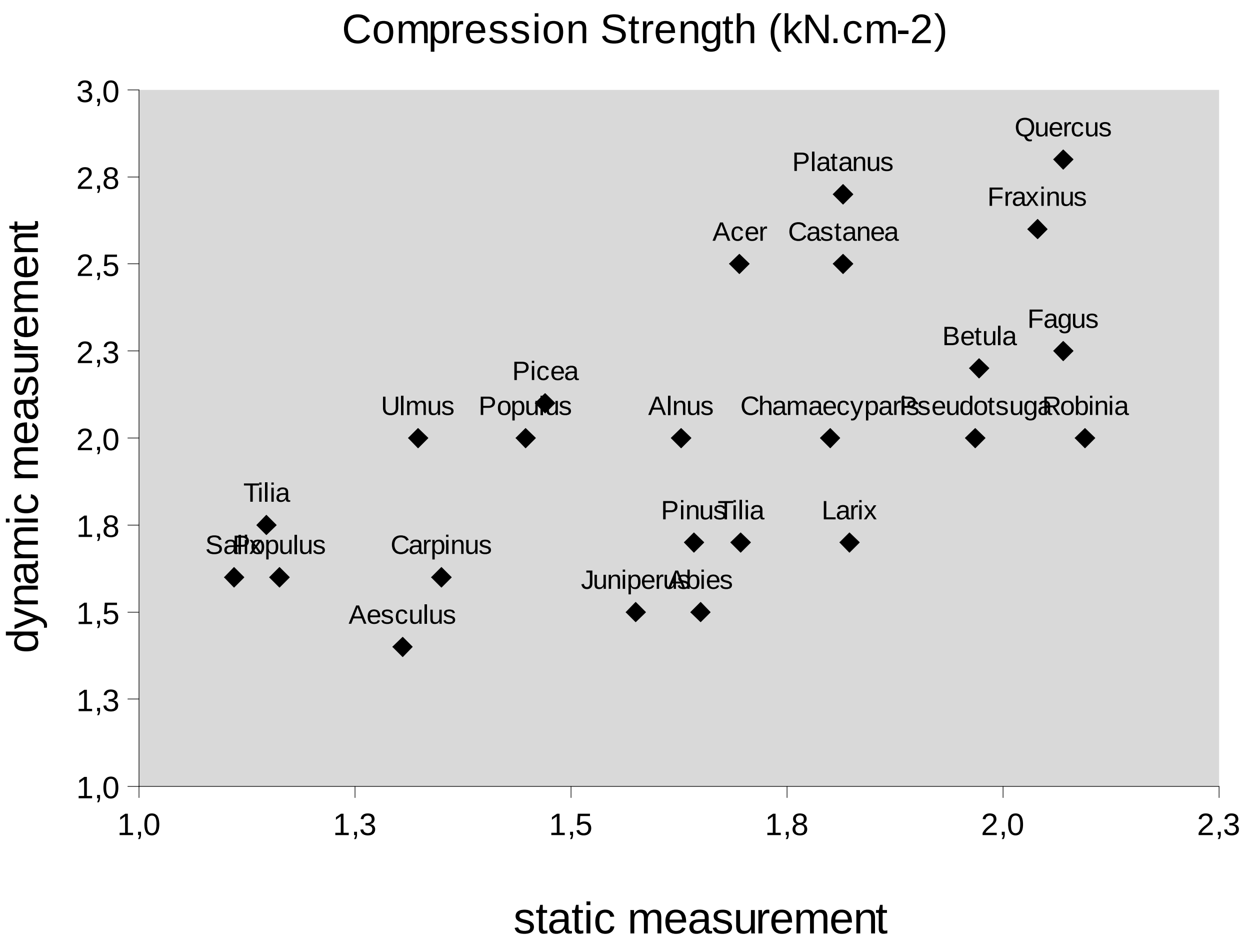


Relationship between static and dynamic measurement of modulus of elasticity in green condition.

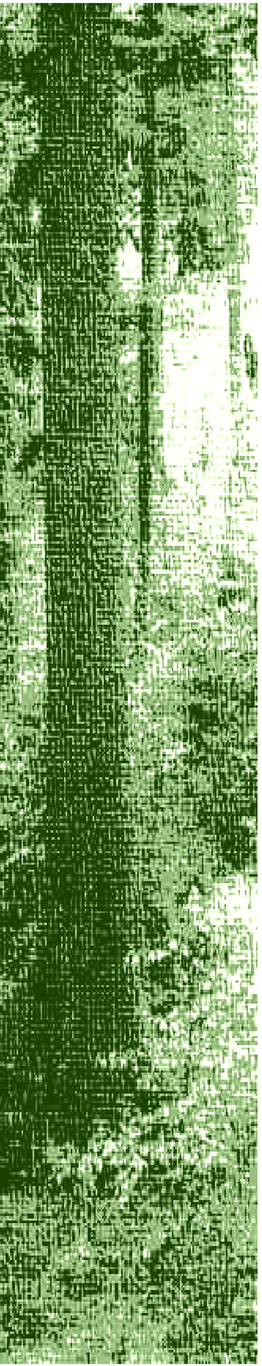


4.2 Wood properties

Relationship between properties from static and dynamic material tests



Relationship between static and dynamic measurement of compression strength at proportional limit in green condition.



4.3 Loads applied to tree

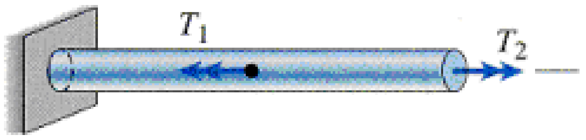
Objectives

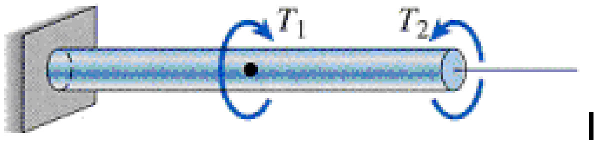
1. Identification of forces acting on tree.
2. Comparison of such forces respectively, the relative importance.
3. Determination of mechanical stresses caused by the wind and the weight of the tree.
4. Determination of how loads differ considerably in trunks and branches.

4.3 Loads applied to tree

The Loads – axial loads (normal and shear stresses) and moments (bending and torque):

- The main factor is the **wind**.
- The „others“ include own **weight** of the tree, **additional loads** – the snow, the ice, the water (from rain), birds and other animals (for instance arborists …), and **torque** due to eccentricity of crown center of gravity.
- Loads caused by the wind are much more higher then others.
- The gravitational force is relatively weak compared with the force of the wind on the crown until the tree starts to sway well away from the vertical axis.





4.3 Loads applied to tree

Summary of mechanical stresses acting in trees

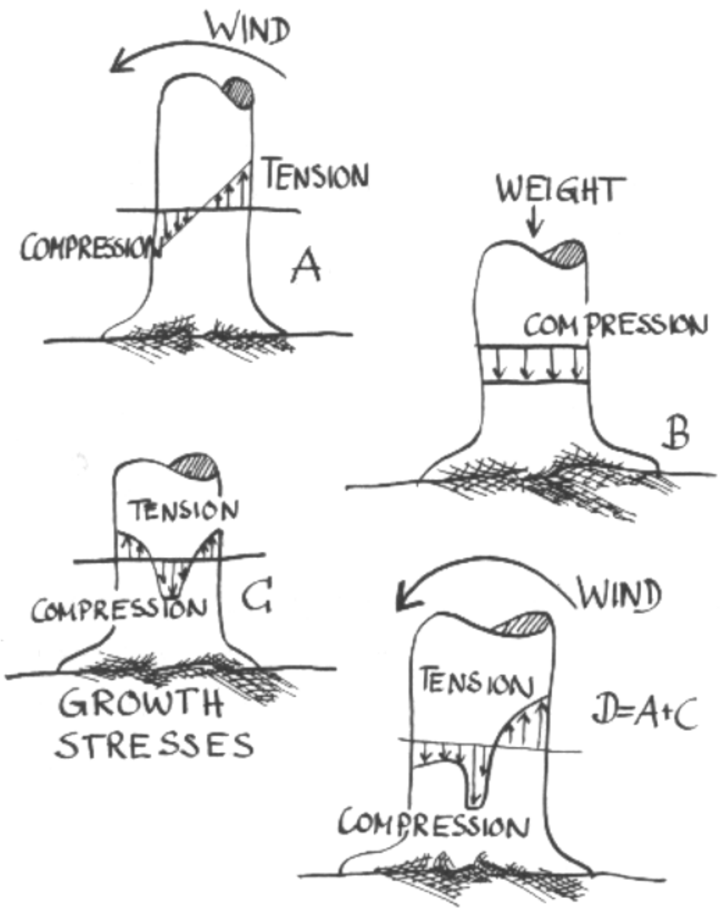
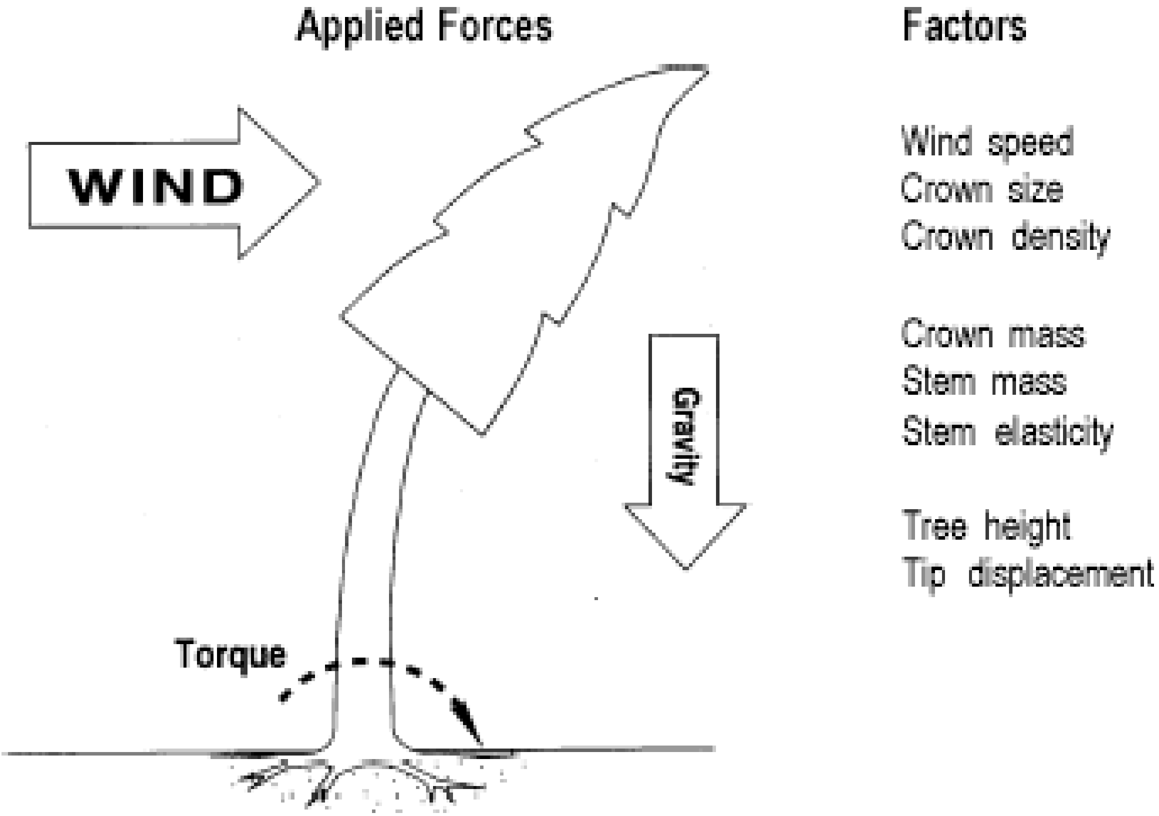


Figure 9: Main sources and effects of mechanical stresses acting in trees

Mattheck (1995)

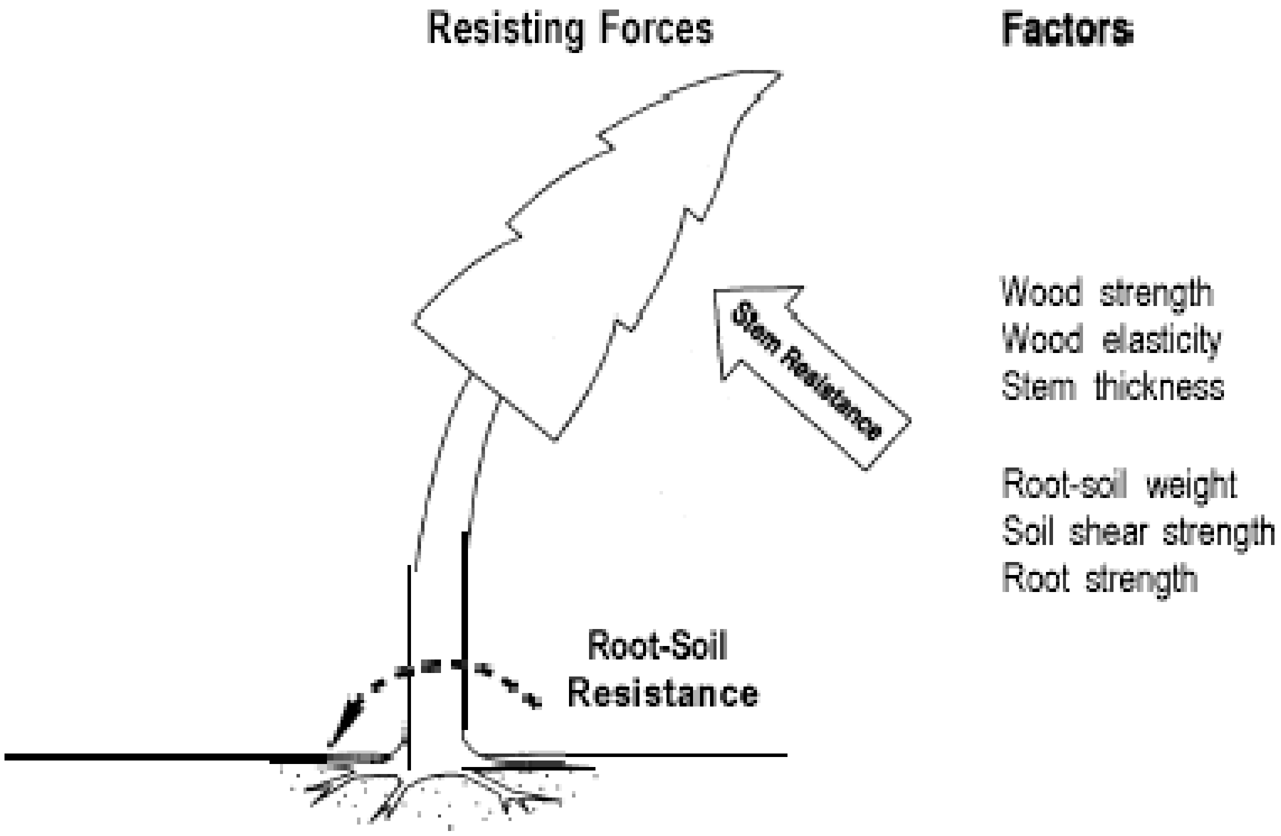
4.3 Loads applied to tree

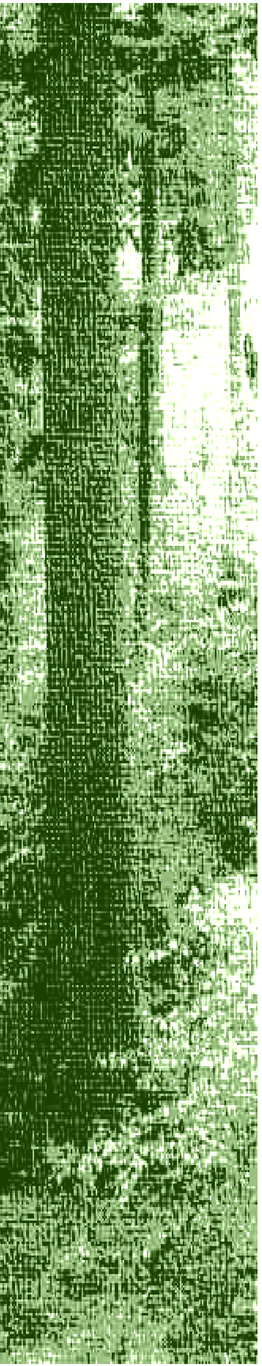
Factors affecting wind and gravitational forces acting on a tree.



4.3 Loads applied to tree

Factors affecting the resistance to wind and gravitational forces acting on a tree.





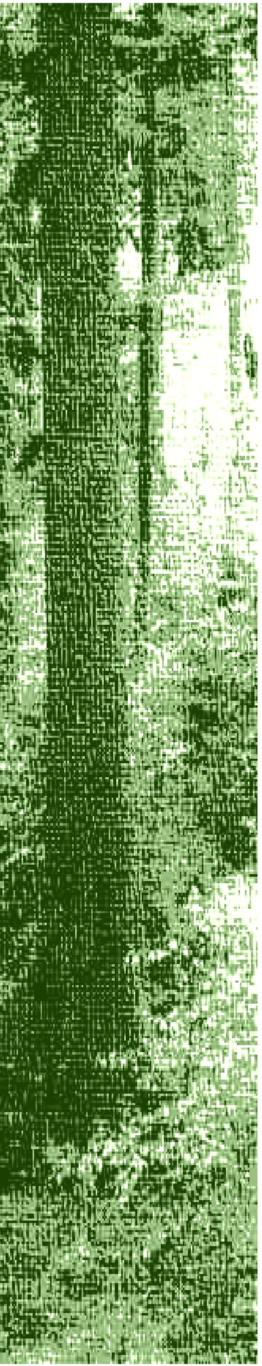
Conclusion

- Trees adapt their stem and root growth in response to the wind loading to which they are subjected in order to resist breakage or overturning.

- By understanding the behaviour of trees in strong winds and the mechanisms of root anchorage it has become possible to develop mechanistic models that predict

    1. the critical wind speeds for damage to occur and
    2. how these are affected by the properties of the trees

- Such an approach allows predictions of the impact of any arboricultural operations on tree stability and the design of strategies for reducing wind damage.



5.1 Application of mechanics of materials

Relationships between external loads and the intensity of internal loads and the resulting deformations based on the size, shape and type of material used.

5.2 Stability and failure of tree

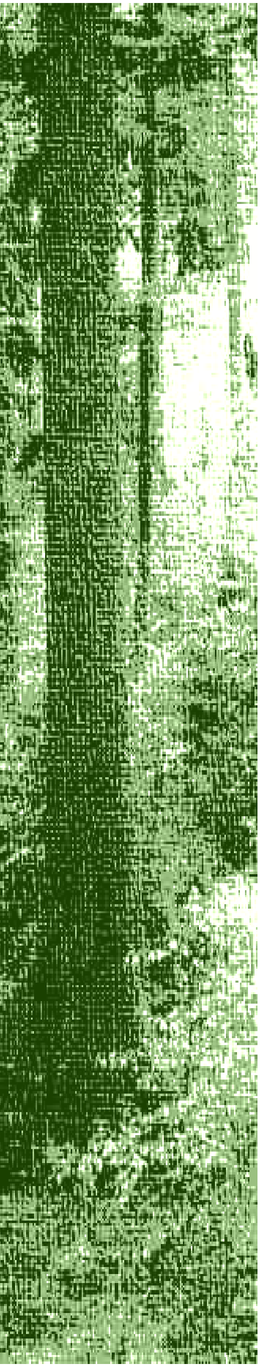
Failure occurs when forces acting on a tree exceed the resistance to breakage or uprooting of the root/soil system.

5.3 Factors influencing tree stability

The factors that affect windthrow and breakage of trees are those that influence the effectiveness of root anchorage, the strength and aerodynamic properties of the tree, and the direction and characteristics of the wind within and above the stand.

5.4 Influence of defects

Hazardous defects are visible signs that the tree is failing.
A tree with defects is not hazardous, however, unless some portion of it is within striking distance of a target.



5.1 Application of mechanics of materials

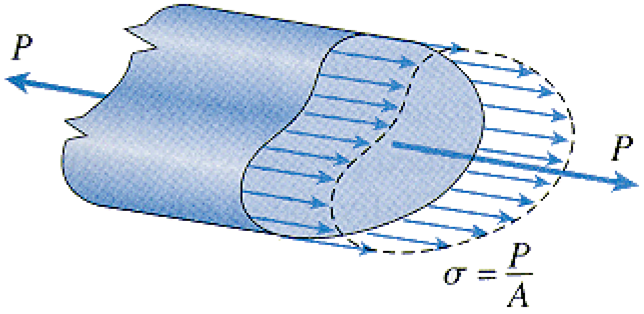
Objectives

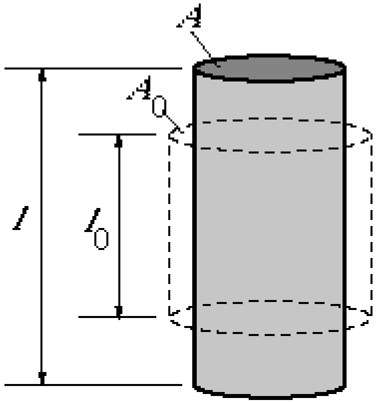
1. Understand the axial, shear, and bending stresses associated with simple trunk design and analysis.
2. Understand the stress-strain and load-displacement relationships for axial members – *tree as column*.
3. Learn to calculate the stress, strain and displacement for beams under various loading conditions – *tree as cantilever*.
4. Learn to calculate the principal stresses in members and how the principal stresses relate to failure.
5. Use mechanics of materials to analyze structures.

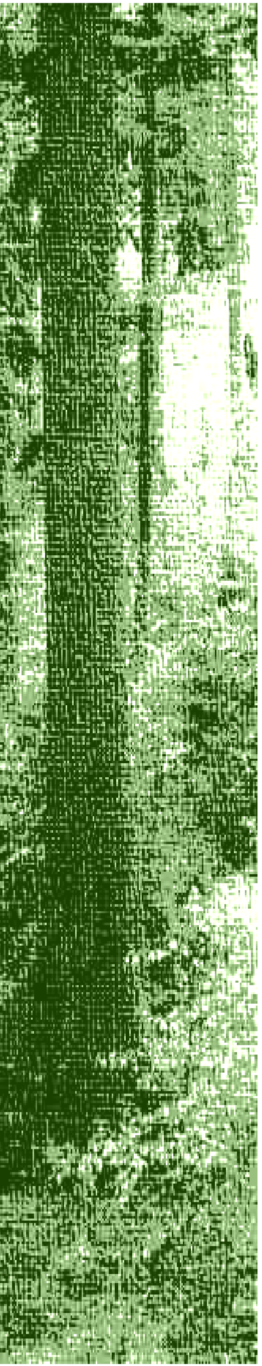
5.1 Application of mechanics of materials

Assumptions

- Prismatic bar (a straight structural member having a constant cross section throughout its length)
- Loads act through centroids of the cross sections
- Homogeneous material (the same throughout all parts of the bar)



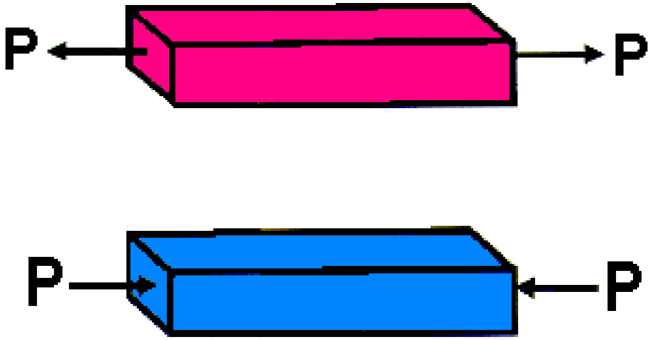


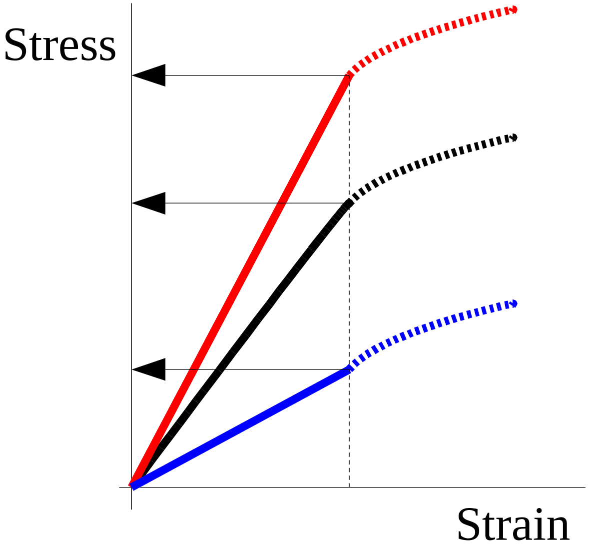


5.1 Application of mechanics of materials

Key Terms

- Axial Force – load directed along the longitudinal axis of the bar
- Cross Sectional Area – internal *face* of a bar taken perpendicular to the longitudinal axis
- Stress – force per unit area (normal stress, uniaxial stress) (units: psi, Pa)
- Strain – elongation per unit length (normal strain, uniaxial strain) (dimensionless)





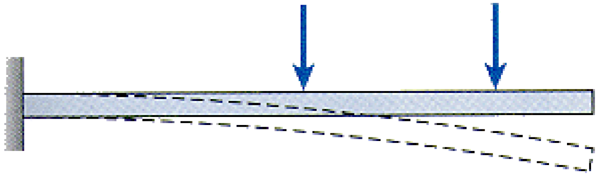
5.1 Application of mechanics of materials

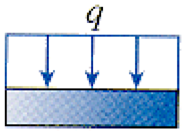
Key Terms

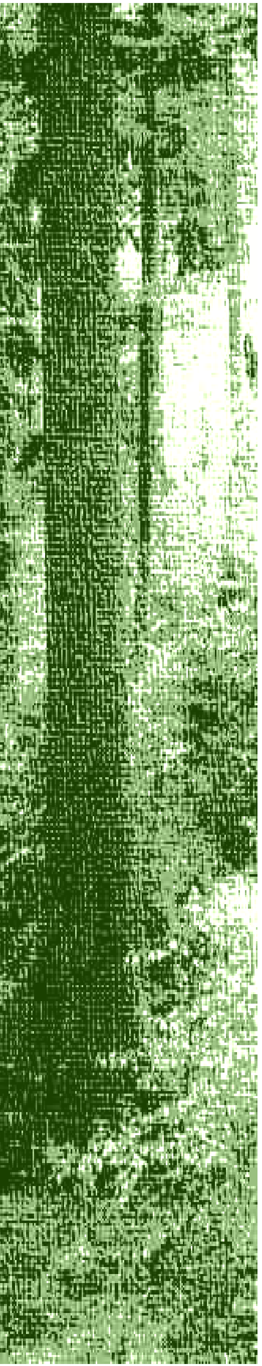
- Axial members- support forces with vectors directed along the axis of the bar
- Torsional members- support torques (couples) with moment vectors directed along the axis of the bar
- Beams- support forces and/or moments with vectors perpendicular to the axis of the bar
- Plane of bending- deflections will occur in a plane if the beam is symmetric around this plane

Load Types

- Concentrated (point) loads
- Distributed loads



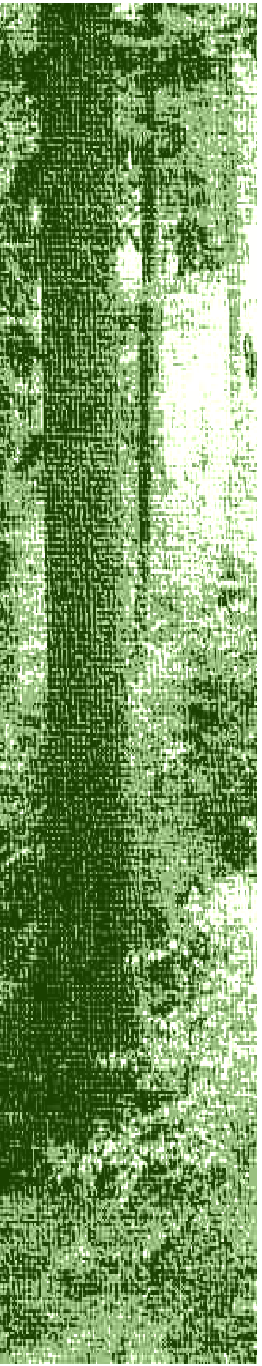




5.1 Application of mechanics of materials

Key Terms

- Structure - any object that must support or transmit loads
- Factor of safety, n - the ratio of actual strength to required strength (generally values from 1 to 10 are used) (structure will presumably fail for n less than 1)
- Margin of safety - an alternative definition to "factor of safety" (commonly used in the aircraft industry) (structure will presumably fail for margins of safety less than or equal to zero) (usually given as a percent)
- Allowable stress - the stress that must not be exceeded anywhere in the structure to satisfy the factor of safety
- Allowable load- permissible or safe load
- Response - how the structure will behave to loads, temperature changes, etc.
- Properties - types of members and their arrangement and dimensions, types of supports and their locations, materials used and their properties



5.1 Application of mechanics of materials

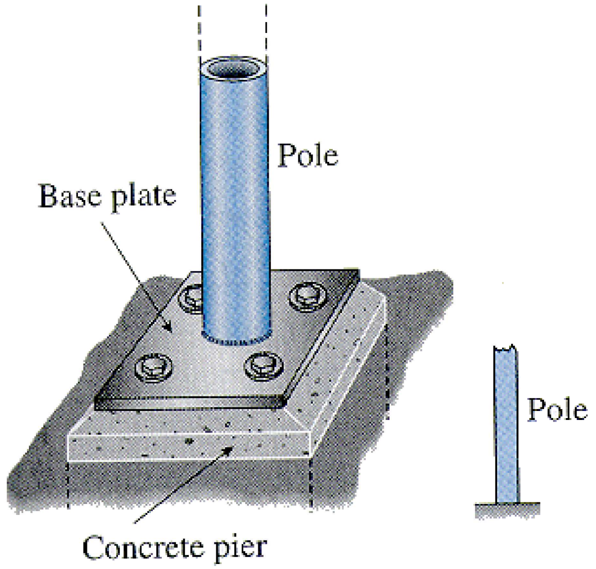
Key Terms

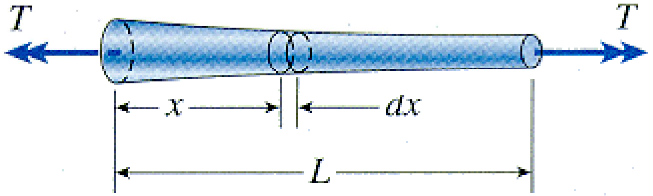
- Analysis - the *properties* of the structure are given and the *response* is to be determined
- Design - the desired *response* is given and the *properties* of the structure are to be determined (usually a longer and more involved process)
- Stiffness - the ability of the structure to resist changes in shape (stretching, bending, twisting)
- Strength- the ability of the structure to resist failure (compression, tension, bending)
- Stability - the ability of the structure to resist buckling of columns (i.e. slender compression members)
- Loads - active forces that are applied to the structure by some external cause (known in advance)
- Reactions - passive forces that are induced at the supports of the structure (must be calculated)

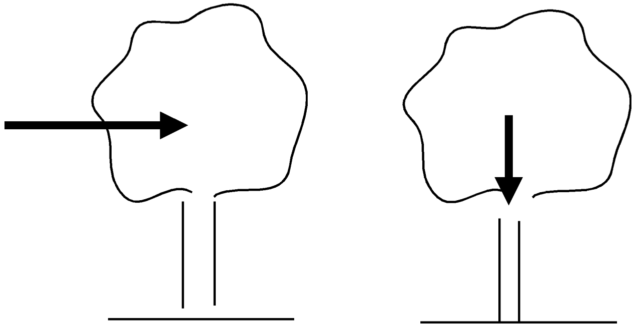
5.1 Application of mechanics of materials

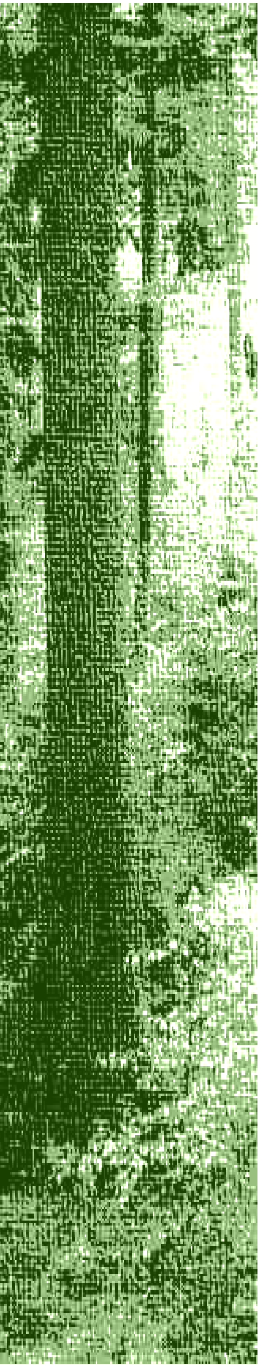
Assumption / limitation

- elastic cantilever beam, rigidly fixed on one side and free on the other
- croos-section varies with height, and this non-uniform taper can be described by a mathematical function
- transverse section of the stem is considered with an area *A* and a section moduli *W*
- in order to calculate the self-weight of the tree, its canopy weight can be evaluated as a point vertical force applied in its centre of gravity
- in order to calculate the wind load, a horizontal point load applied also in the canopy centre of gravity can substitute it



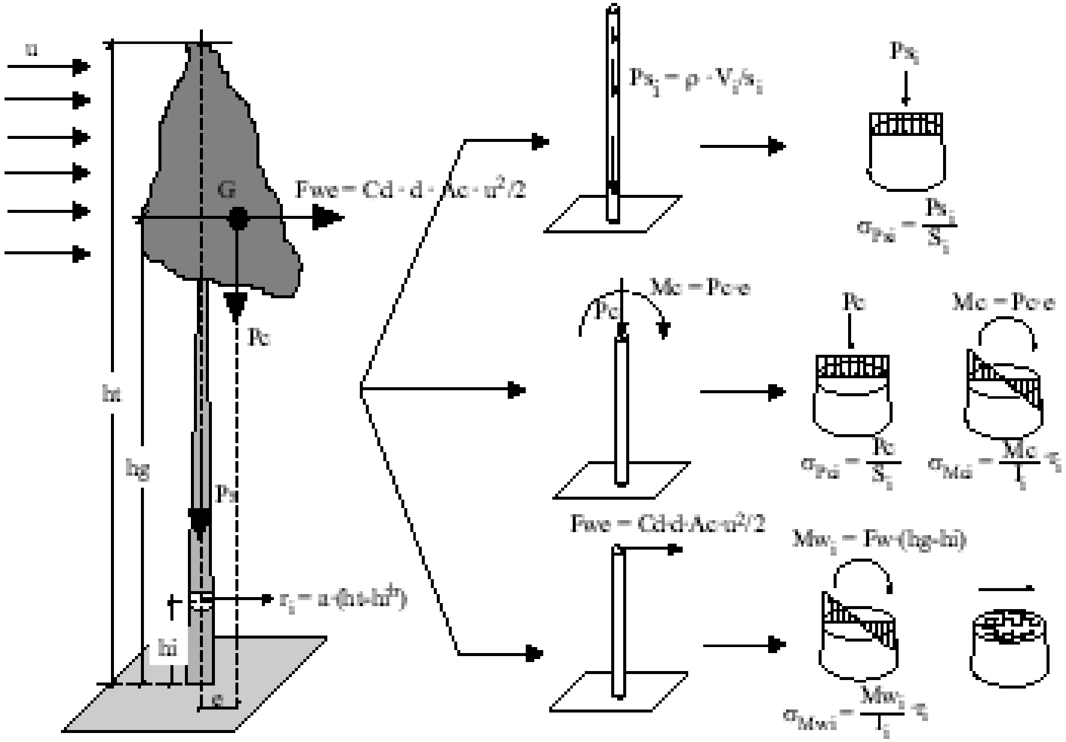






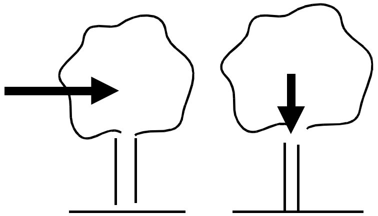
5.1 Application of mechanics of materials

Tree in consideration Forces Stresses



Sources	Loads
Stem	Compression (normal stress)
Crown	Compression (normal stress) Bending moment
Wind	Bending moment Torsion moment

5.1 Application of mechanics of materials



Key concept

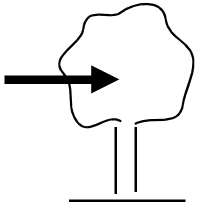
- The forces acting upon a tree are divided into

  1. the **horizontal force** due to the wind and
  2. the **vertical force** due to gravity, including the stem and crown weights and the weight of snow.

- Trees are assumed to

  1. be stressed in cross-section by axial forces or moments (**flexure formula, normal stress**)
  2. deflect and/or to stretch to a point of no return when acted upon by wind (**deflection formula**)

5.1 Application of mechanics of materials



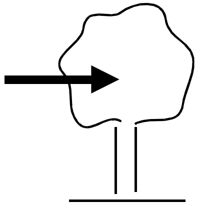
1. Force due to wind (horizontal)

- There are a number of possible methods for calculating the wind loading on a tree. These include direct calculation from a knowledge of the drag coefficient and leaf area of the tree canopy (Jones, 1983), spectral methods using the approach pioneered by Davenport (1961) or an empirical approach using the measured drag of trees (Mayhead et al., 1975).
- The wind speed (*u*) over a forest canopy is given by a logarithmic or power profile:

$$v(z) = v(z_0)\left(\frac{z}{z_0}\right)^{\alpha}$$

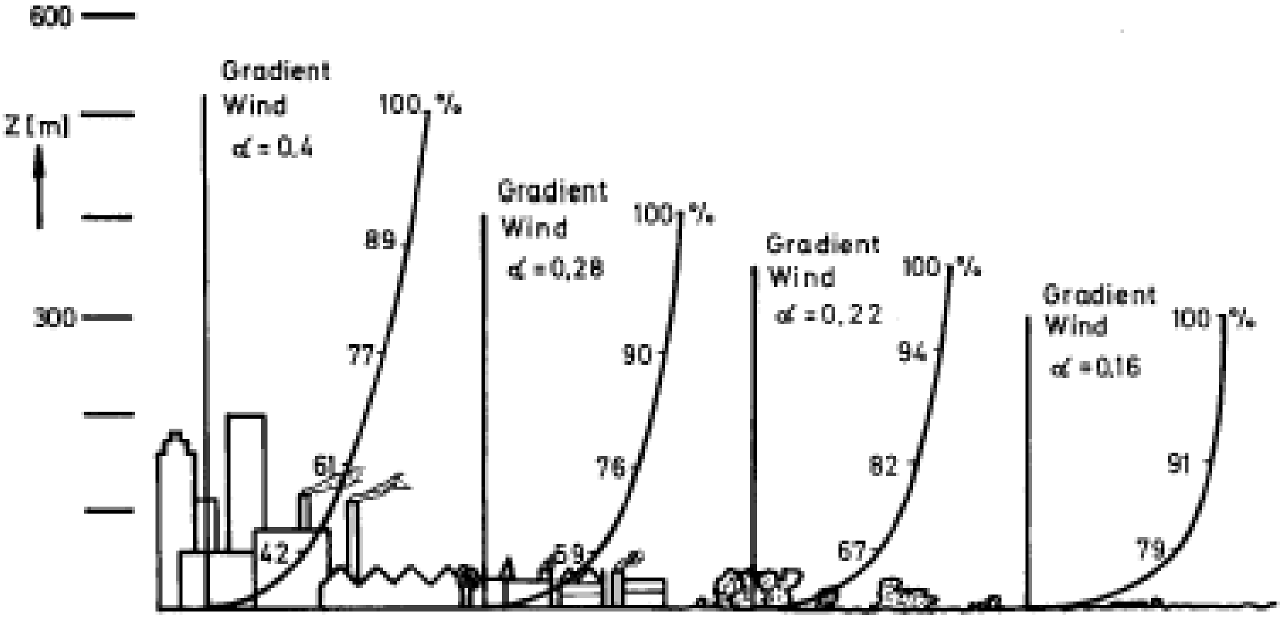
- The mean wind loading and gravity-based forces are calculated at each height in the canopy using a predicted wind profile and the vertical distribution of stem and crown weights.

5.1 Application of mechanics of materials

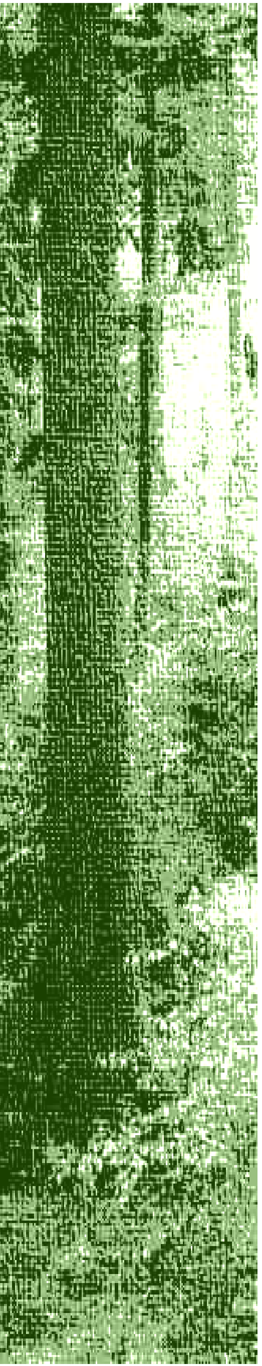


1. Force due to wind (horizontal)

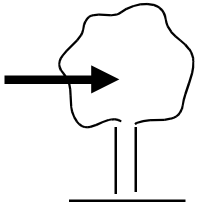
The new Eurocode 1 includes four terrain categories with different roughness-parameters and in addition to that there are special windmaps based on different mean wind velocities for different locations:



Profile of the mean wind velocity for different roughness-classes.



5.1 Application of mechanics of materials



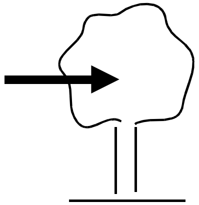
1. Force due to wind (horizontal)

- The total mean wind-induced force is the sum of the wind forces acting at each point on the stem and crown that is given (Jones, 1983; Peltola et al., 1999) at height *z* by:

$$F = 0{,}5\,\rho c_x A v^2$$

where v - the mean wind speed,
A - the area of the stem and crown against which the wind acts,
c_w - the drag coefficient, and
ρ - the density of the air.

5.1 Application of mechanics of materials

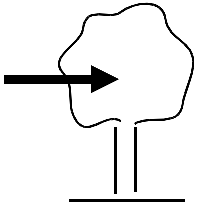


1. Force due to wind (horizontal)

- The wind act in the area of the tree crown as in the sail of a ship.
- We can replace the acting forces in each one part of crown with the one solitary force acting in the centre of gravity of the crown.
- Than the calculation of the stresses and bending moments is enabled.

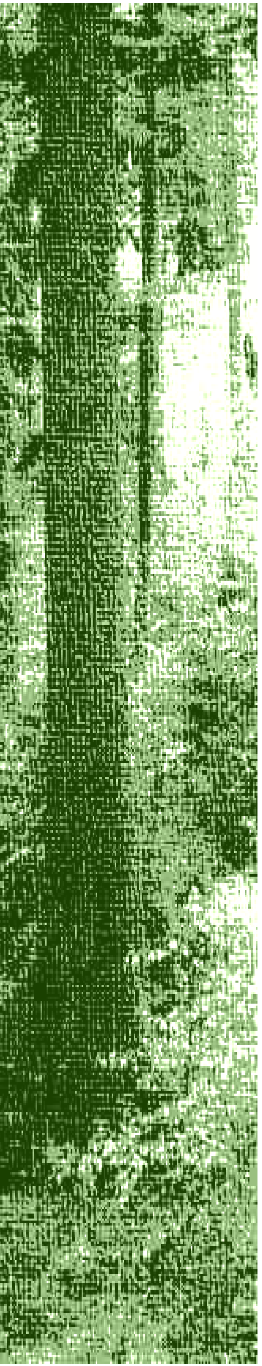
  - Note that the force increase with the sail area (***A***), but with the square of the velocity (***v***) !
  - The ***Cx*** is the drag coefficient of the crown (porosity); it depends on the species, on the wind velocity and other factors.
  - Greek letter ρ denotes the density of the air (1,2 kg.m^{-3}).

5.1 Application of mechanics of materials

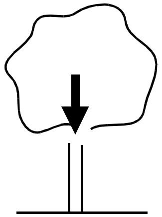


1. Force due to wind (horizontal)

- The drag force on the crown is proportional to the area of branches and stems exposed to the wind, the drag coefficient of the foliage (i.e. how efficiently it intercepts wind), and the square of the wind speed (i.e. when the wind speed doubles, the drag force on the crown increases by a factor of four).
- Wind tunnel studies with whole trees have shown that the drag force is nearly proportional to the projected area of the canopy, drag coefficient, and wind speed.
- However, as wind speed increases, the canopy tends to bend and deflect and become more streamlined.
- This force is transmitted to the stem, causing it to bend and sway.



5.1 Application of mechanics of materials



2. Forces due to crown and stem (vertical)

The weight of the tree is divided into stem weight and canopy weight. As for the stem load, each section of the trunk is at any time supporting the weight of the portion of trunk above

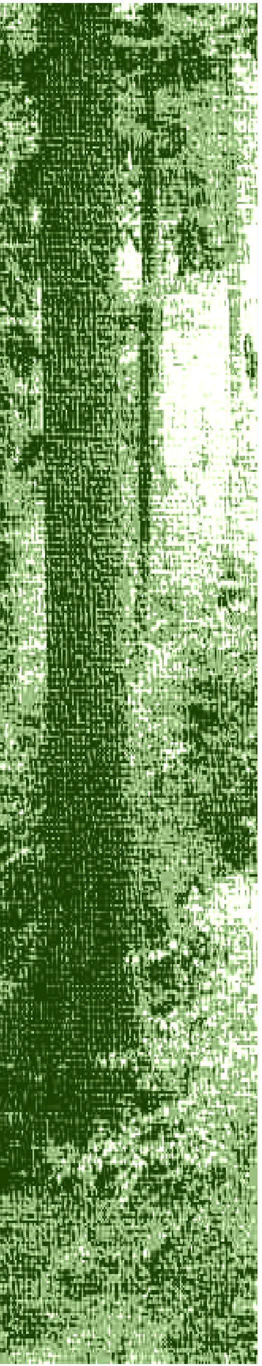
$$F_{stem} = V_{stem} G_{stem} g$$

The canopy weight Fc is applied as a point load in the centre of gravity of the crown generating constant axial stresses like

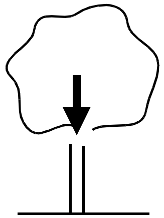
$$F_{crown} = m_{crown} g$$

Usually, the centre of gravity of the crown will be eccentric, and the distance to stem *e*, and height h_{cg} can define its position

$$F_{crown} = m_{crown} \sin\left(arctg\left(\frac{e}{h_{cg}} \right) \right) g$$



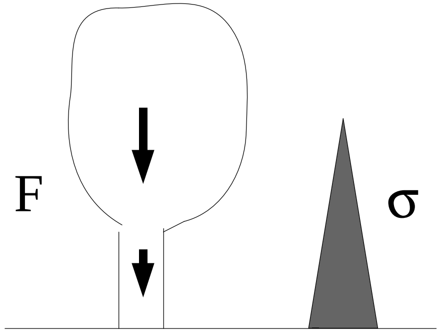
5.1 Application of mechanics of materials

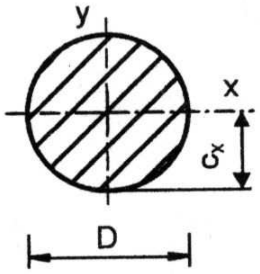


3. Axial stress (normal stress)

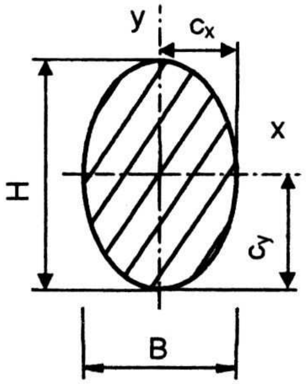
Axial stresses due to stem and crown mass vary along the stem with a maximum at a position which depends on taper.

$$\sigma_{tree} = \frac{F_{crown} + F_{stem}}{A}$$

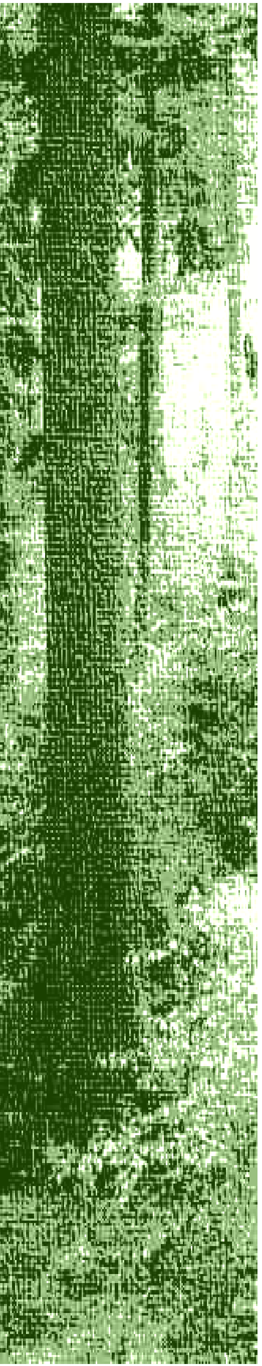




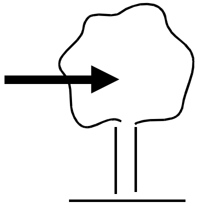
$$A = \frac{\pi}{4} D^2$$



$$A = \frac{\pi}{4} HB$$



5.1 Application of mechanics of materials

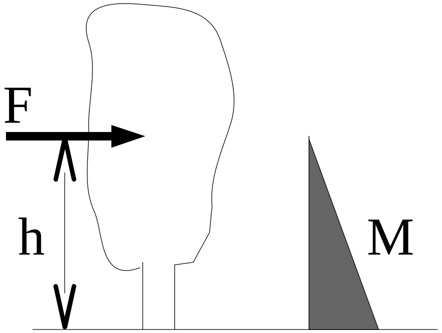


4. Flexure formula

a) bending moments

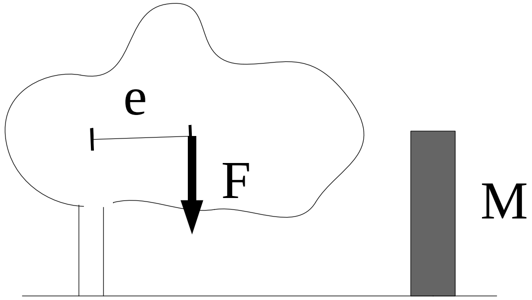
- bending – mean wind force acting on the crown centre and the height of center of gravity
- total maximum bending moment is at the base of the stem
- bending moment varies with the height

$$M_{wind} = F_{wind}\, h_{cg}$$

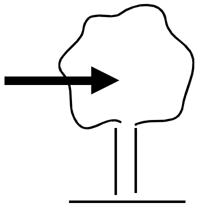


- the eccentric load induces a bending moment which is constant along the stem

$$M_{crown} = F_{crown}\, e$$



5.1 Application of mechanics of materials

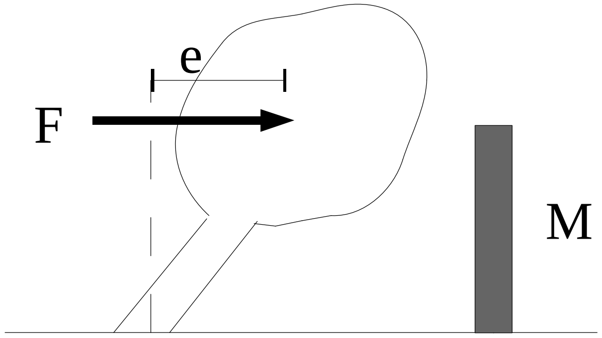


4. Flexure formula

b) torsion moments

- wind acting on eccenricaly shifted center of crown gravity
- the resultant load there is torque and stress acting on the tree there is shear

$$T_{wind} = F_{wind}\, e$$



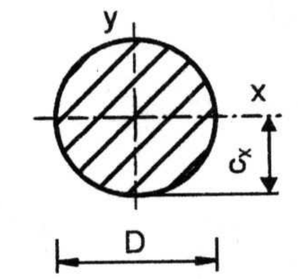
5.1 Application of mechanics of materials

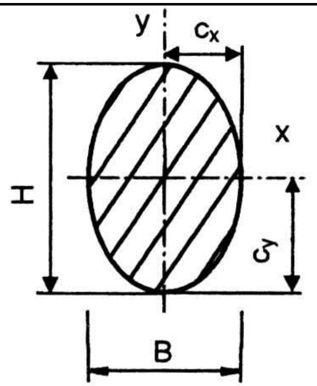
4. Flexure formula

c) section modulus

- both bending and torsion stresses are indirectly proporcional to section moduli *W* given by equations:

BENDING





$$W = \frac{\pi D^3}{32}$$

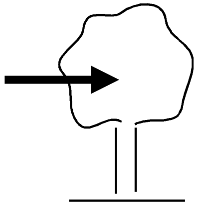
$$W_x = \frac{\pi}{32} H^2 B$$

$$W_y = \frac{\pi}{32} HB^2$$

TORQUE

$$W_T = 2W$$

5.1 Application of mechanics of materials

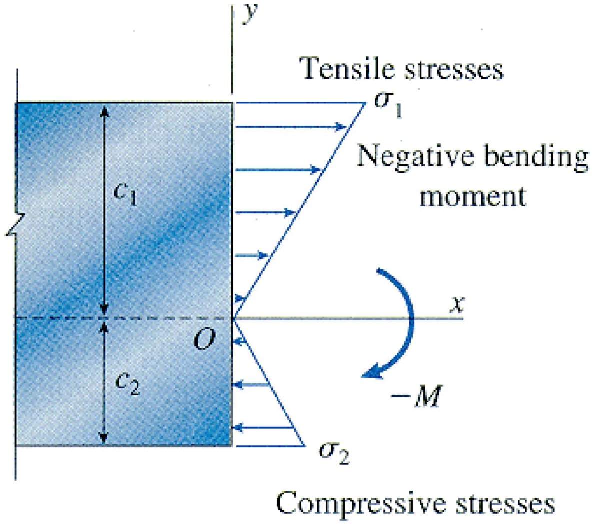


4. Flexure formula

d) bending stress

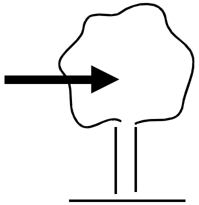
$$\sigma_{wind} = \frac{M_{wind}}{W}$$

$$\sigma_{crown} = \frac{M_{crown}}{W}$$



- bending stress = RESISTANCE to BREAKAGE (BENDING)
- wind, crown and stem induced stress in the outer fibres of the tree stem
- stress can be calculated only at given height
- when stress exceeds the distinct value – compression strength at proportional limit – the stem will break.

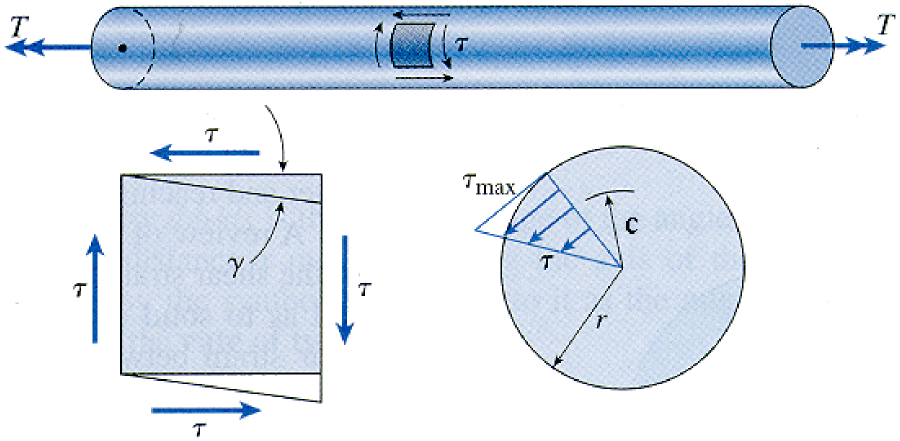
5.1 Application of mechanics of materials



4. Flexure formula

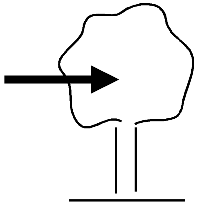
e) torsion stress

$$\tau_{wind} = \frac{T_{wind}}{W_T}$$



- torsion stress = RESISTANCE to BREAKAGE (TORSION)
- wind, crown and stem induced stress in the outer fibres of the tree stem
- stress can be calculated only at given height
- when stress exceeds the distinct value – shear strength at proportional limit – the stem will break.

5.1 Application of mechanics of materials

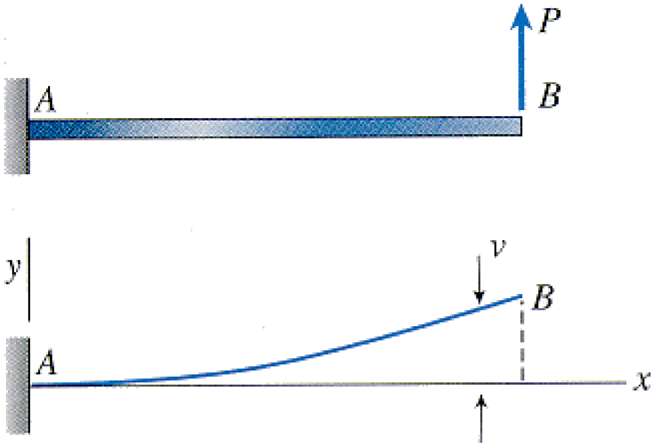


5. Deflection formula

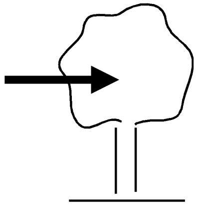
a) bending moment

- in a static system the uprooting forces are usually calculated as bending moments at the base of the stem
- if the uprooting bending moment exceeds the resistive bending moment of the tree at a particular angle of deflection, the tree will deflect further
- tree will give away if the uprooting moment exceeds its maximum resistive bending moment, with the relative strengths of the stem and roots determining the mode of failure

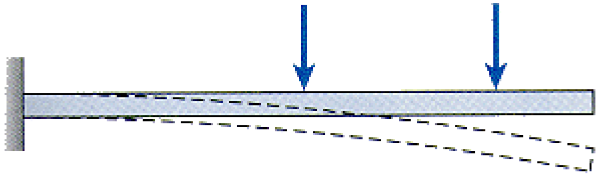
$$EI\frac{d^2v}{dx^2} = M$$



5.1 Application of mechanics of materials



5. Deflection formula



a) bending moment

Key Terms

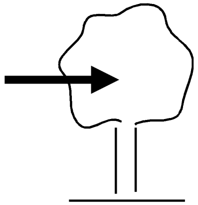
- Plane of bending - deflections will occur in a plane if the beam is symmetric around this plane
- Deflection, *v* - the displacement of any point along the beam from its original position, measured in the y direction

$$v = \frac{F x^2}{6 EI} (3 L - x)$$

- Angle of rotation, θ - the angle between the x-axis and the tangent to the deflection curve
- Slope of the deflection curve: d*v*/dx = tan θ (tan θ = θ for small angles)

$$v' = \frac{F x}{2 EI} (2 L - x)$$

5.1 Application of mechanics of materials



5. Deflection formula

a) bending moment

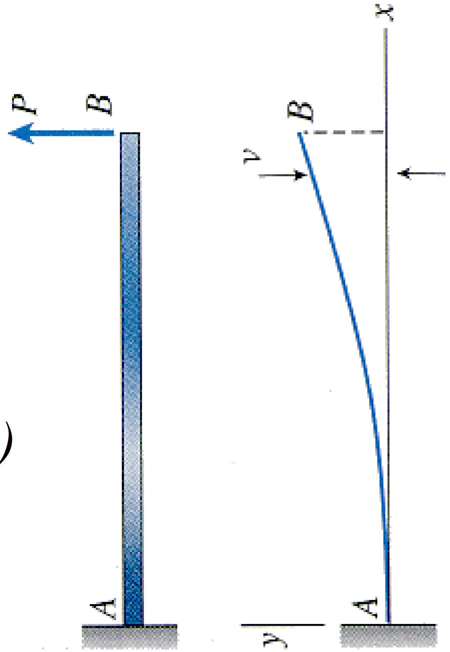
- deflection or angle of rotation = RESISTANCE TO OVERTURNING

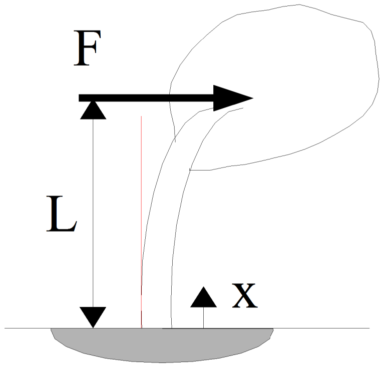
deflection of stem

$$v = \frac{F\,x^2}{6\,EI}(3L - x)$$

slope of deflection curve (angle)

$$v' = \frac{F\,x}{2\,EI}(2L - x)$$





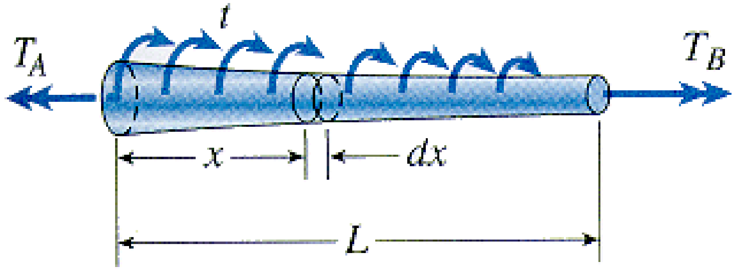
5.1 Application of mechanics of materials

Factor of safety – the ratio of actual STRESS to required STRENGTH (generally values from 1 to 10 (100 to 1000%) are used)

Structure will presumably fail for factor of safety less than 1 (<100%)

$$\boxed{factor\ of\ \ safety = \frac{\sigma_{compression}}{\sigma_{wind} + \sigma_{crown} + \sigma_{tree}} 100}$$

$$\boxed{factor\ of\ \ safety = \frac{\tau_{shear}}{\tau_{wind}} 100}$$

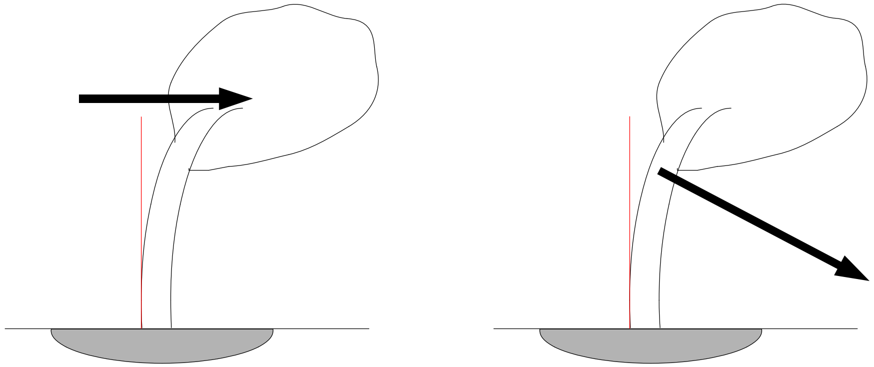


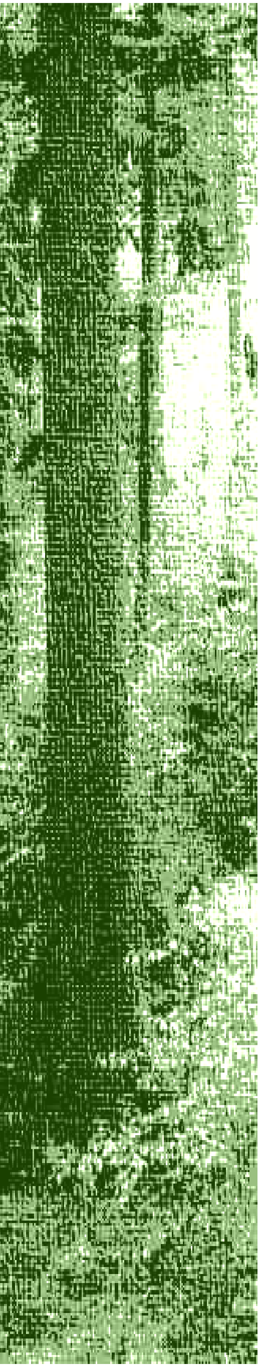
5.1 Application of mechanics of materials

Factor of safety – the ratio of actual STRESS to required STRENGTH (generally values from 1 to 10 (100 to 1000%) are used)

Structure will presumably fail for factor of safety less than 1 (<100%)

$$\boxed{\mathit{factor\ of\ safety} = \frac{\mathit{slope\ of\ deflection\ curve}}{\mathit{inclination\ of\ tree}}\,100}$$



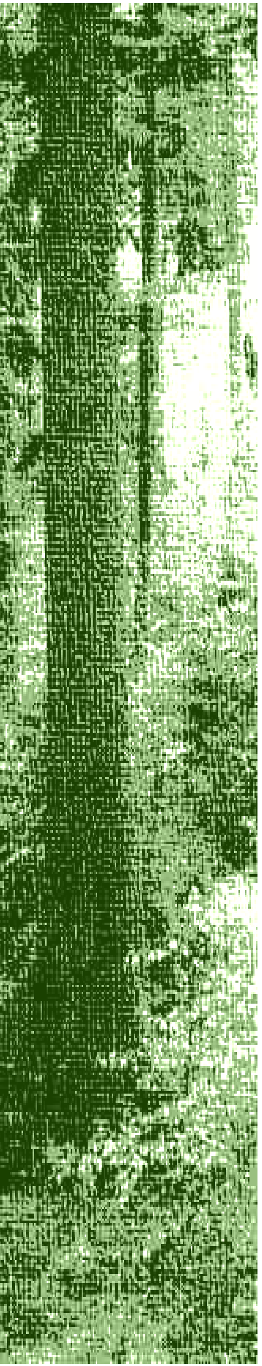


5.2 Failure of tree

Objectives

The objective is to determine the largest stresses anywhere in the structure.
No new theories are involved – only applications of previously derived formulas and concepts:

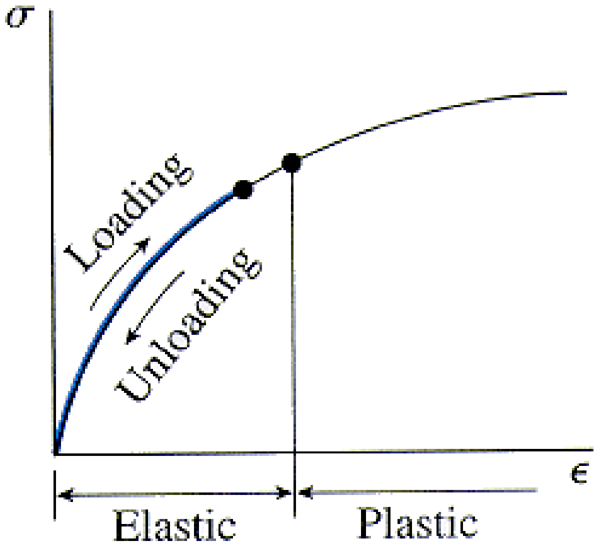
1. Select a point in the structure where the stresses and strains are to be determined (usually where the stresses are the largest).
2. For each load, determine the stress resultants at the point (look at axial force, twisting moment, bending moment, shear force) .
3. Calculate the normal and shear stresses due to each stress resultant ($\sigma = F/A$, $\sigma = M/W$) .
4. Combine the individual stresses.
5. Repeat the process for additional points, until you are confident you have found the largest stresses anywhere in the structure.



5.2 Failure of tree

Key Terms

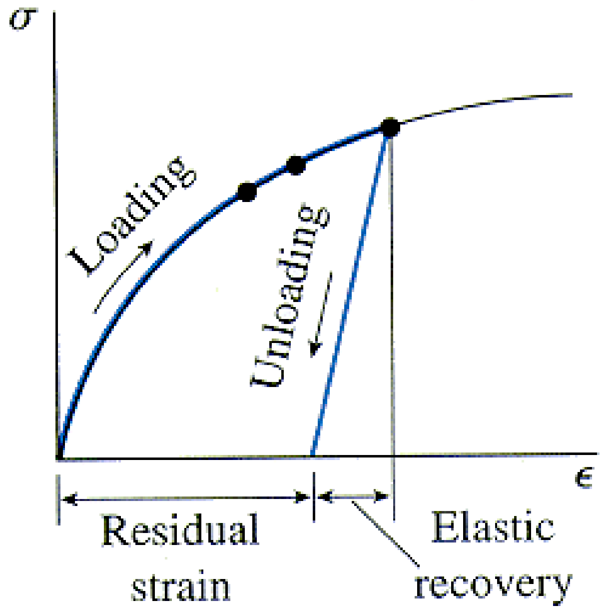
Elasticity - a material property that causes the specimen to return to its original dimensions when the load is removed



Residual Strain - the permanent strain exhibited in the material when the load is removed

Elastic Limit - the limiting stress where the material will still return to its original dimensions

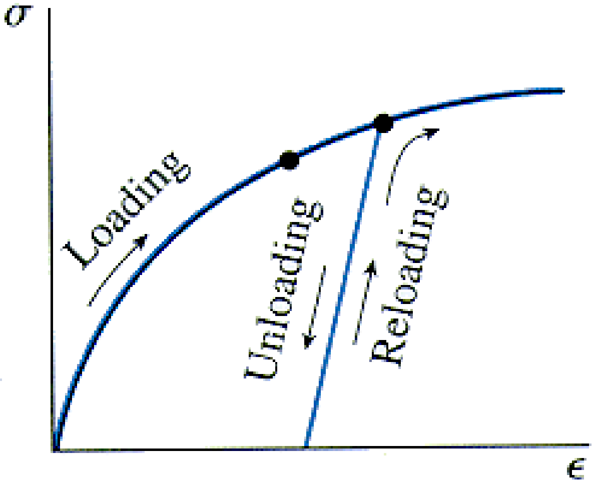
Plasticity - inelastic behavior of the material beyond the elastic limit



5.2 Failure of tree

Key Terms

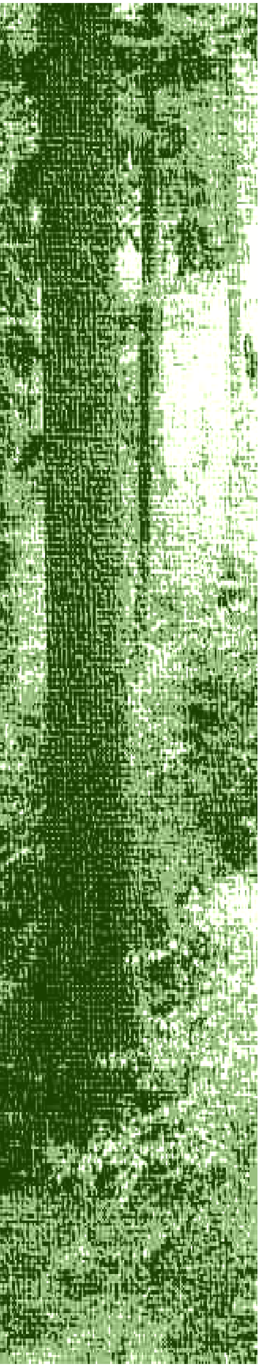
Reloading - applying a subsequent load after the material has experienced a loading resulting in permanent deformation



NOTE:

Permanent deformation changes the material properties:

- a) the linear-elastic region is increased
- b) the proportional limit, elastic limit, and yield point are raised
- c) plasticity is reduced (material becames more brittle)



5.2 Failure of tree

Key concepts

- Trees adapt their stem and root growth in response to the wind loading to which they are subjected in order to resist breakage or overturning.

- By understanding the behaviour of trees in strong winds and the mechanisms of root anchorage it has become possible to develop mechanistic models that predict

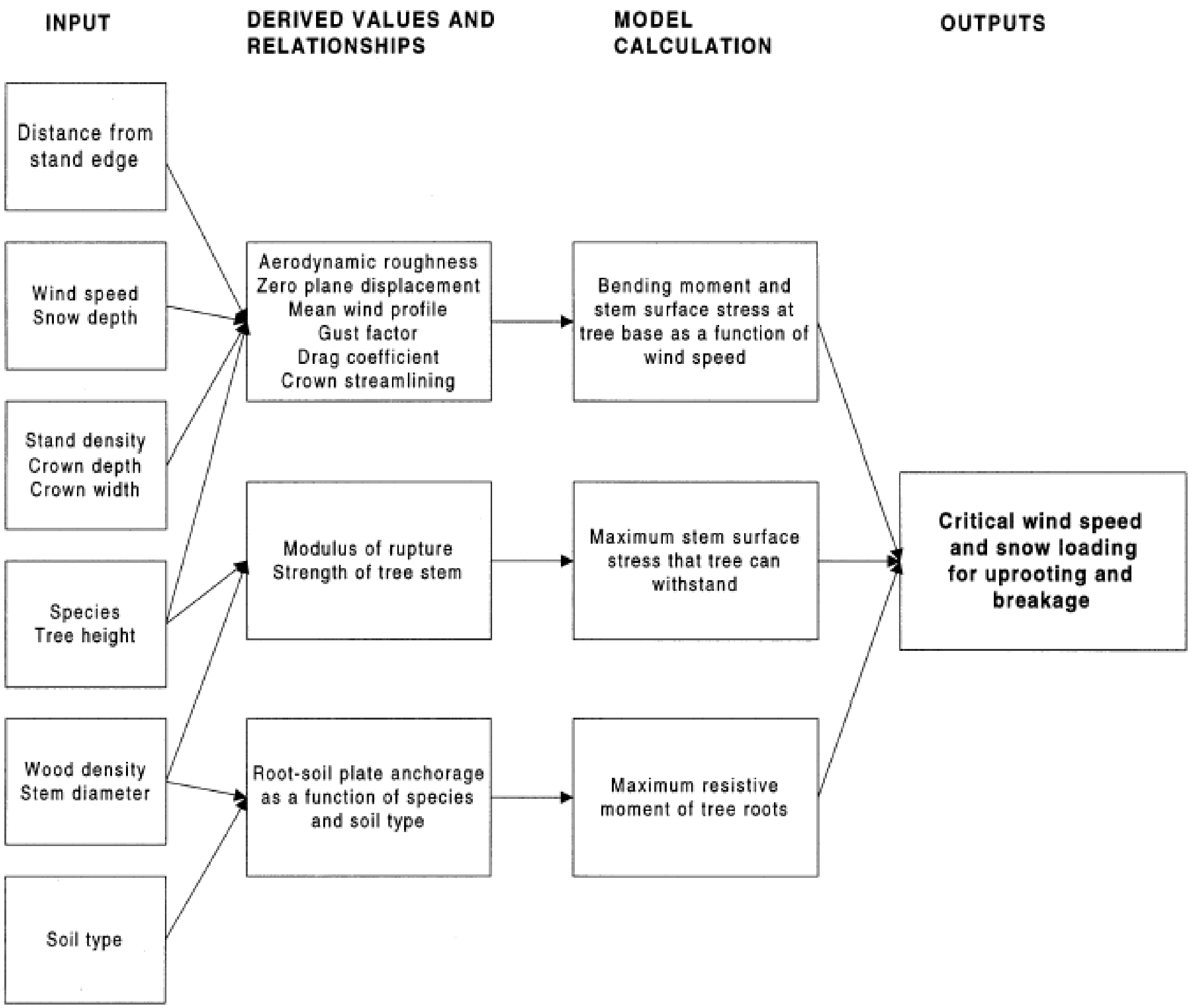
    1. the critical wind speeds for damage to occur and
    2. how these are affected by the properties of the trees

- Such an approach allows predictions of the impact of any arboricultural operations on tree stability and the design of strategies for reducing wind damage.

5.2 Failure of tree

The basic structure of models is very similar and a general schematic relevant to models is shown in Fig.

The major differences lie in the method for calculating the values at each stage of the model.



INPUT

DERIVED VALUES AND RELATIONSHIPS

MODEL CALCULATION

OUTPUTS

Distance from stand edge

Wind speed
Snow depth

Stand density
Crown depth
Crown width

Species
Tree height

Wood density
Stem diameter

Soil type

Aerodynamic roughness
Zero plane displacement
Mean wind profile
Gust factor
Drag coefficient
Crown streamlining

Modulus of rupture
Strength of tree stem

Root-soil plate anchorage as a function of species and soil type

Bending moment and stem surface stress at tree base as a function of wind speed

Maximum stem surface stress that tree can withstand

Maximum resistive moment of tree roots

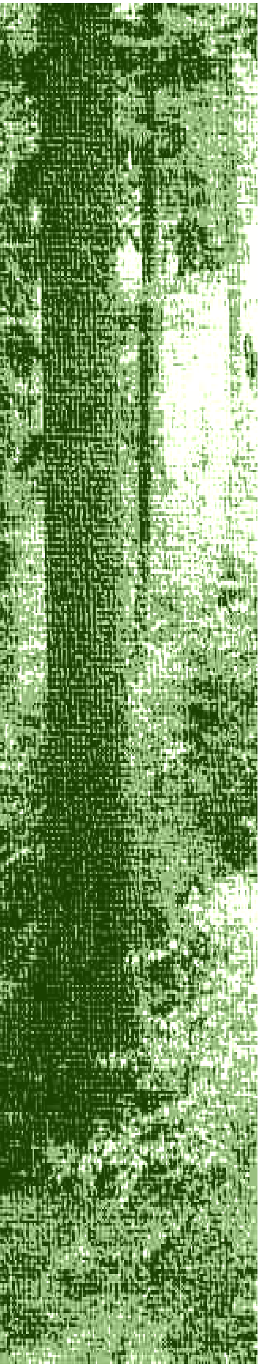
Critical wind speed and snow loading for uprooting and breakage

5.2 Failure of tree

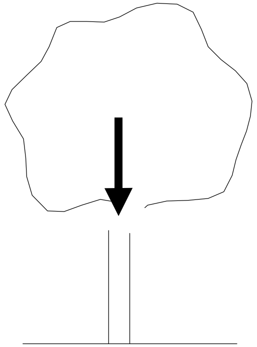
Process of failure of tree

1. breakage – a tree will break down if the total axial stress due to wind and tree mass exceeds the compression strength at proportional limit in the outer fibres of lee side.

2. overturning (uprooting) – a tree will overturn if the total extreme bending moment due to the wind / load exceeds the support provided by the root-soil plate anchorage.



5.2 Failure of tree



Resistance to breakage

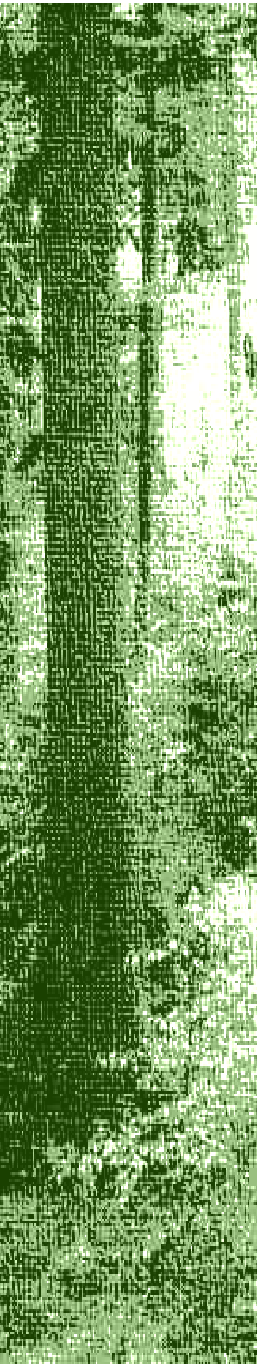
1. Tree as free-standing column

- Upright and free-standing column fixed at base
- Loaded by crown and stem mass (gravity)
- Can fail by
  a) compression or
  b) global buckling

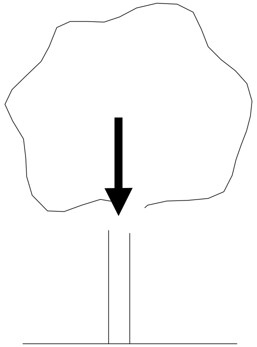
Compression	**Buckling**
$\sigma = \frac{F_{crown} + F_{stem}}{A}$	$\sigma = \frac{\pi^2 EI}{4 L^2 A}$

$$factor\ of\ safety = \frac{\sigma_{prop.limit}}{\sigma} \geq 1$$

$\sigma \leq$ strength in compression



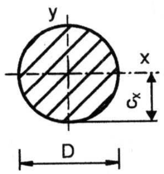
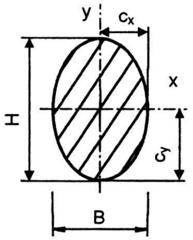
5.2 Failure of tree

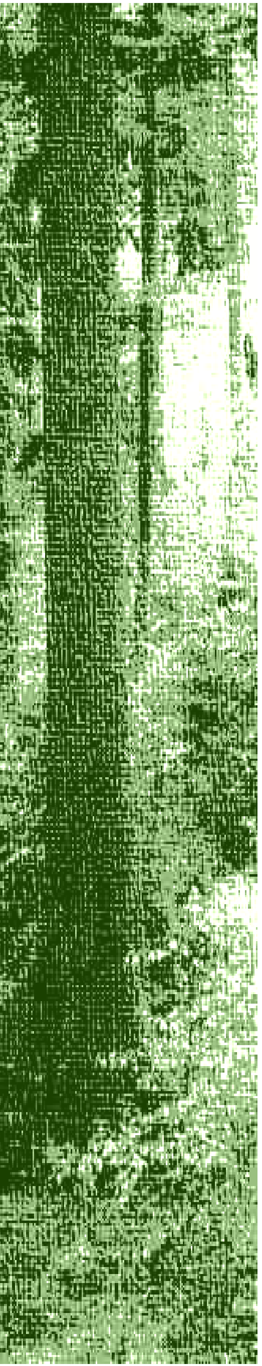


Resistance to breakage

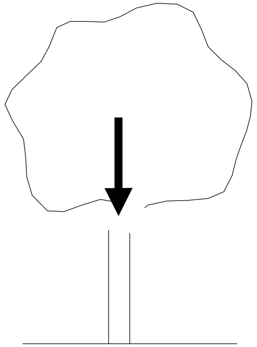
1. Tree as free-standing column

- Maximal stress ≤ strength in compression
- Strength is constant
- Resistance to breakage = balance between load and area

Load	**Area**	
Function of tree hight = LENGTH (L)	 $A=\frac{\pi}{4}D^2$ $A=\frac{\pi}{4}\left(D^2-d^2\right)$	 Function of DIAMETER (D^2) $A=\frac{\pi}{4}HB$ $A=\frac{\pi}{4}\left(HB-hb\right)$

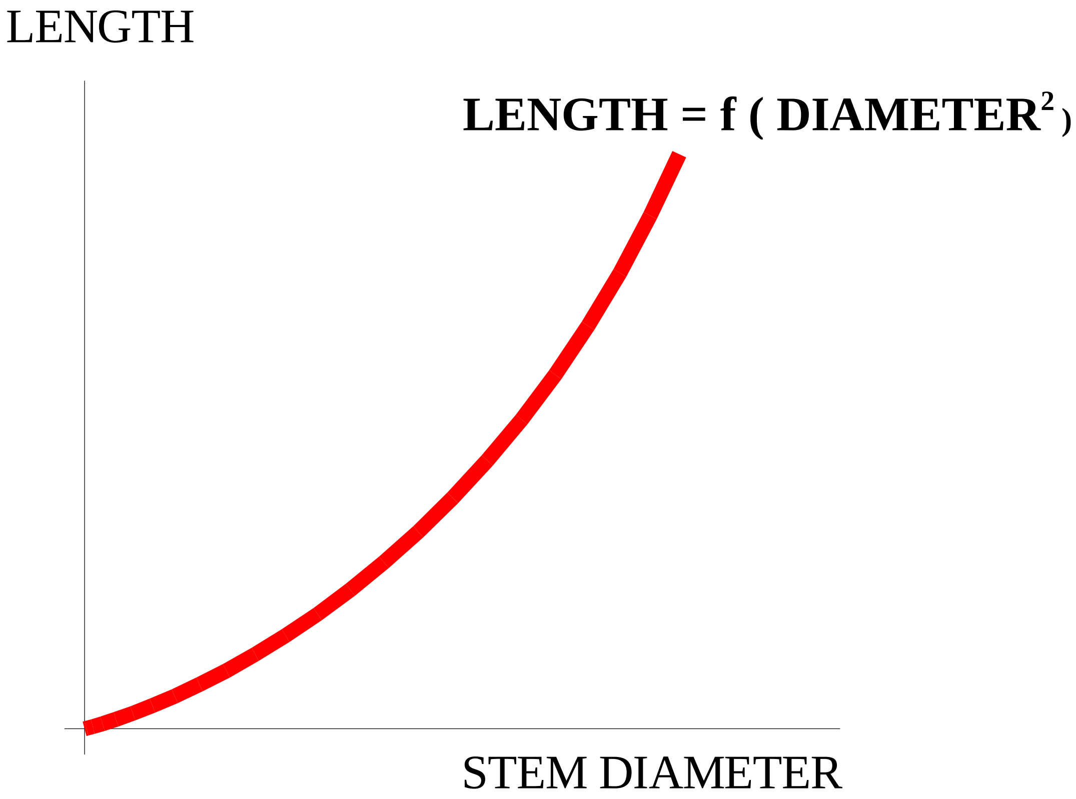


5.2 Failure of tree

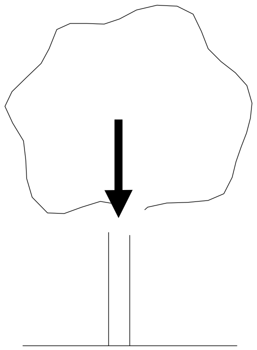


Resistance to breakage

1. Tree as free-standing column



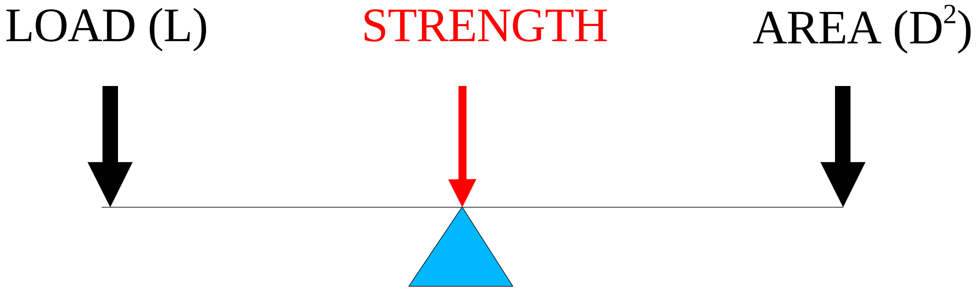
5.2 Failure of tree



Resistance to breakage

1. Tree as free-standing column

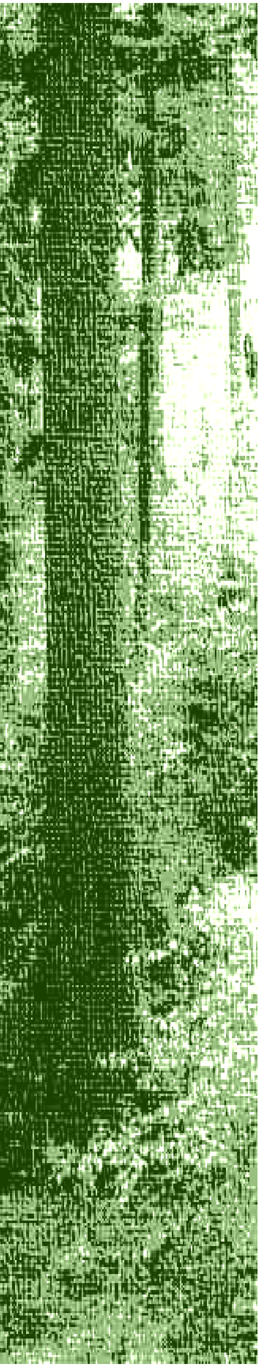
LOAD = STRENGTH x AREA



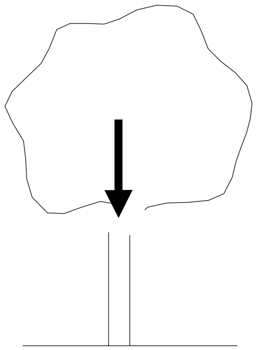
LOAD (L)

STRENGTH

AREA (D^2)



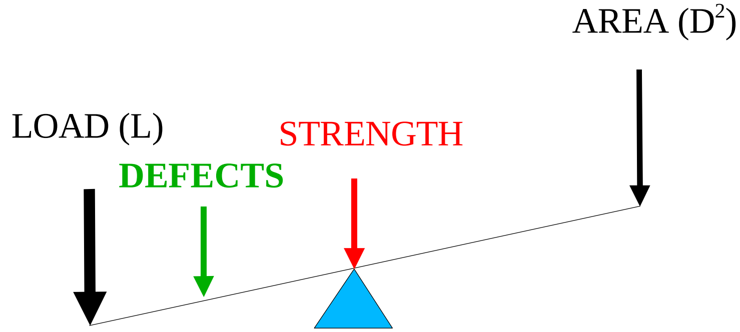
5.2 Failure of tree

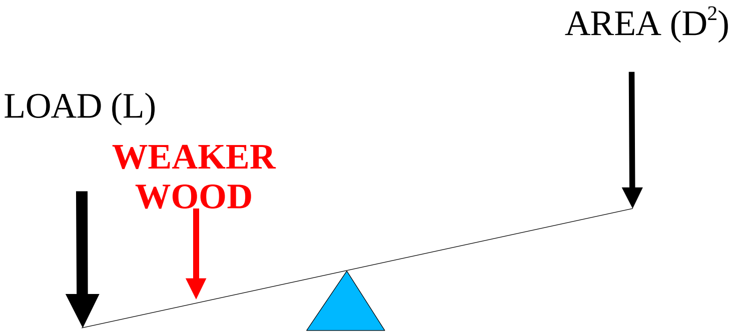


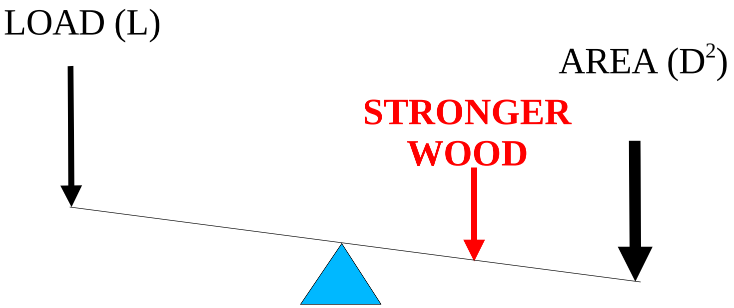
Resistance to breakage

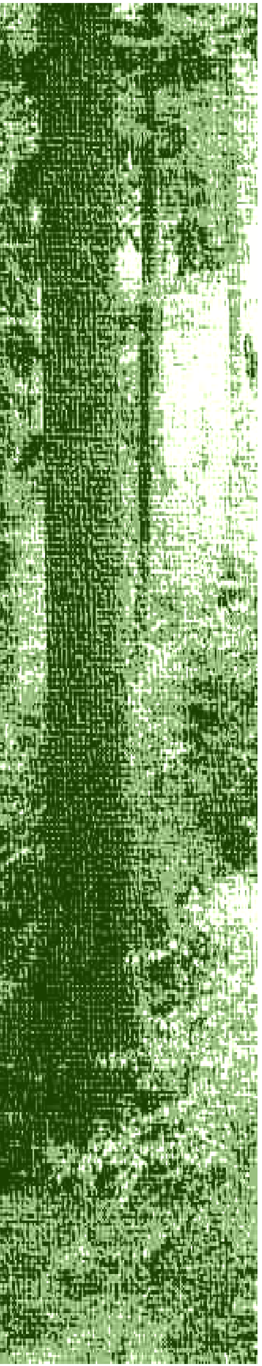
1. Tree as free-standing column

LOAD = STRENGTH x AREA

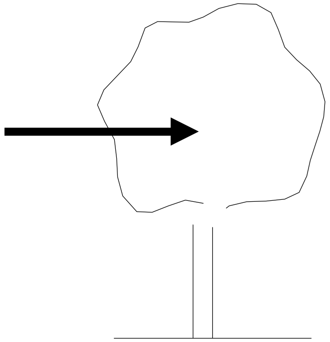








5.2 Failure of tree



Resistance to breakage

2. Tree as CANTILEVER

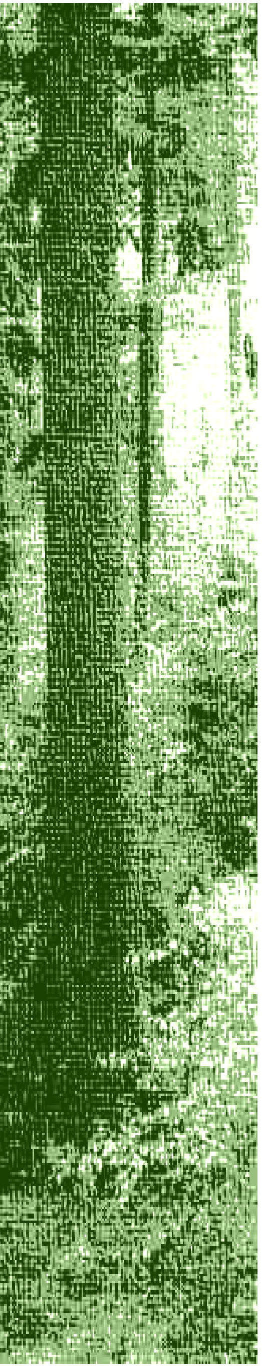
- Cantilever resisting a bending moment
- Loaded by wind force
- Can fail by

a) bending or
b) torsion

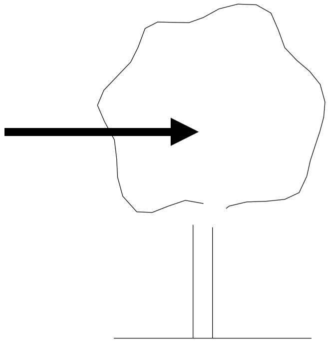
Bending	**Torsion**
$\sigma = \frac{M_{wind} + M_{crown}}{W}$	$\tau = \frac{M_{wind}}{W_T}$

$$factor\ of\ safety = \frac{\sigma_{prop.limit}}{\sigma} \geq 1$$

$\sigma \leq$ strength in compression OR shear



5.2 Failure of tree



Resistance to breakage

2. Tree as CANTILEVER

- Maximal stress ≤ strength in compression
- Strength is constant
- Resistance to breakage = balance between moment and area (section moduli)

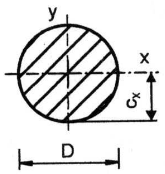
Moment

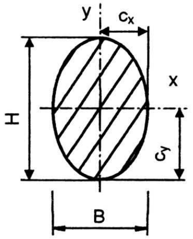
$$M = F\, h_{cg}$$

$$F_{wind} = \frac{1}{2} c_w \rho\, v_z^2 A$$

Function of tree hight = LENGTH (L) and sail area = AREA (A)

Area





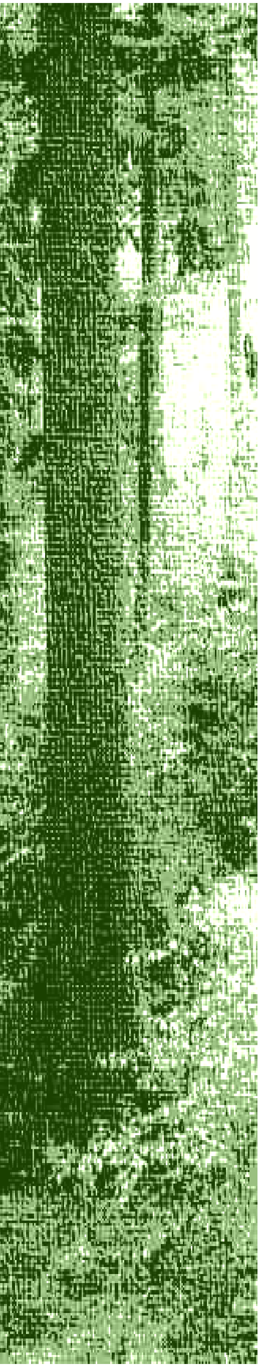
Function of DIAMETER (D^3)

$$W = \frac{\pi D^3}{32}$$

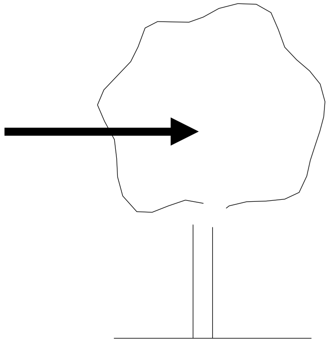
$$W_x = \frac{\pi}{32} H^2 B$$

$$W = \frac{\pi}{32} \frac{D^4 - d^4}{D}$$

$$W_x = \frac{\pi}{32} \frac{H^3 B - h^3 b}{H}$$



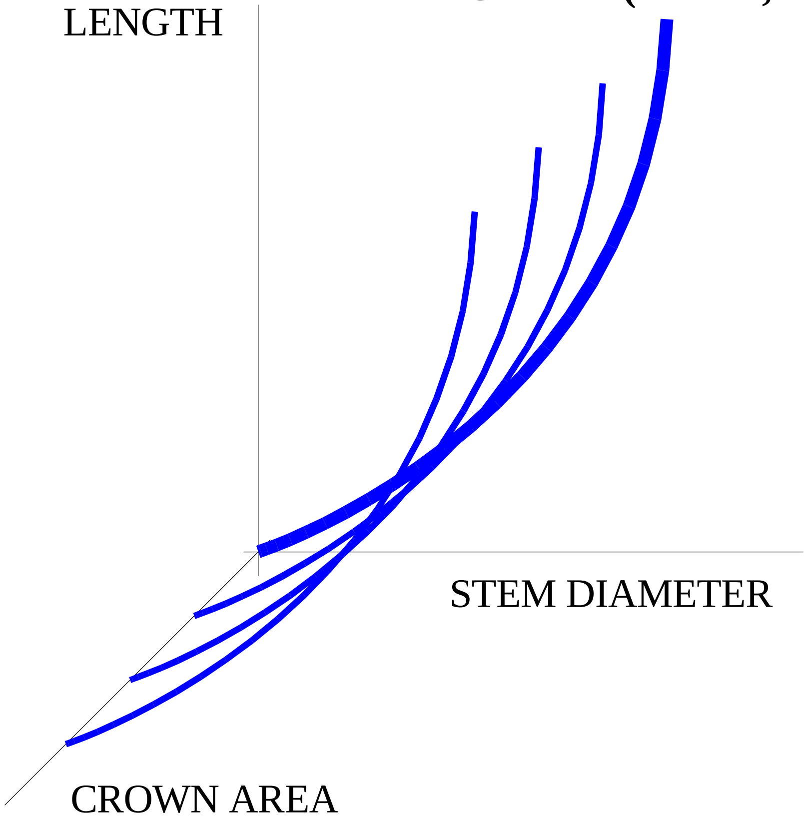
5.2 Failure of tree

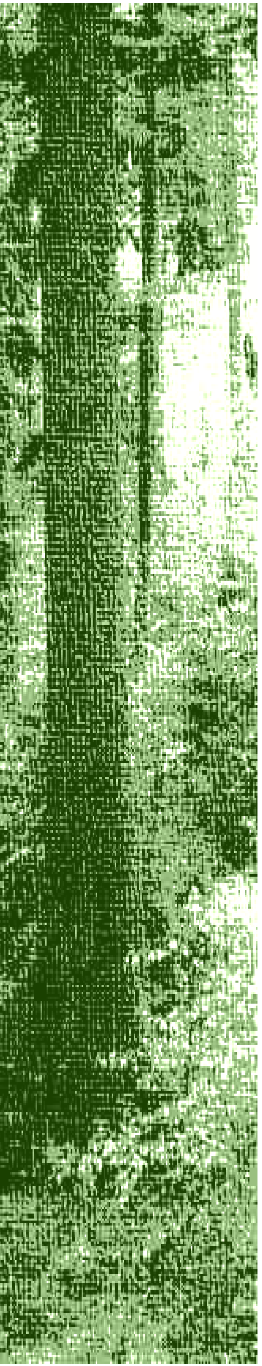


Resistance to breakage

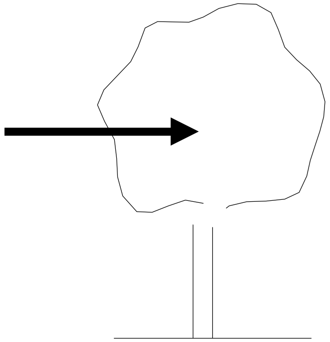
2. Tree as CANTILEVER

LENGTH = f (AREA, DIAMETER ^{3})





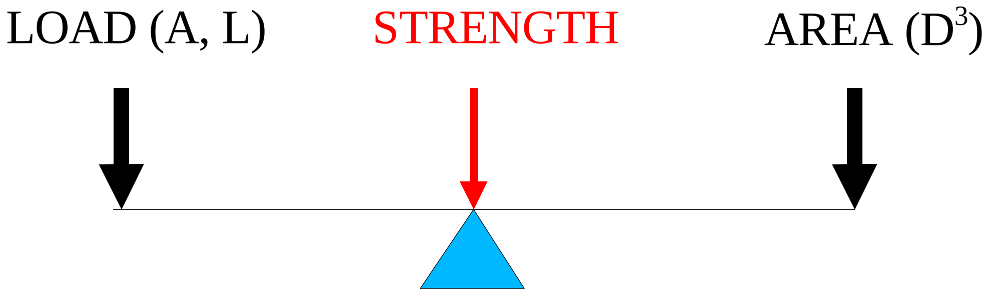
5.2 Failure of tree



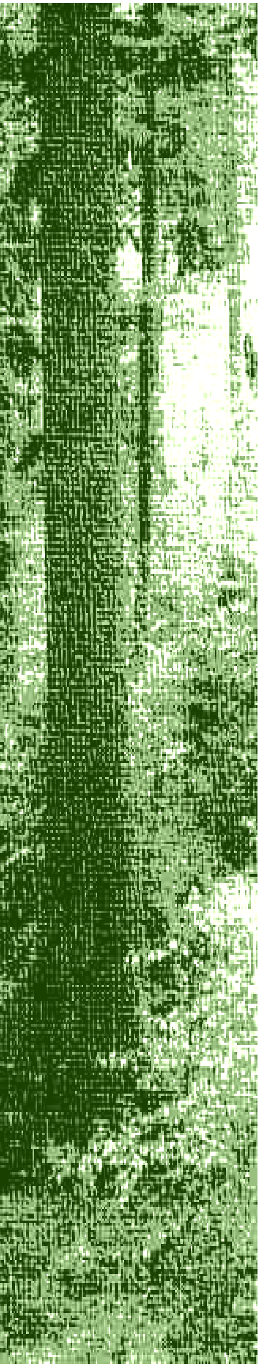
Resistance to breakage

2. Tree as CANTILEVER

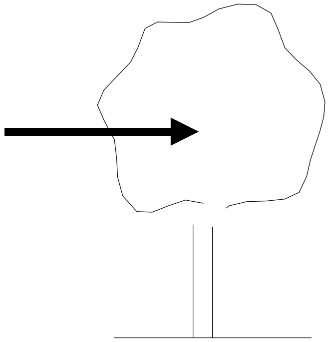
MOMENT = STRENGTH x SECTION MODULUS
WIND FORCE x LEVER ARM = STRENGTH x AREA (D^3)



LOAD (A, L)
STRENGTH
AREA (D^3)



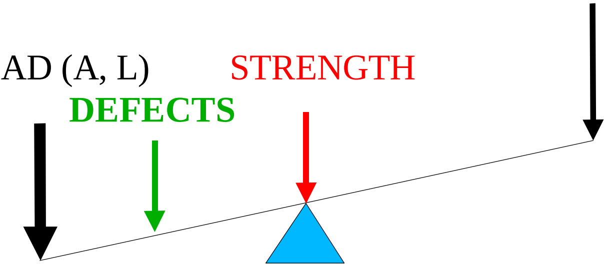
5.2 Failure of tree

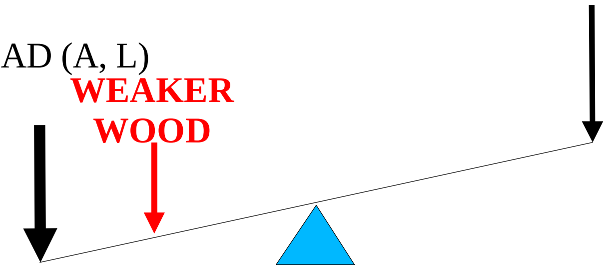


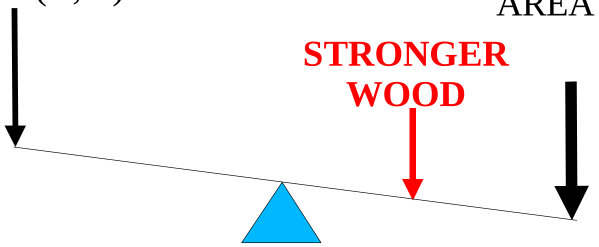
Resistance to breakage

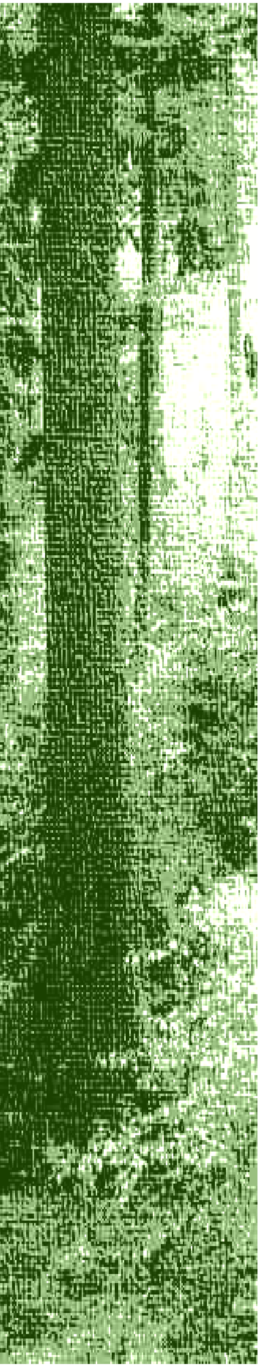
2. Tree as CANTILEVER

MOMENT = STRENGTH x SECTION MODULUS
WIND FORCE x LEVER ARM = STRENGTH x AREA (D^3)





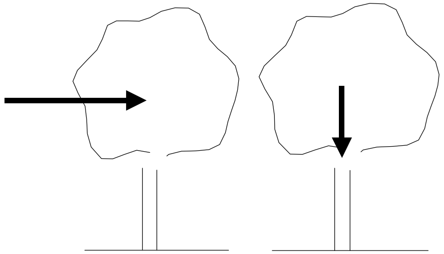


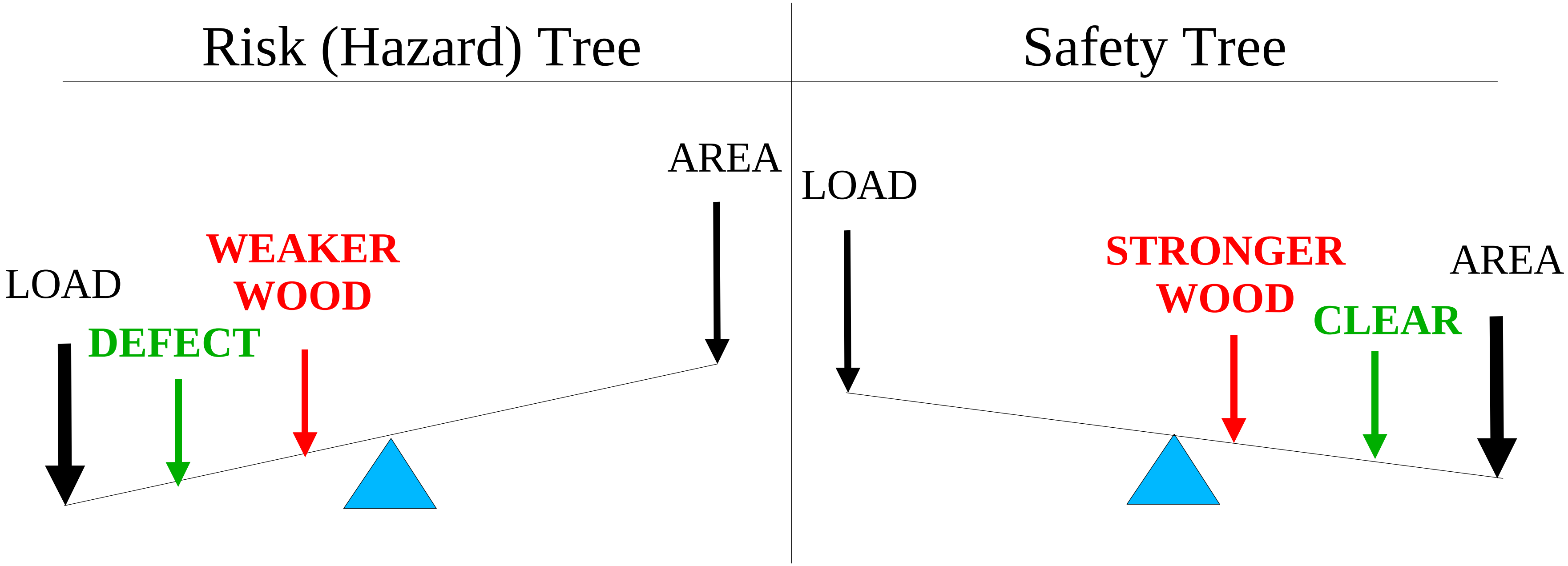


5.2 Failure of tree

Resistance to breakage

CONCLUSION





Risk (Hazard) Tree

LOAD

DEFECT

WEAKER WOOD

AREA

Safety Tree

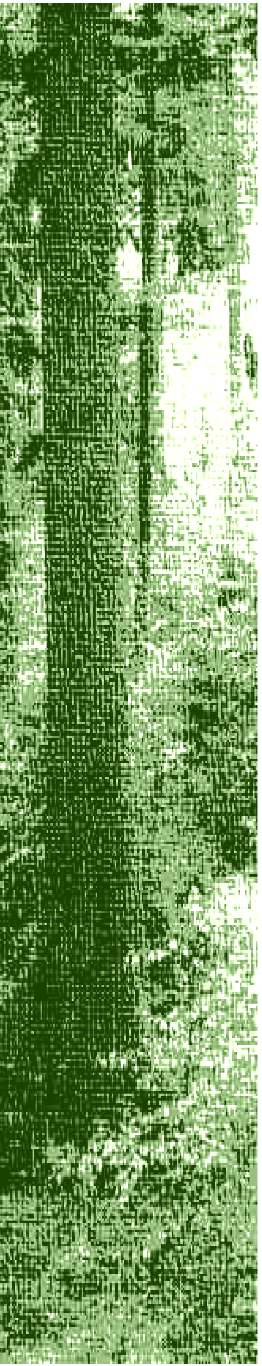
LOAD

STRONGER WOOD

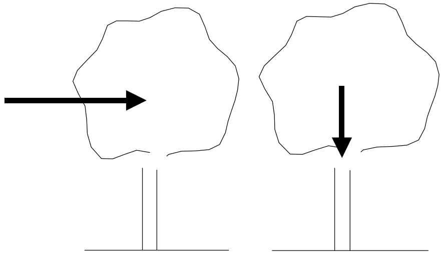
CLEAR

AREA

SIA – LOAD (tree hight) and AREA
SIM – WOOD STRENGTH and DEFECTS



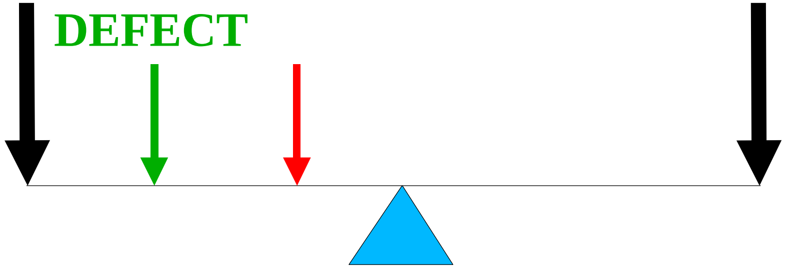
5.2 Failure of tree



Resistance to breakage

CONCLUSION

Risk (Hazard) Tree → Safety Tree



REDUCED
LOAD

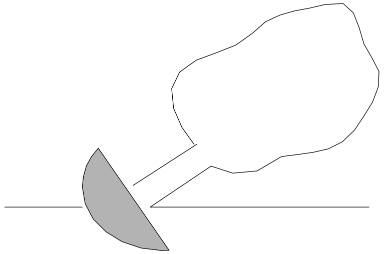
WEAKER
WOOD

DEFECT

INCREASED
AREA

SIA – LOAD (tree hight) and AREA
SIM – WOOD STRENGTH and DEFECTS

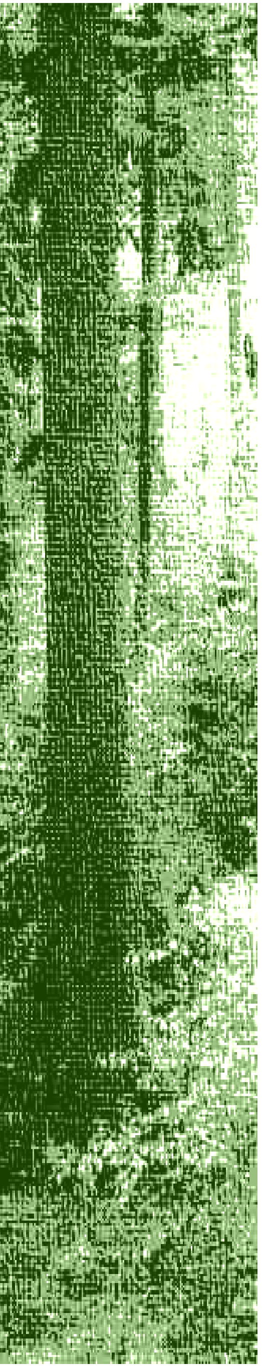
5.2 Failure of tree



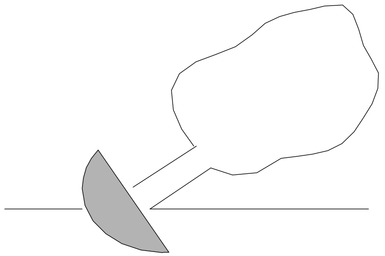
Resistance to overturning (uprooting)

1. Tree as CANTILEVER

- Cantilever resisting a bendeing moment
- Loaded by wind force or own mass
  - a) *wind* action on the crown causes defection of the stem
  - b) leaning stem can uproot the tree because its centre of gravity moves over the hinge point in the root system
- The uprooting moment is resisted by bending of the tree stem and various components of root anchorage:
  1. the weight of the root-soil plate,
  2. the strength of the windward roots,
  3. the strength of the root hinge and
  4. the soil strength at the base of the root-soil plate.



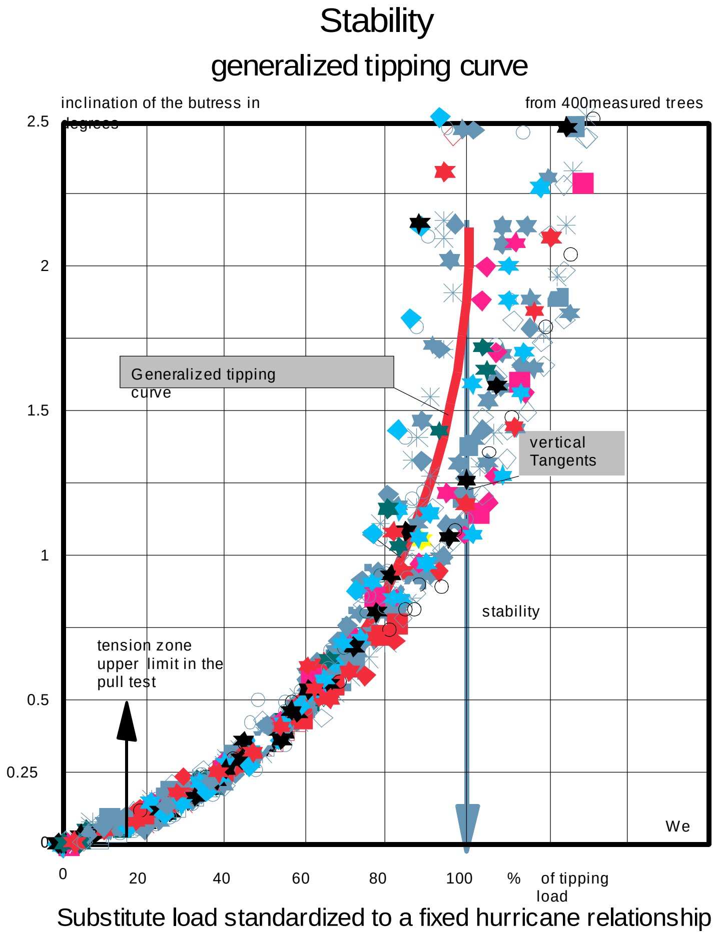
5.2 Failure of tree



Resistance to overturning (uprooting)

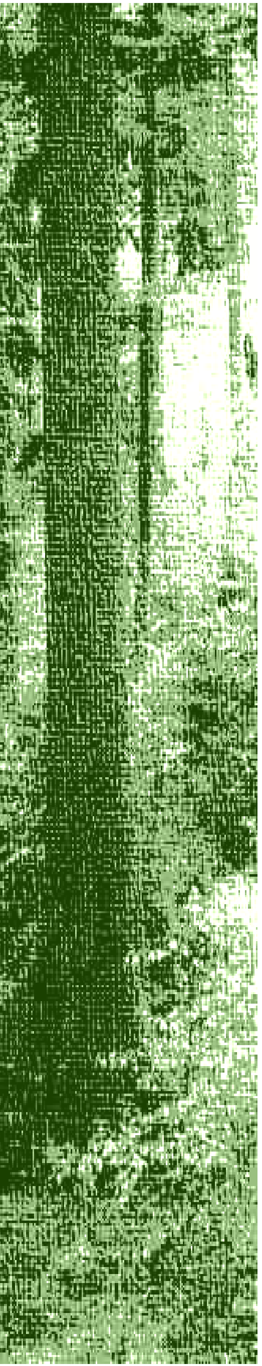
1. Tree as CANTILEVER

If the uprooting moment exceeds the resistive bending moment of the tree at a particular *angle of deflection*, the tree will deflect further.
The tree will give way if the uprooting moment exceeds its maximum resistive bending moment, with the relative strengths of the stem and roots determining the mode of failure.

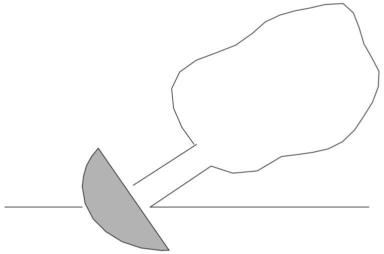


The evaluation of extremely tipped trees shows that the pattern is always the same: no further load increase is possible between 2° and 3° inclination. The Inclinometer method is based on this.

Wessolly (1996)



5.2 Failure of tree



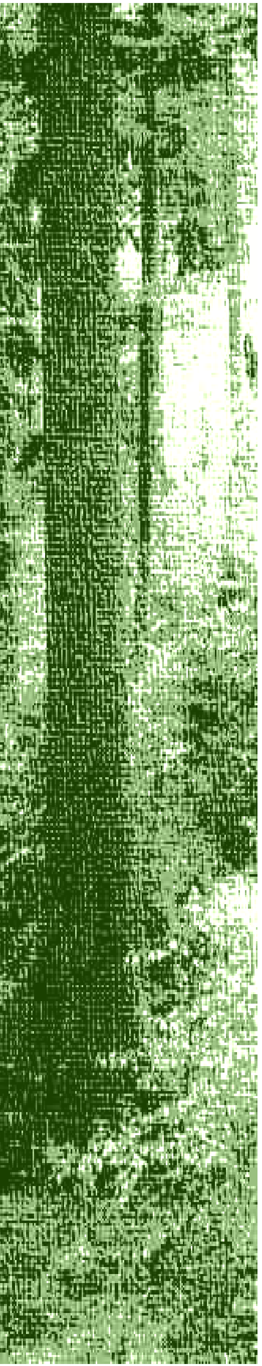
Resistance to overturning (uprooting)

1. Tree as CANTILEVER

- Maximal angle (slope of deflection) ≤ 2-3° of inclination accordinng to experiments
- Angle depends on hight position ($\phi = f(x)$)
- Resistance to overturning = balance between load, area (moment of inertia) and stiffness (E-modulus)

Deflection	**Slope of deflection (angle)**
$v=\frac{Fx^2}{6\ EI}(3L-x)$	$v'=\frac{Fx}{2\ EI}(2L-x)$

$$\text{factor of safety}=\frac{\text{slope of deflection curve}}{\text{inclination of tree}}\leq 1$$



5.2 Failure of tree

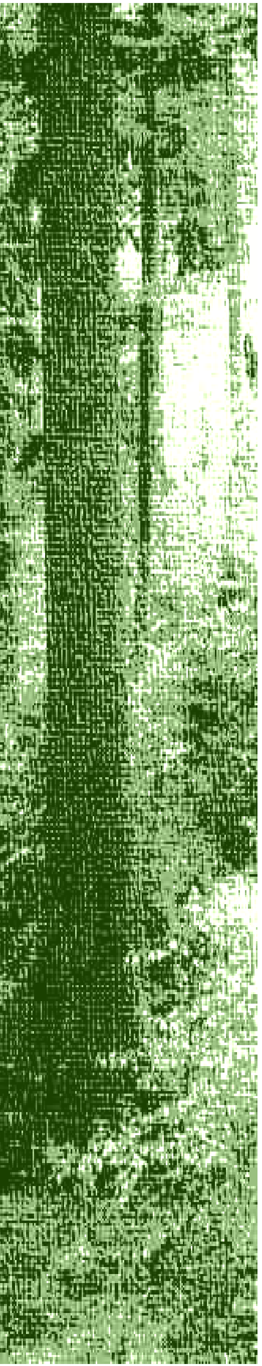
Conclusion

1. No scientific training is needed to understand the following discussion - sound commonsense is enough.

2. Just remember that assessing fracture safety of a structure by all the relevant standards (BIOMECHANICS of TREE) is based on computational statics.

3. This means that (1) load, (2) material and (3) geometry must be known in order to solve the statics equation.

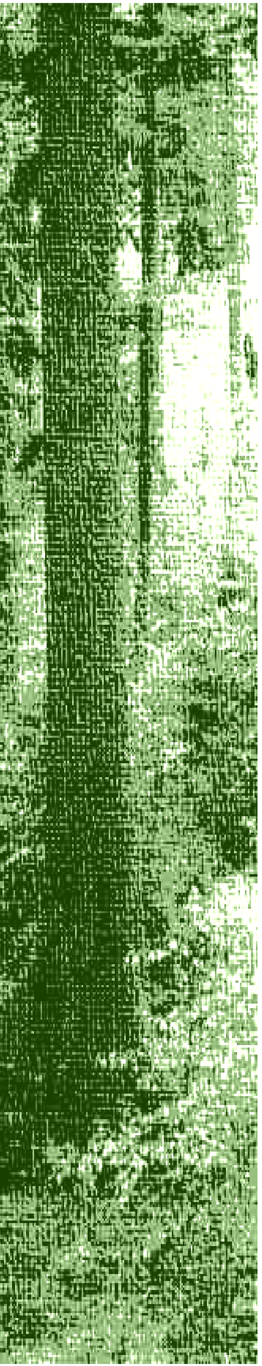
4. The basic question is: **what stem diameter does a tree of given size (tree hight and crown area) need on its site so that it can withstand a severe storm (hurricane) with safety?**



5.3 Factors influencing tree stability

- The factors that affect windthrow and breakage of trees are those that influence the effectiveness of root anchorage, the strength and aerodynamic properties of the tree, and the direction and characteristics of the wind within and above the stand.

- For simplicity these can be separated into
    1. individual tree characteristics,
    2. stand characteristics,
    3. root zone soil characteristics,
    4. topographic exposure characteristics,
    5. meteorological conditions.

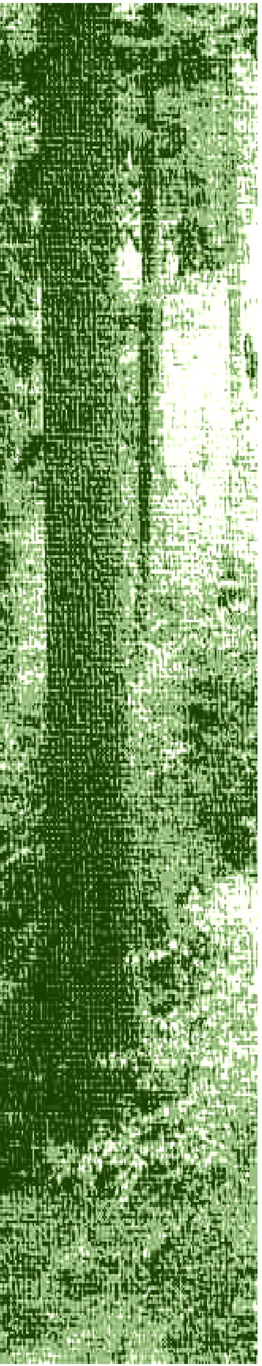


5.3 Factors influencing tree stability

1. Individual Tree Characteristics

At the individual tree level, the following characteristics affect tree stability:

- the height, diameter, and shape of the bole
- the crown class and size of crown
- the strength and elasticity of the bole, branches, and needles
- the rooting depth and area, size and number of roots, and whether or not adjacent tree root systems interlock
- the tree defects

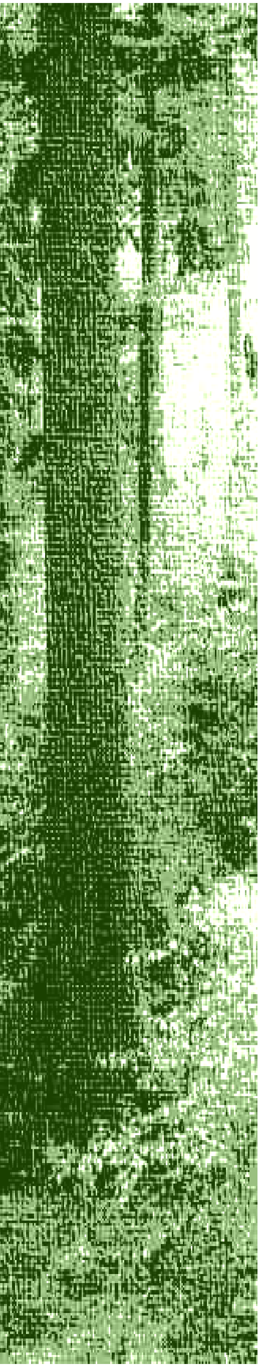


5.3 Factors influencing tree stability

2. Stand Level Characteristics

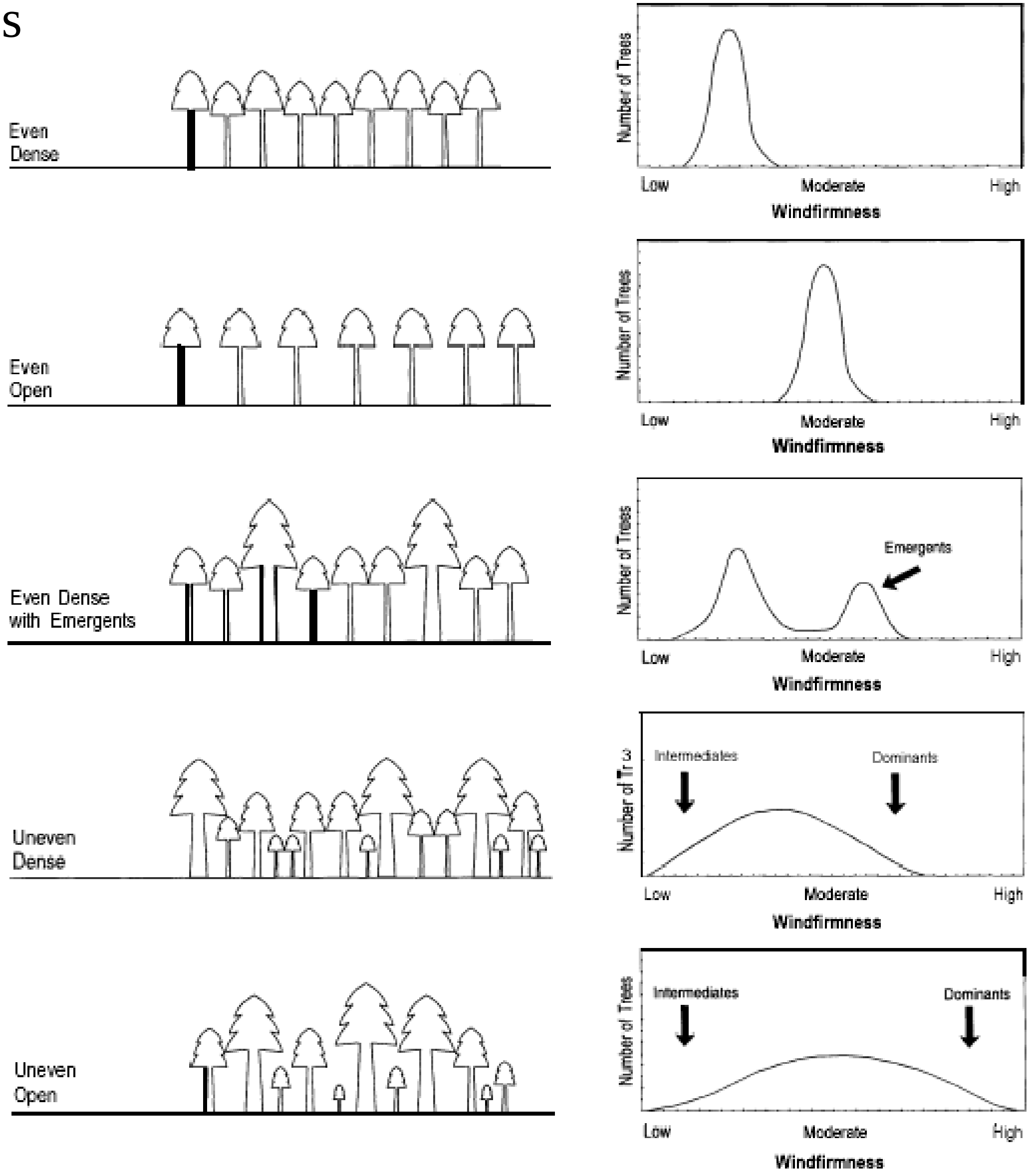
At the *stand level*, individual trees can be made more or less prone to windthrow through the effects of:

- stand height and density
- species composition
- silvicultural treatments (thinning, pruning, edge feathering, ripping, draining, etc.).



5.3 Factors influencing tree stability

2. Stand Level Characteristics



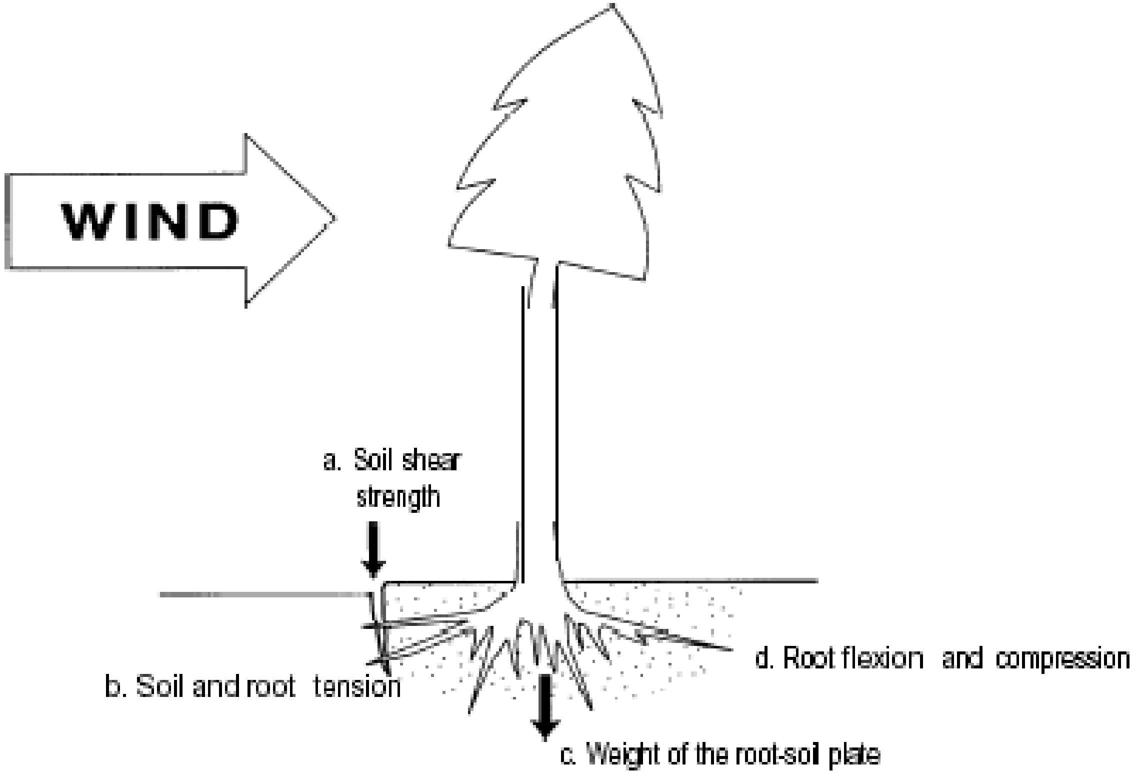
A comparison of distributions of the relative windfirmness of individual trees comprising stands with different structural characteristics.

5.3 Factors influencing tree stability

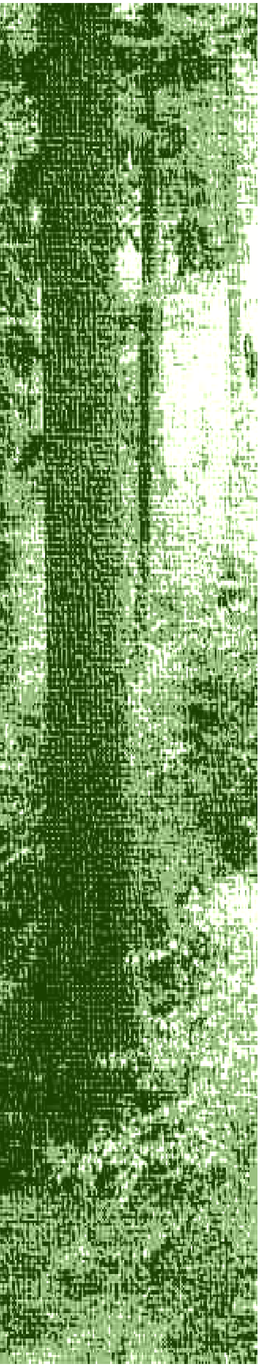
3. Soil Characteristics

Soil characteristics affect windthrow through the interaction of:

- depth
- drainage
- structure, density, texture, and the anchorage strength of the root system.



Root and soil factors affecting resistance to overturning.



5.3 Factors influencing tree stability

4. Topographic Characteristics

Topographic characteristics affect windthrow by modifying:

- wind exposure
- wind direction, speed and turbulence.

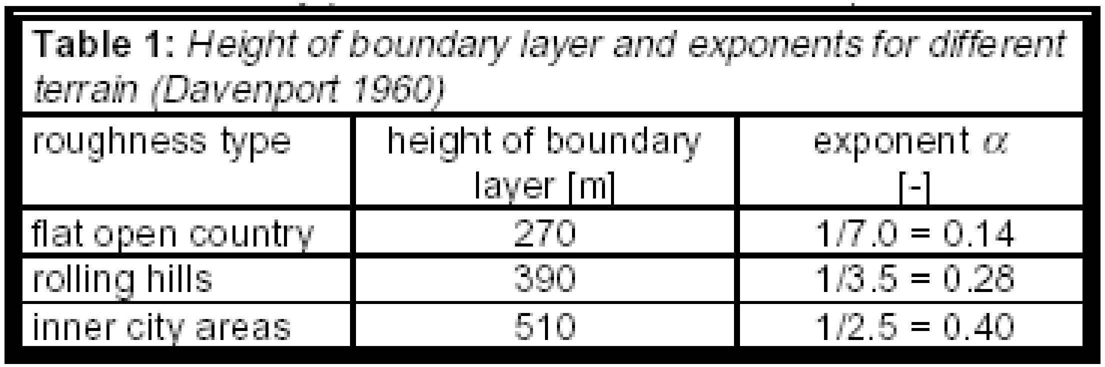
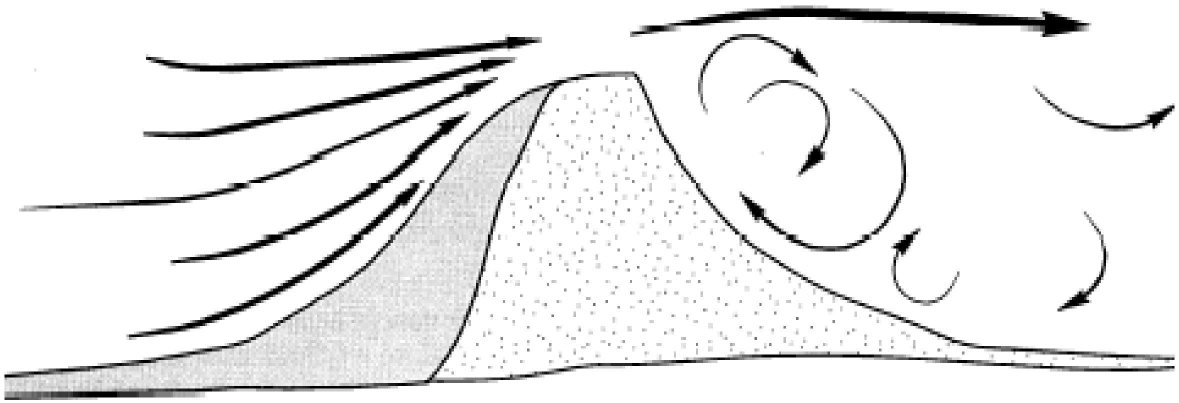
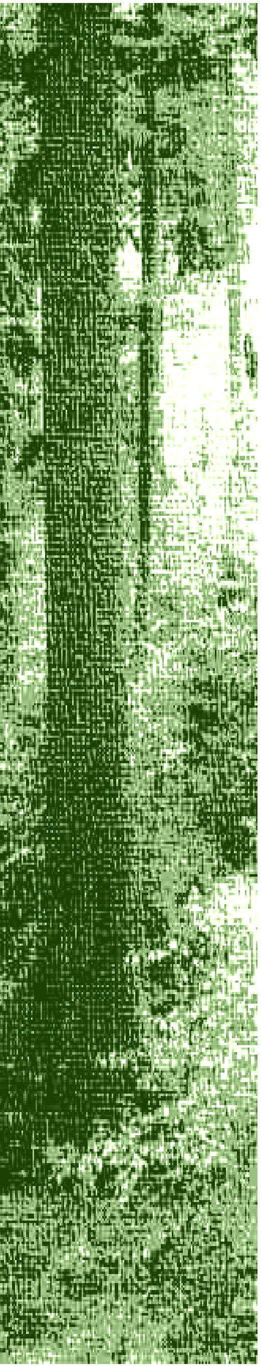


Table 1: *Height of boundary layer and exponents for different terrain (Davenport 1960)*

roughness type	height of boundary layer [m]	exponent α [-]
flat open country	270	1/7.0 = 0.14
rolling hills	390	1/3.5 = 0.28
inner city areas	510	1/2.5 = 0.40

Wind flow over a hill showing flow acceleration on the windward slope and turbulence (roller eddies) on the leeward slope.



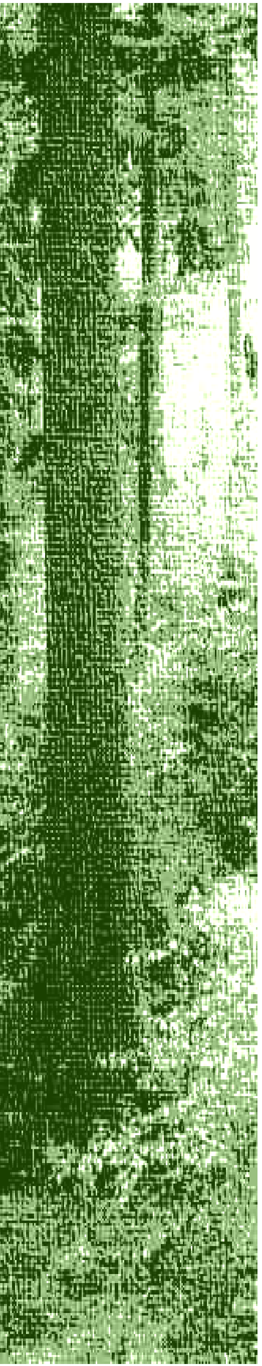


Conclusion

- The concept of biomechanics refers to mechanical phenomena observed in a living plant, like a tree, that can be explained by the mere application of the usual analysis of structure and material mechanics.

- As an example, the global or local deformations of a tree submitted to sudden wind can be calculated by classical structure mechanics provided that sufficient information is given on

  1. geometry,
  2. material properties and
  3. wind–structure interaction.

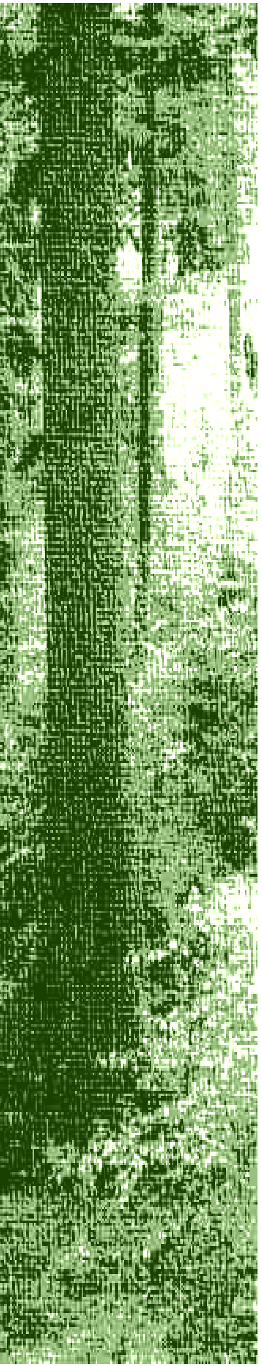


Conclusion

- The assessment of the mechanical safety factor of the tree structure is a clearly defined engineering concept with generally accepted rules.

- It involves an accurate appraisal of the forces occurring as well as the determination as to whether the tree’s structure and material can withstand these forces.

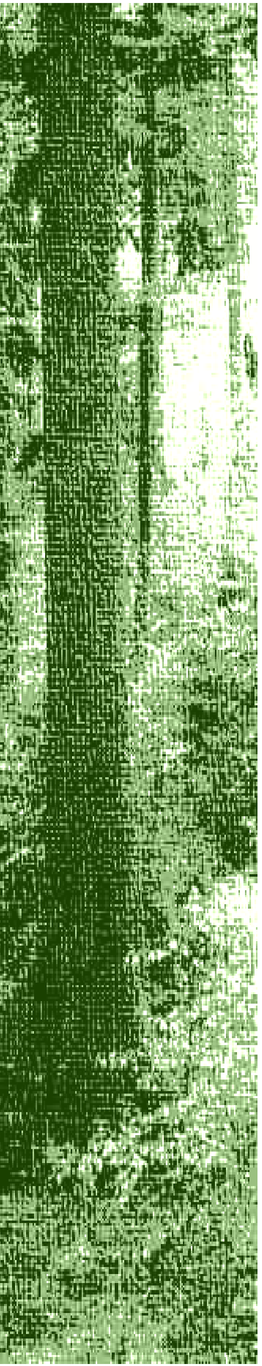
- The procedure is represented in the model of the statics triangle, which demonstrates the inherent correlation of loads, tree geometry and wood properties.



Some of the earlier inroads into a systematic approach to hazard evaluation were made by the Parks Service in the USA (in 1963, **Wagener,** in 1967, **Paine**, gathered data on tree failure related to **species**, **size** and **part** of tree. This early work paved the way for the systems that continue to develop today.

There are 6 current tree inspection systems in wide use:

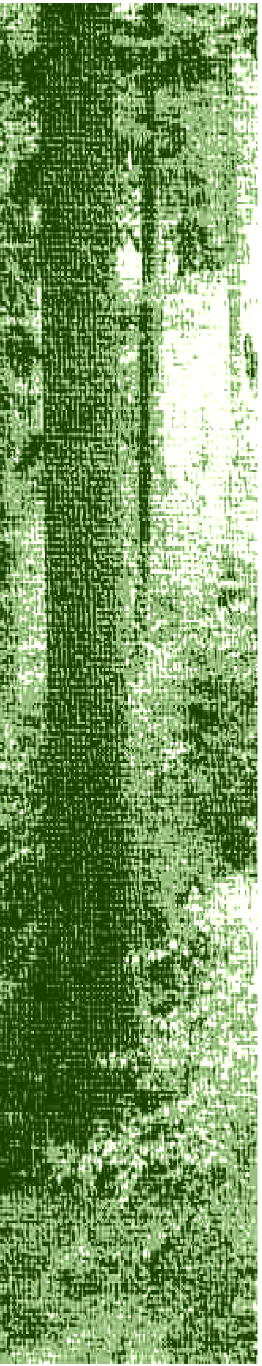
1. The Visual Tree Assessment method (**VTA**)
2. The Evaluation of Hazard Trees in Urban Areas (**EHT**)
3. Statics-Integrated Assessment (**SIA**) and Statics-Integrated Methods (**SIM**)
4. The Forestry Commission in the United Kingdom developed a quantitative windthrow hazard classification scheme
5. The Windthrow Handbook for British Columbia Forests
6. Mechanistic approaches (static and dynamic models)



6.1 SIA

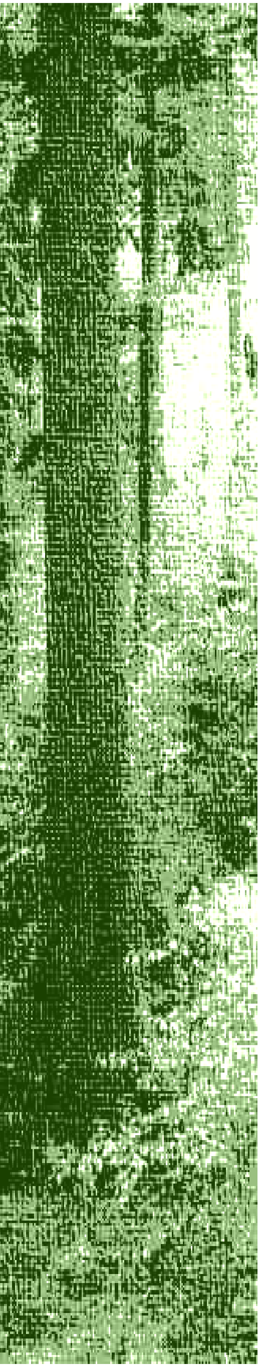
6.2 SIM – pulling test

6.3 Comparison to other methods

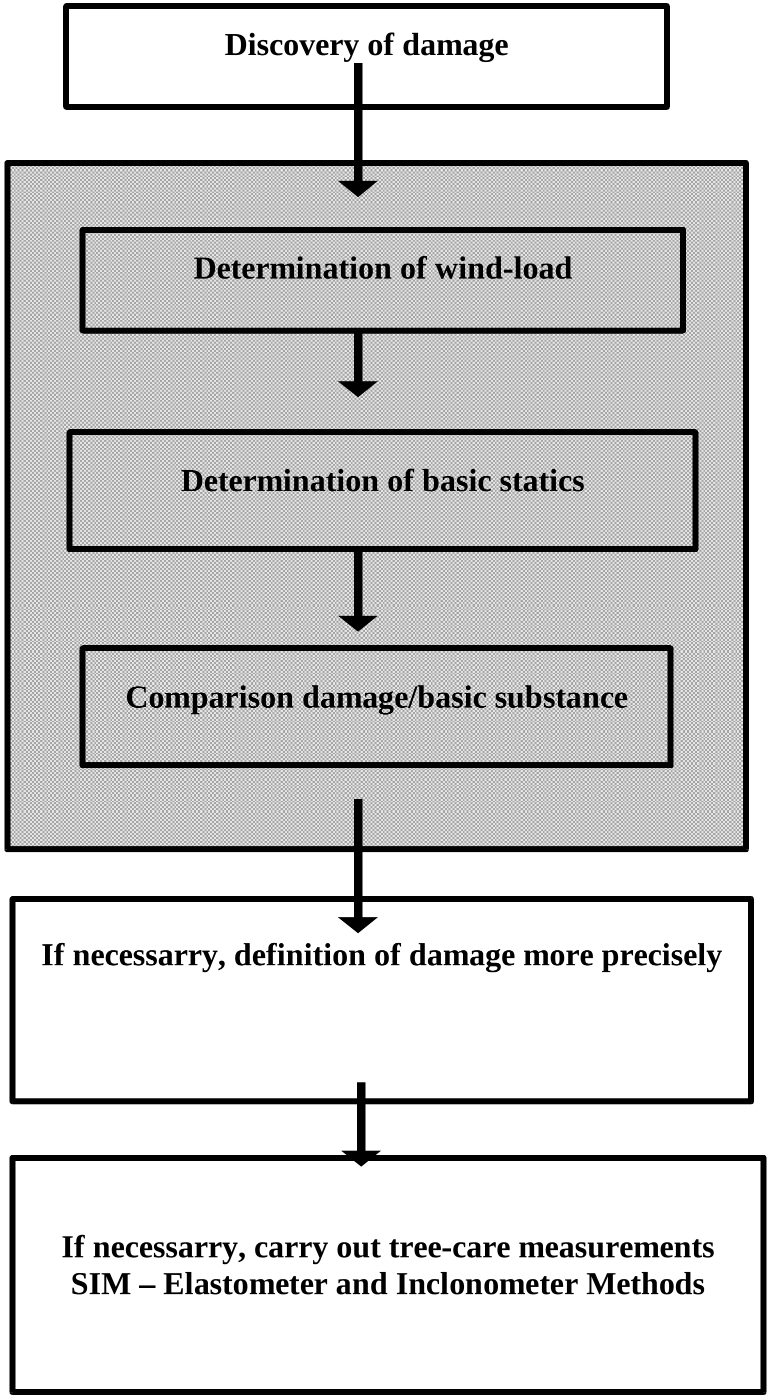


6.1 Statics-Integrated Assessment (SIA)

- The method of **S**tatics-**I**ntegrated **A**ssessment (SIA; in Switzerland SIB) has been developed on the basis of of practical measurements and safety surveys of trees.
- The basic question solved there is: **what stem diameter does a tree of given size need on its site so that it can withstand a severe storm (hurricane) with safety ?**
- The **SIA** method **focuses on the load** - the wind load on a tree depends on its absolute size, crown form and wind permeability.
- It works with four basic forms of crown appearance:
    1. a slender cylinder on a pillar,
    2. a ball on a pillar,
    3. an ellipsoid on a pillar,
    4. and a heart-shape.
- Tree species can be grouped when their wood strength differences and wind resistance coefficients are equalized.
- The compression strengths of the individual woods according to **the Stuttgart Strength Catalogue** are also a basis of the SIA, as is the different wind permeability of the crowns.



- The flow-diagram shows the new way of thinking.
- First access the tree from its basic substance and not concentrate on the damage or symptoms.
- In most cases this saves time and expensive investigation.
- The SIA method simplifies determination of the basic substance; the practioner only needs to measure tree height and stem diameter precisely.
- A simple form guides the user through.



Discovery of damage

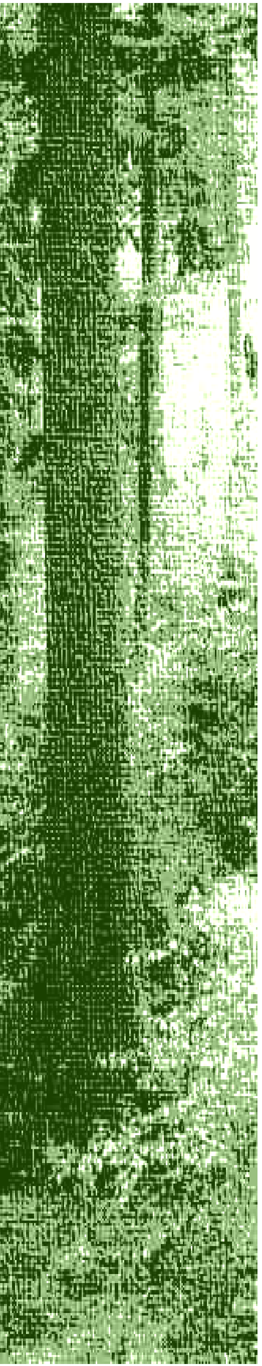
Determination of wind-load

Determination of basic statics

Comparison damage/basic substance

If necessarry, definition of damage more precisely

If necessarry, carry out tree-care measurements
SIM – Elastometer and Inclonometer Methods



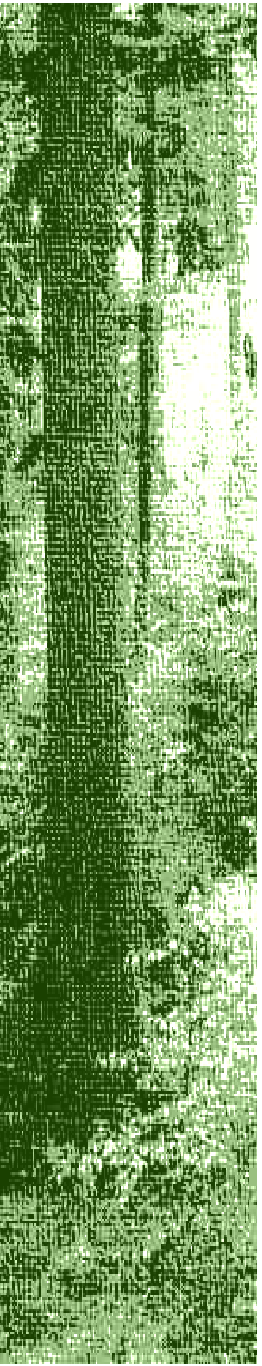
6.2 Statics-Integrated Methods (SIM)

- SIM is the final stage in diagnosing the safety of important trees.
- Before this the practitioner should be able to make an on-site decision on the safety of the trees as regards traffic, in accordance with the statics situation.

- Decisive factors involved there are
  1. load,
  2. wood-material properties
  3. geometry of trees.

- Remember .....

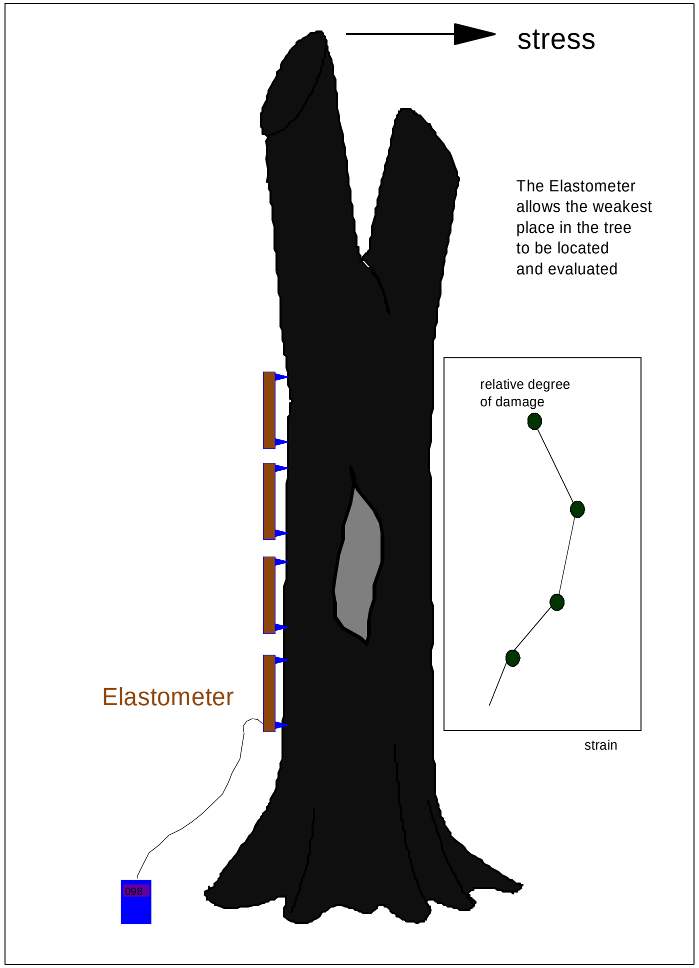
Components of Tree Stabilty and
Biomechanics of Tree

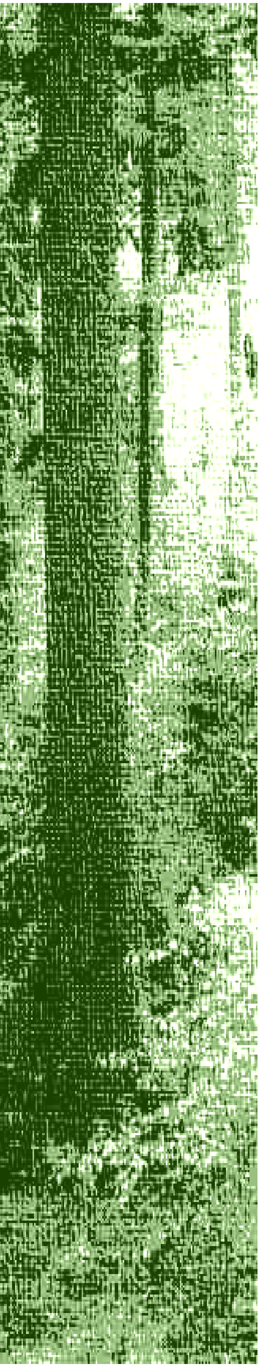


6.2 Statics-Integrated Methods (SIM)

- Inclinometer method - the establishment of a generalized tilt curve valid for all trees shows that stability can be determined without injury by a *pulling test* by measurements of tilt.

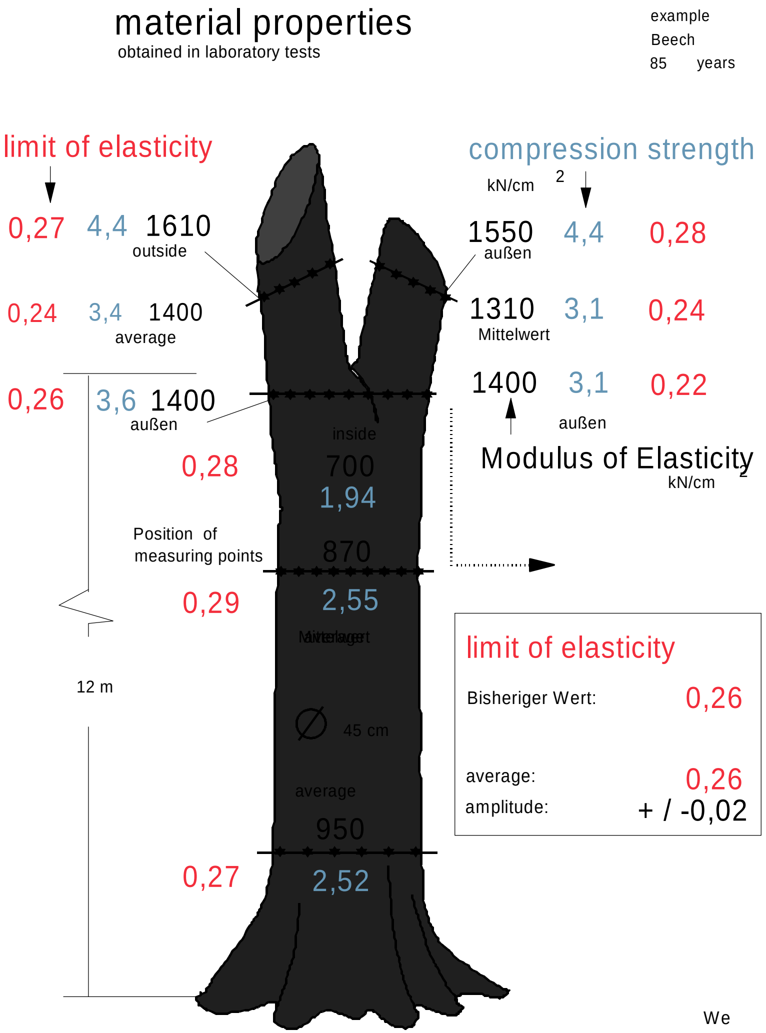
- Elastometer method - the development of the approach, which non-destructively measures the stretching of the representative peripheral fibres for *the pulling test* were the consequence of the failure process of trees under bending load is assessed.





6.2 Statics-Integrated Methods (SIM)

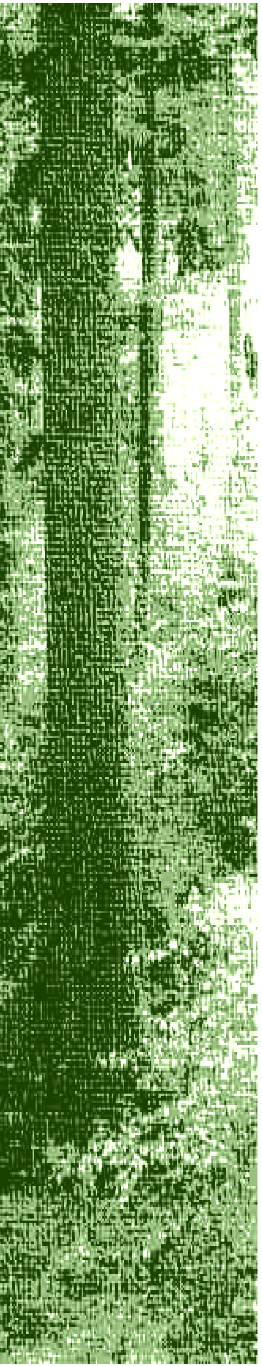
- The Elastometer measures the stretching of the peripheral fibres, and can non-destructively analyze the tree from the outside and also locate the place which gives danger most, even with hidden cavities.
- In comparison with the mean E-modulus (stiffness) of all the measured trees of the same species, we obtain the residual carrying capacity of the hollow tree as compared to the solid cross-section.
- The residual carrying capacity or residual wall thickness is important for completing the overall picture of the tree's statics, and for making a prediction.



limit of elasticity

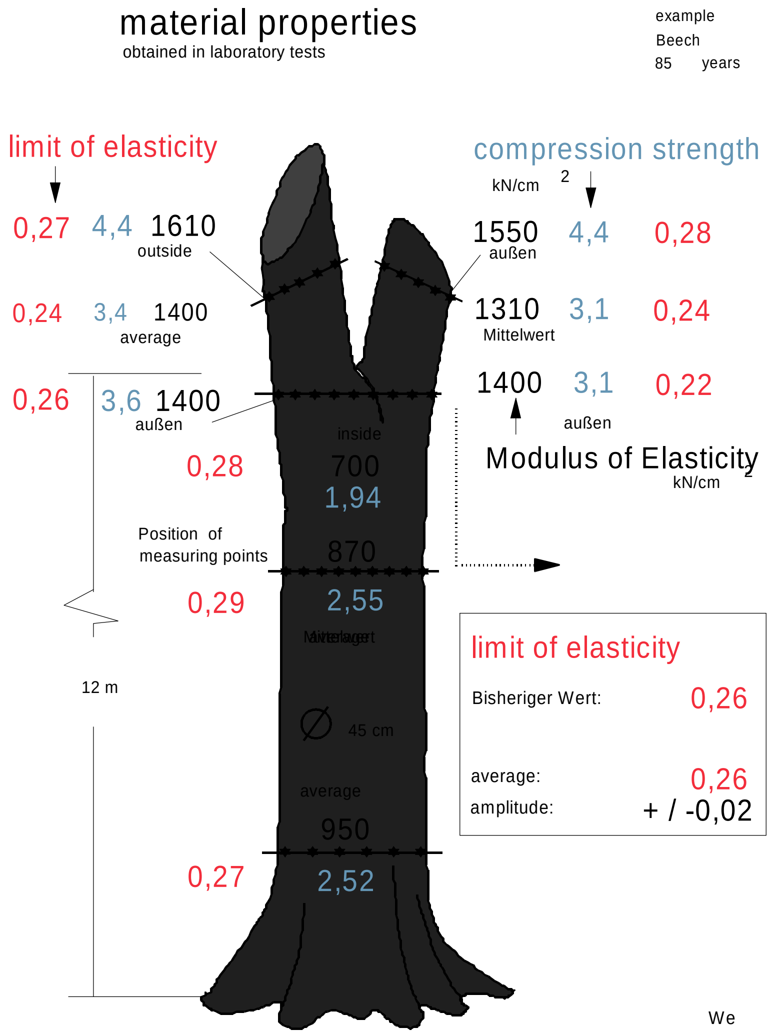
Bisheriger Wert: 0,26

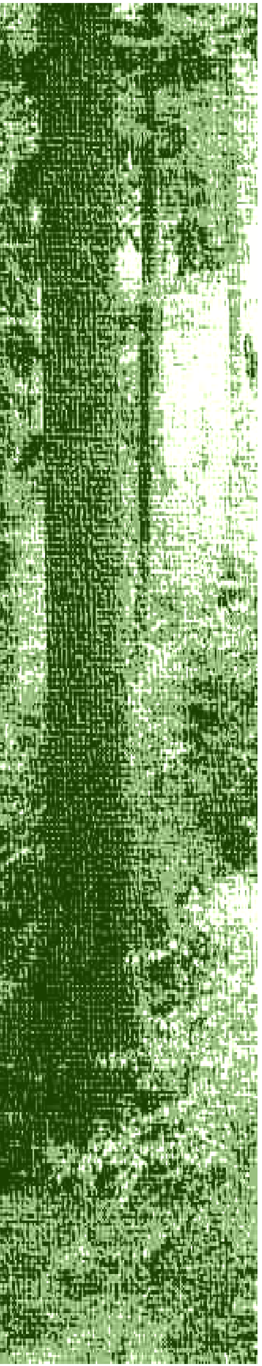
average: 0,26
amplitude: + / -0,02



6.2 Statics-Integrated Methods (SIM)

- The Inclinometer measures ......
- In comparison with theretical and/or calculated deflection or slope of deflection (angle) we obtain
  - a) the residual carrying capacity of the hollow tree as compared to the solid cross-section
  - b) the assessment of tree fixation to the ground (the measure of rooted area stability) – the rigidity of tree anchorage





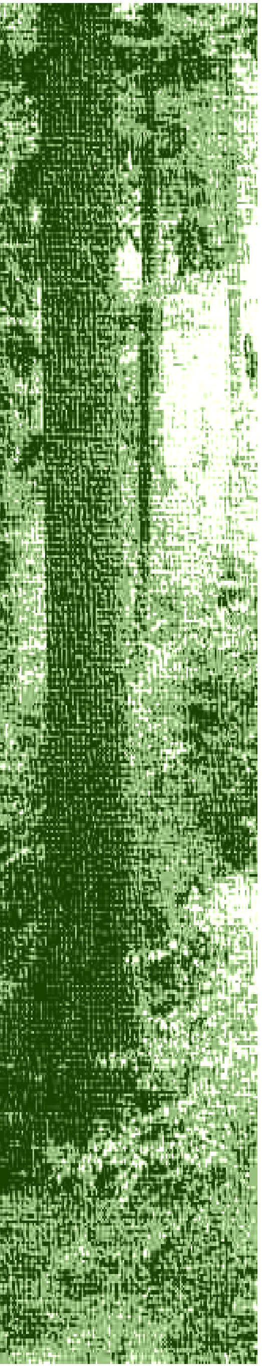
6.2 Statics-Integrated Methods (SIM)

- The failure behaviour of trees in a storm allows only one computational possibility of fracture safety analysis:
  - a) simulation of wind load and Elastometer measurement of the compression of the heaviest-loaded peripheral fibres located directly beneath the bark
  - b) simulation of trunk deflection and Inclinometer measurement along the stem axis

- Their behaviour is representative for the carrying capacity of the cross-section.

- Application of method – guarantee of safety.

- Expert statics-integrated tree monitoring is based on individual-tree analysis of
  1. **load,**
  2. **geometry and**
  3. **material.**

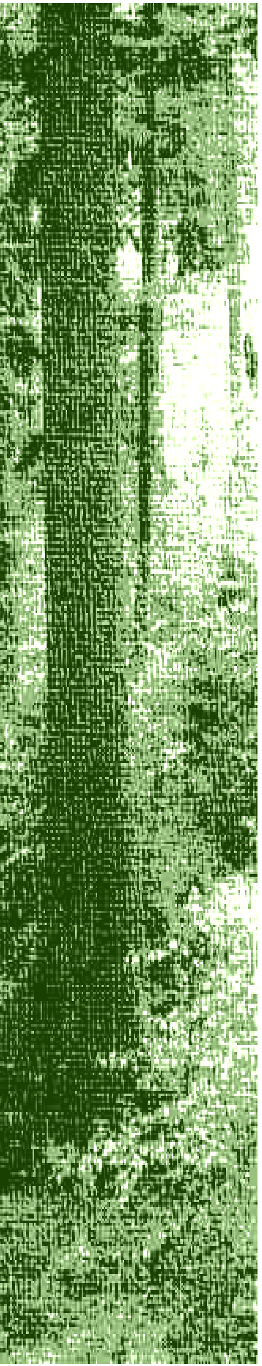


Assessing the safety of a tree, like that of any engineering structure, is a clearly defined engineering task with generally accepted rules. It involves, on the one hand determining as accurately as possible the forces occurring and, on the other hand whether the structure and material can withstand them. The procedure is symbolized in the statics triangle, which consists on the inseparable connection of loads, tree geometry and wood properties.

It would be naturally simpler to determine the safety of trees if nature had kept to closely limited numerical values which could be used to describe a uniform residual wall-thickness or a constant safety stress valid for the entire tree. Since trees consist on roots, stem and crown which are optimized by adaptive growth, their diversity of form suggests that it will not be possible to determine safety by generalized numerical values (as used for example in the VTA method) characterizing the degree of e.g. hollowness or safety without any measurements (as used for example in the SIA and SIM Methods).

The failure behaviour of trees in a storm allows only one computational possibility of fracture safety analysis: simulation of wind load and Elastometer measurement of the compression of the heaviest-loaded peripheral fibres located directly beneath the bark. Their behaviour is representative for the carrying capacity of the cross-section. How much these fibres can be compressed before they are irreversibly damaged is described by both modulus of elasticity (stiffness), and compression strain and stress at proportional limit (rigidity and strength). Only methods based on non-destructive spatial determination of the carrying capacity of a part of a tree and prediction of the fracture load utilising above mentioned constants, can provide verifiable technique both for fracture safety and for tree stability assessment.

Literature



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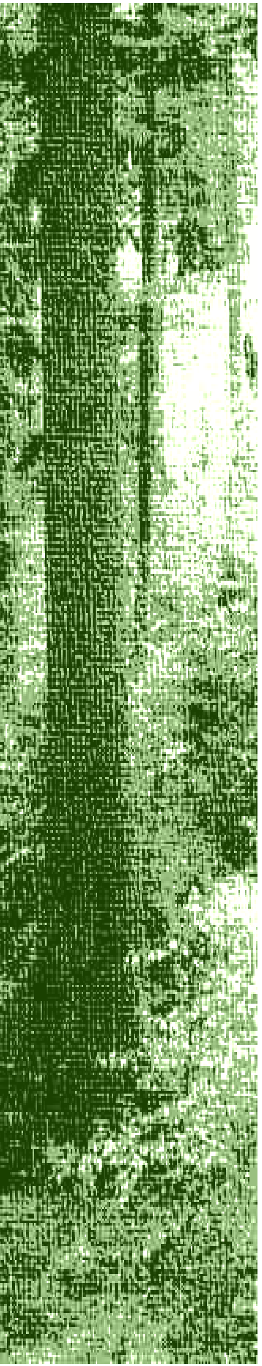

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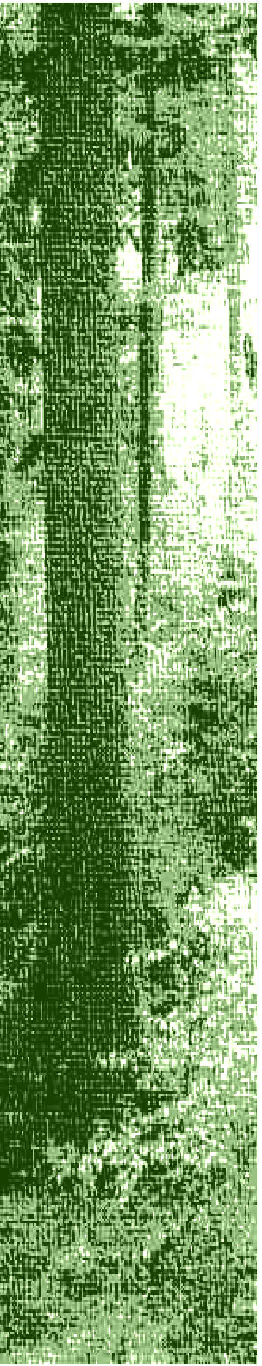

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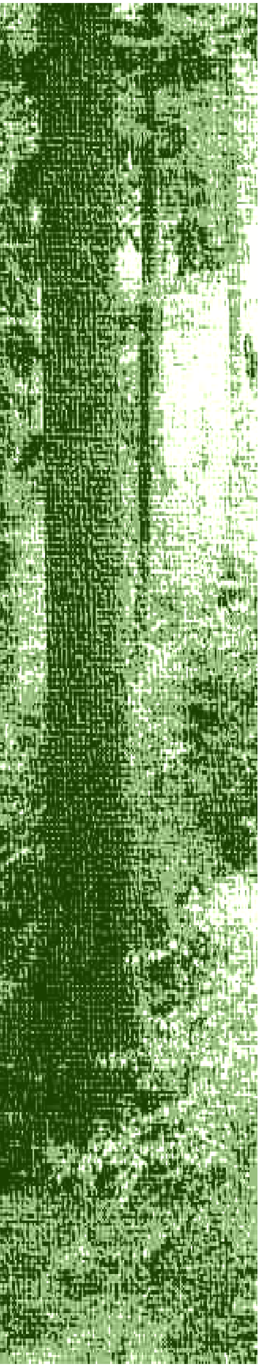

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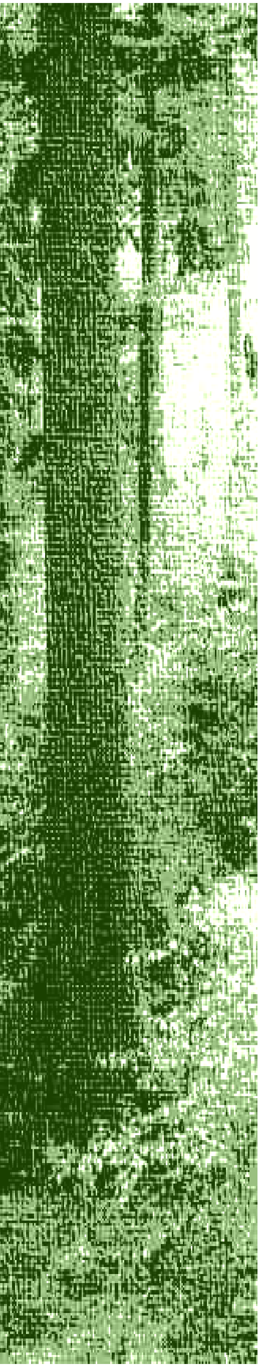

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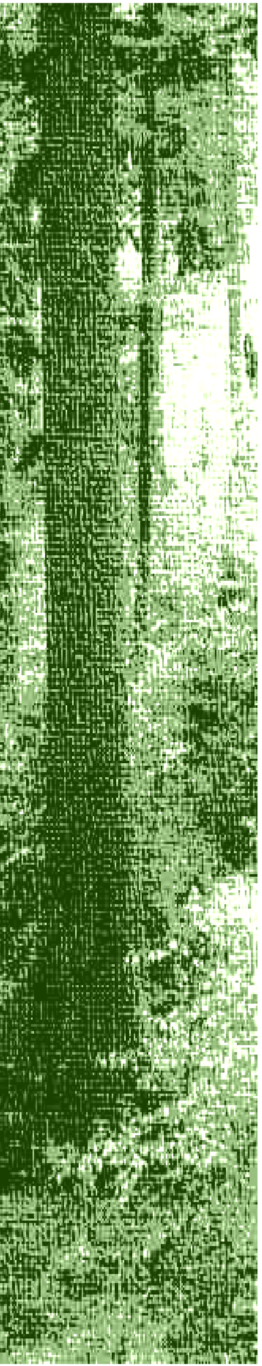

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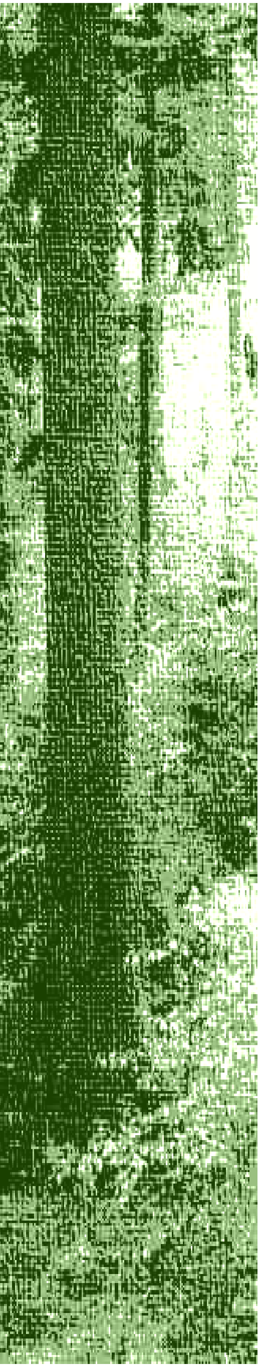

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