Tree Biomechanics

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EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

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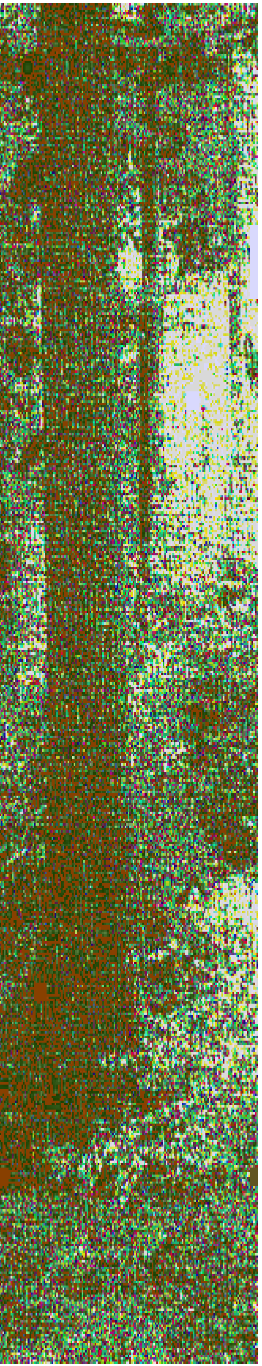
1. Introduction to Biomechanics of Tree

2. Hazard Tree Management

a) Tree risk assessment
b) Problems (defects) identification
c) Biomechanical approach



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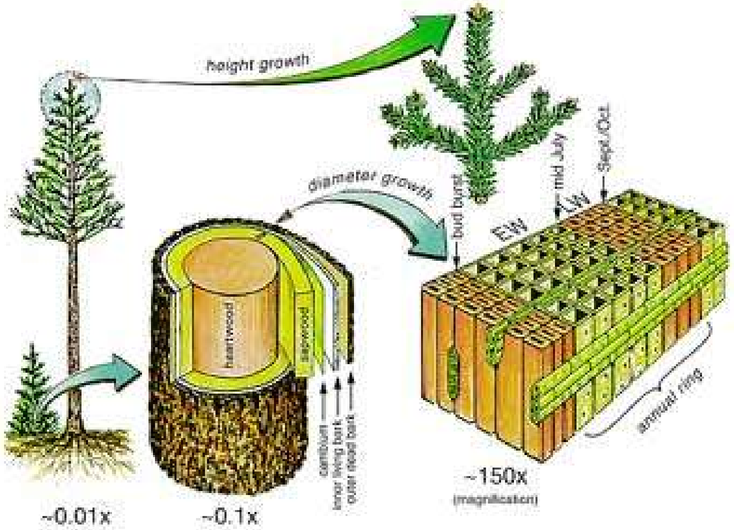
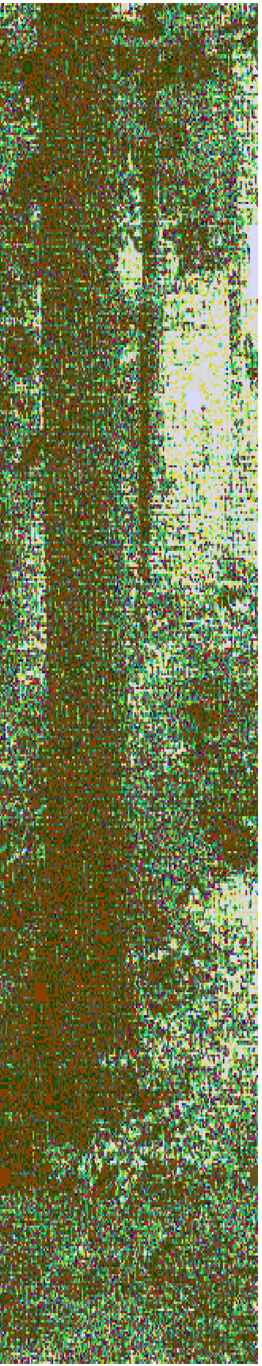
3. Introduction to Wood Science

a) Tree structure and function
b) Tree growth and onthogeny
c) Intro to wood science





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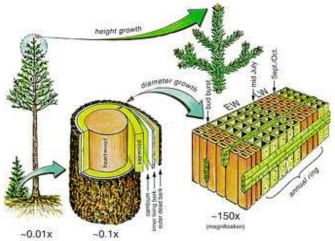
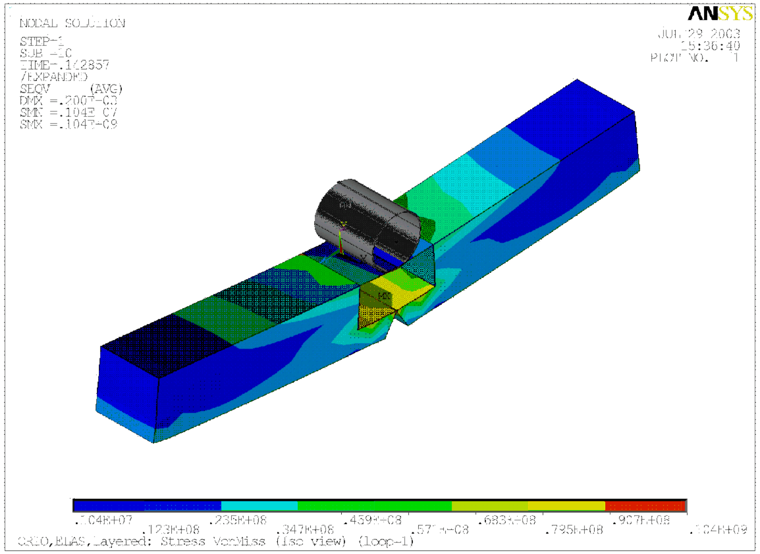
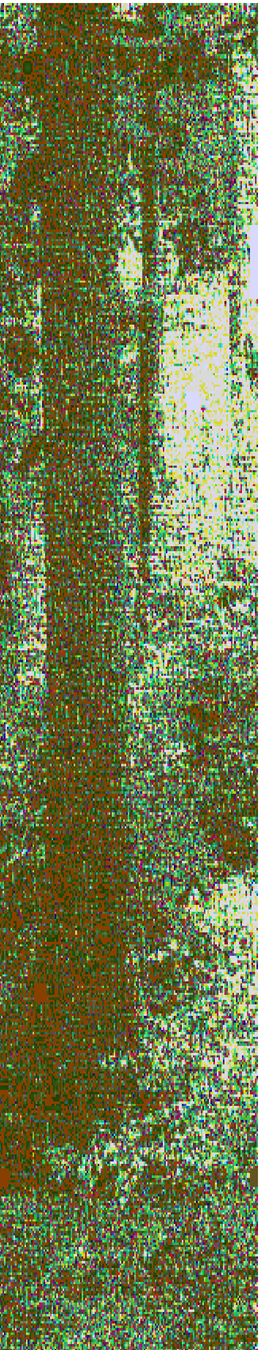


4. Components of Tree Stability

   a) Tree geometry (root, stem, crown)
   b) Wood properties (strength and stiffness)
   c) Loads applied to tree





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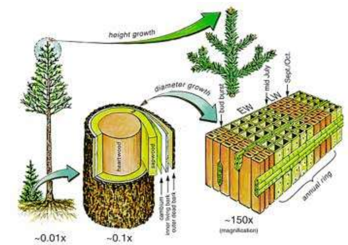

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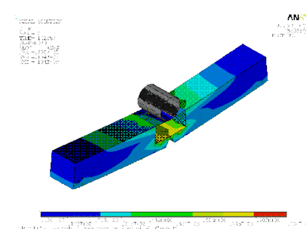
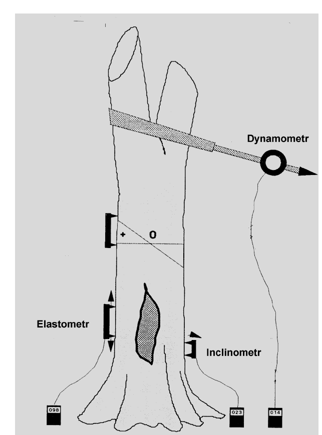
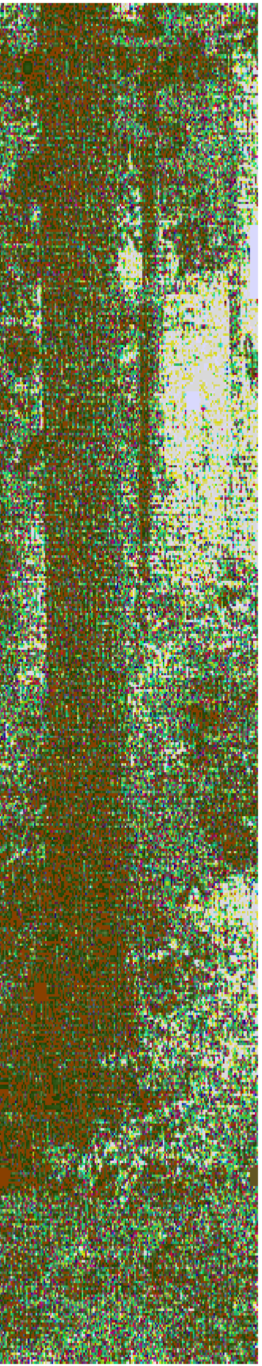


5. Biomechanics of Tree

    a) Application of mechanics of materials
    b) Failure of tree
    c) Factors influencing tree stability





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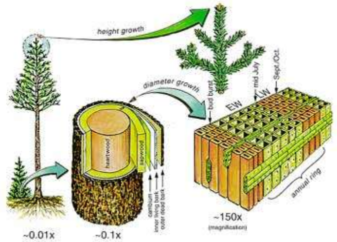

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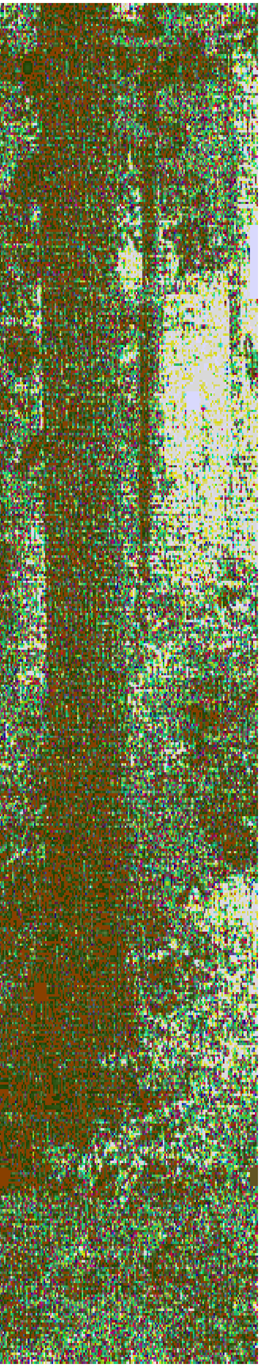
   b) Failure of tree
   c) Influence of defects

6. Practical application – SIA, SIM

1. Introduction to Biomechanics of Tree



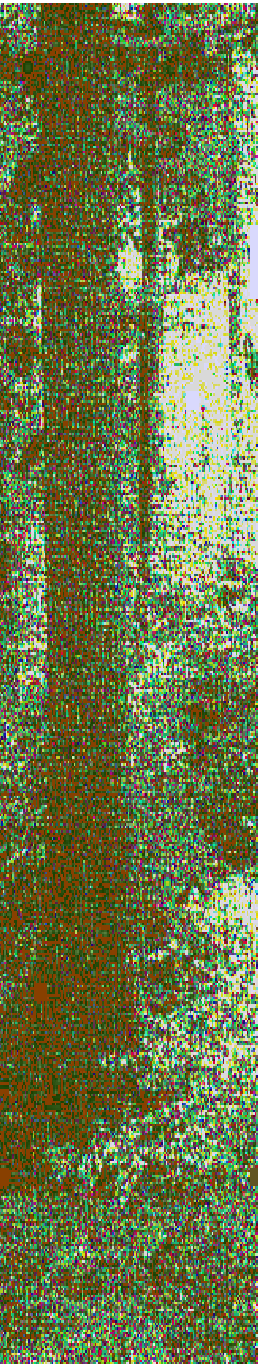
- Focus of interest for forestry and arboricultural research owing to the potential for trees to harm people or property.
- Significant practical implications for tree safety assessments.
- Response to wind loading – breakage or overturning of tree.
- Mechanistic models that predict the critical wind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

1. Introduction to Biomechanics of Tree

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. Quantitatively prediction of fracture safety.
7. Non-destructively monitor exactly the same place for years.

1. Introduction to Biomechanics of Tree



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

1. Introduction to Biomechanics of Tree

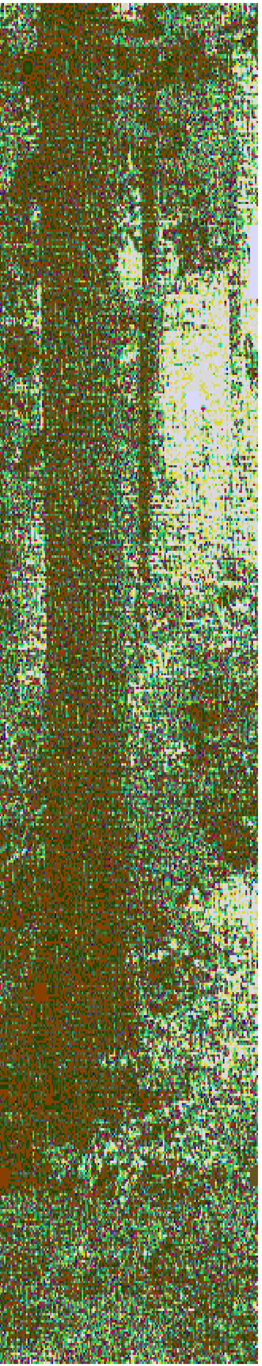
Key terms

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 atructures

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



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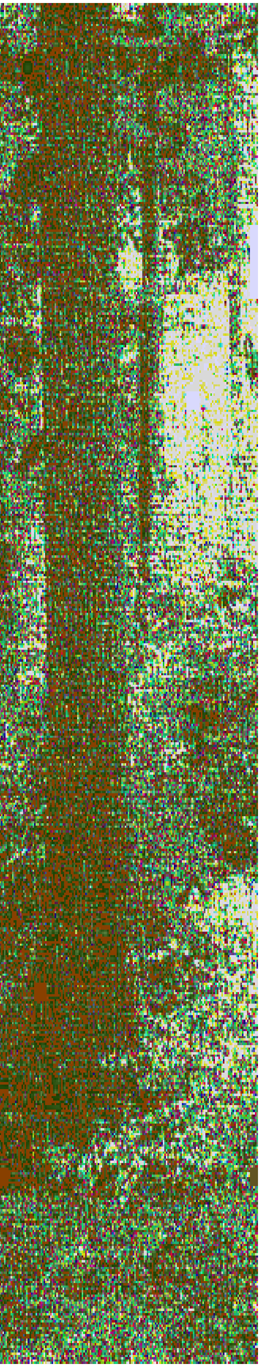
2. Assessment of „static“ picture of tree – often without its history and future development



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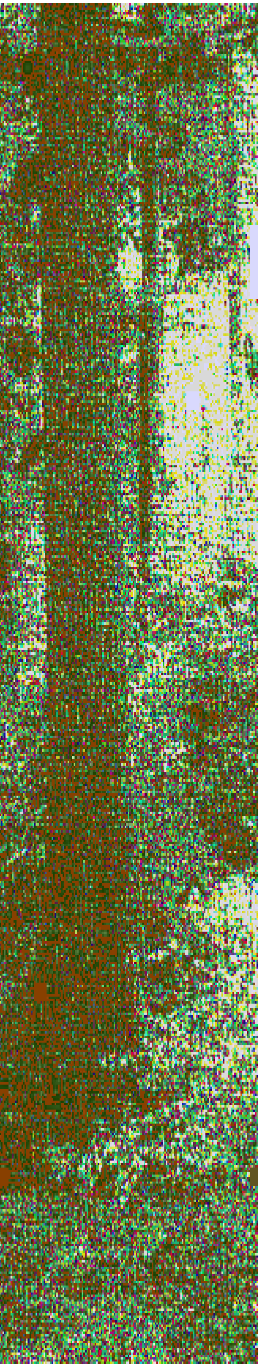
2. Assessment of „static“ picture of tree – often without its history and future development

3. Rooted area – 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)



Conclusion

2. Hazard Tree Management

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.

2.1 Hazard Tree Evaluation

2.2 Problems (defects) identification

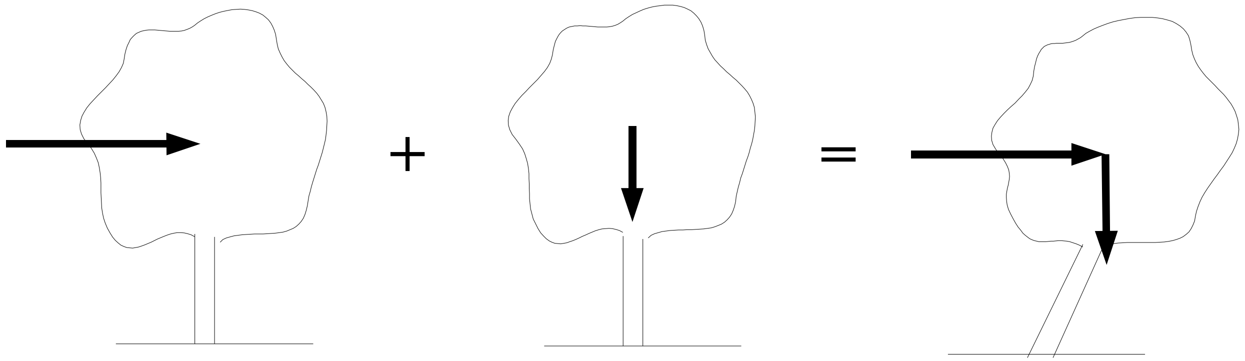
- Recognizing hazardous trees and taking proper corrective actions can protect property and save lives.
- A “hazard tree” is a tree with structural defects likely to cause failure of all or part of the tree, which could strike a “target.”

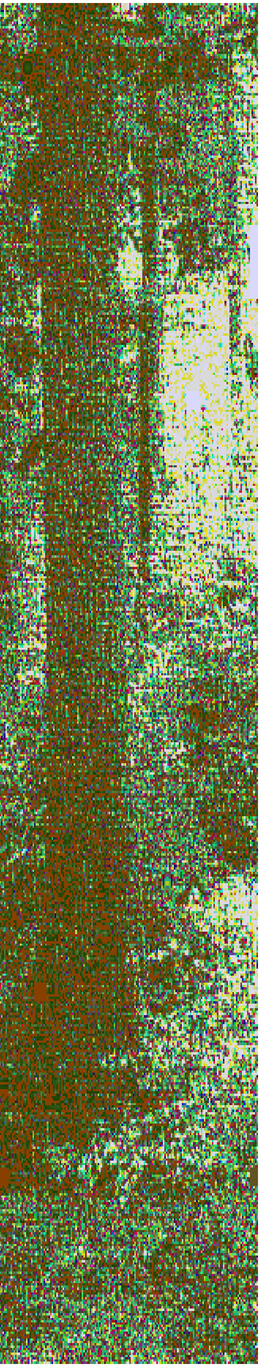
2.1 Hazard Tree Evaluation

2.2 Problems (defects) identification

2.3 Biomechanical approach

- The development of the approach is schematically presented.

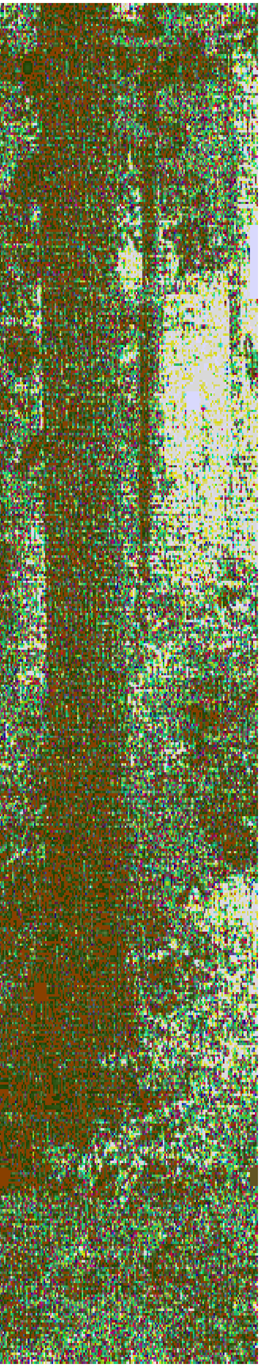




2.1 Hazard Tree Evaluation

Components of Hazard Tree Evaluation

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



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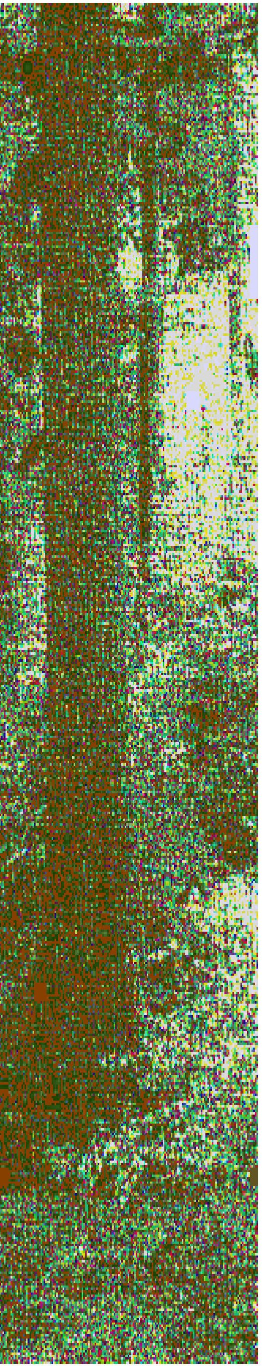
2. Tree
   - History – toping
   - Architecture – growth habit
   - Signs of decay
   - Weak structures
   - Root system



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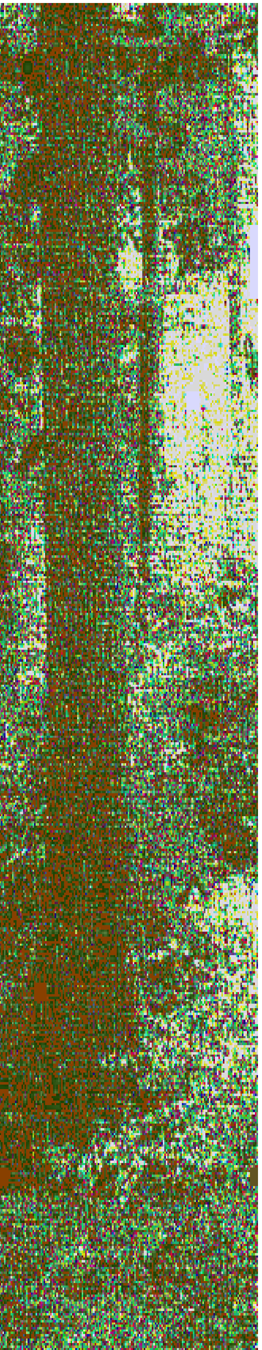
3. Target
   - Potential to fail and injure or damage a target

2. Hazard Tree Management



2.1 Hazard Tree Evaluation

Usually considered factors when inspecting trees

Tree Condition

Poor condition – dead twigs, dead branches, or small, off-color leaves.
Good condition – full crowns, vigorous branches, and healthy, full-sized leaves.

Green foliage in the crown does not ensure that a tree is safe – trunk and branches can be quite defective.

Tree Species

Certain tree species are prone to specific types of defects.
Some species of maple and ash – weak branch unions.

Aspen – breakage at a young age (50-70 years) due to decay and cankers.

Tree Age and Size

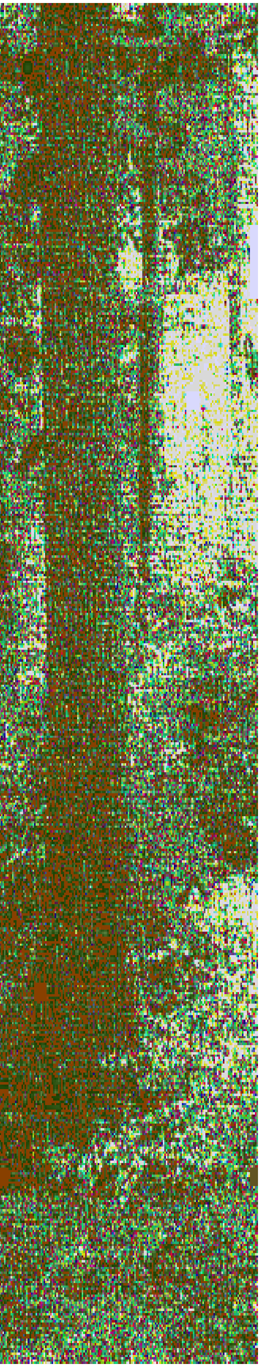
Trees – living organisms subject to constant stress.
Older trees – accumulated multiple defects and extensive decay.

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 (Ressistograph, Arbosinic, ...)
- 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.

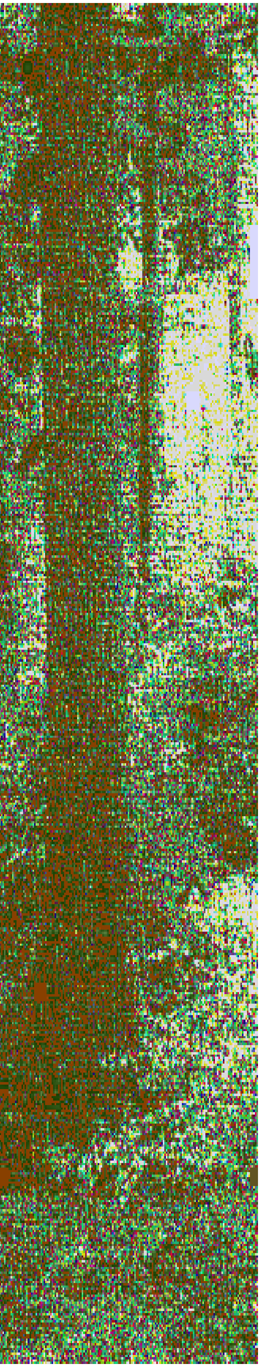
2.2 Problems (defects) identification

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. Hazard Tree Management



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 to 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.

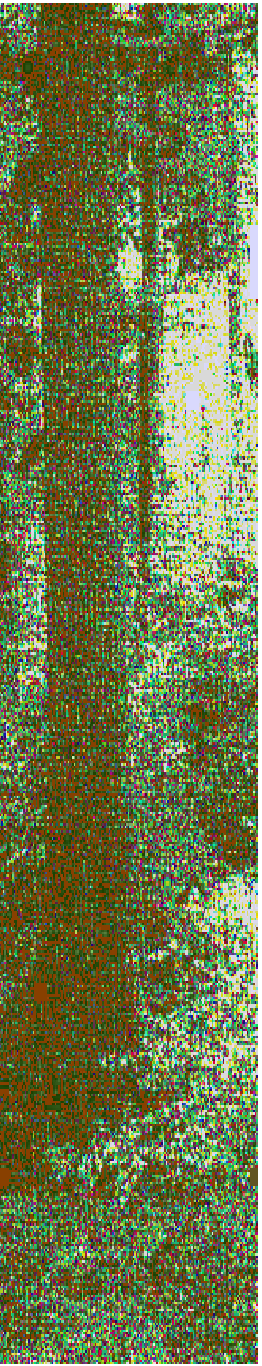
2.3 Biomechanical approach

Special cases (limitations)

- Tree as a forced, damped harmonic oscillator (dynamic response)
- Growth stresses
- Stress position depends on the taper
- Critical wind speeds
- Large tree deflections x beam teory

Assumptions

- The stem of a standing tree can be treated as an elastic cantilever beam, rigidly fixed on one side and free on the other.
- Its diameter varies with height, and this non-uniform taper can be described by a mathematical function.
- The transverse section of the stem is considered to be either circular or elliptic.
- Wind load may be calculated by representing it as a horizontal load applied to the canopy centre of gravity.



Conclusion

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.

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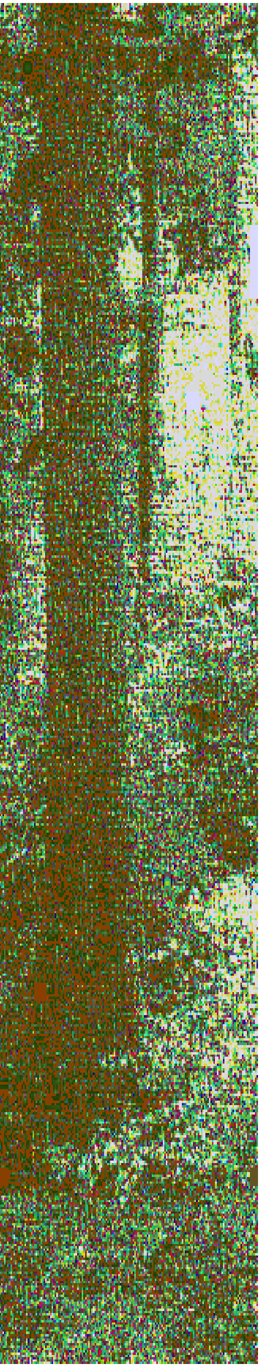
3.2 Tree growth and ontogeny

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

3. Introduction to Wood Science



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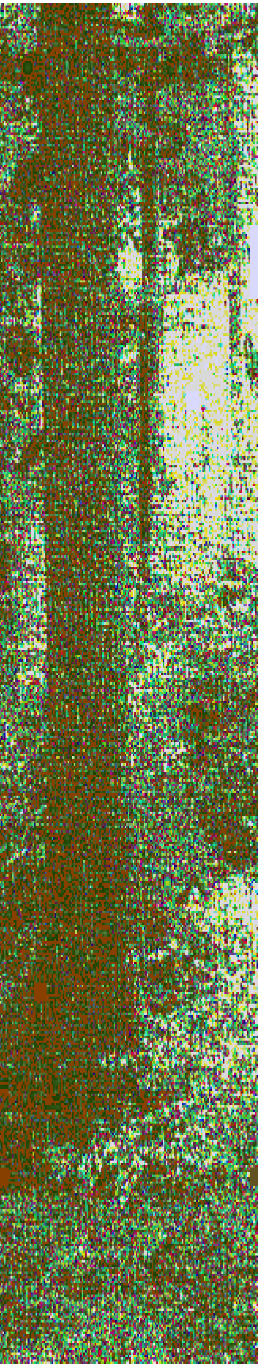
3.3 Intro to wood science

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

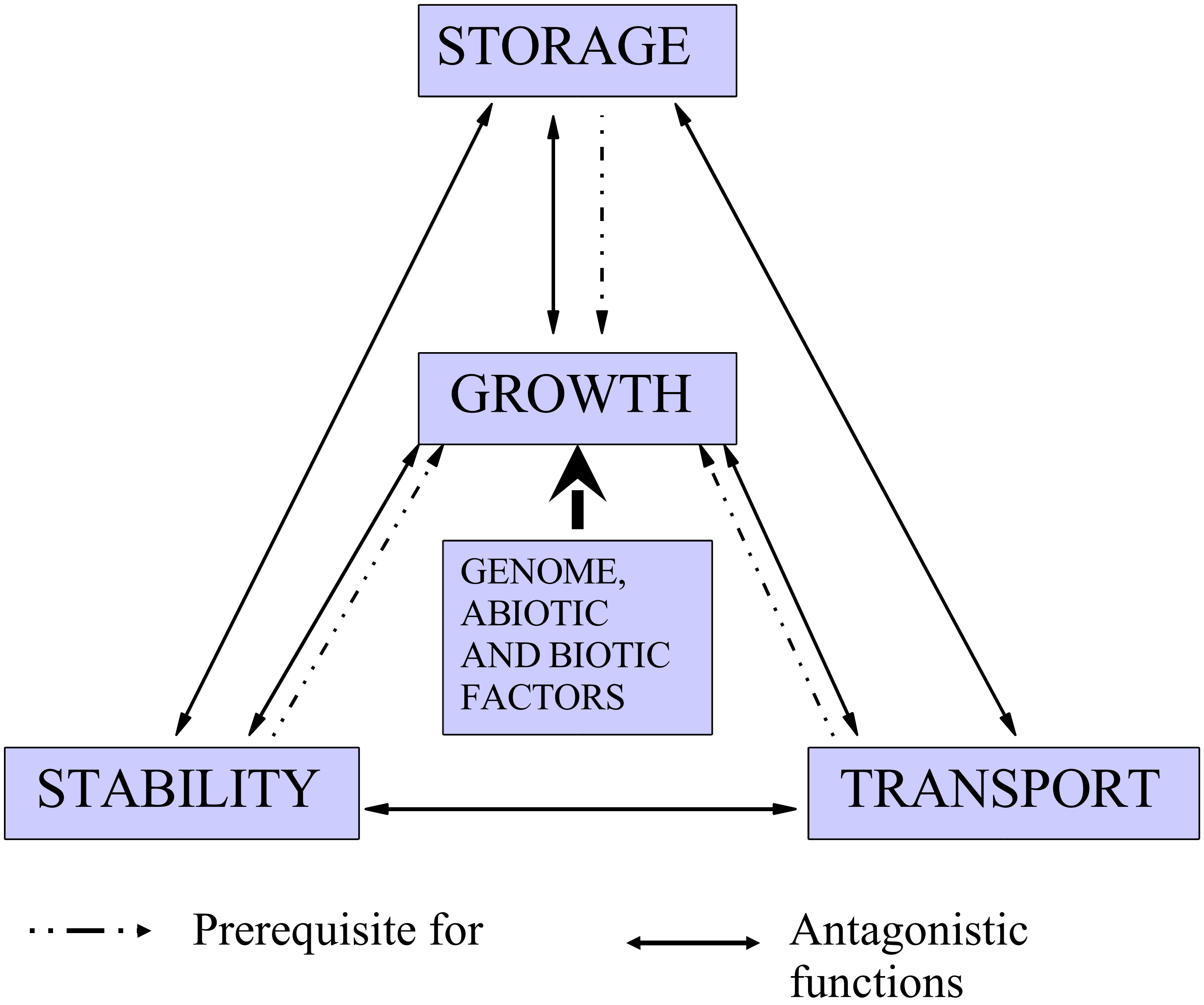
(4) nutrients and water must be **stored**

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



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.

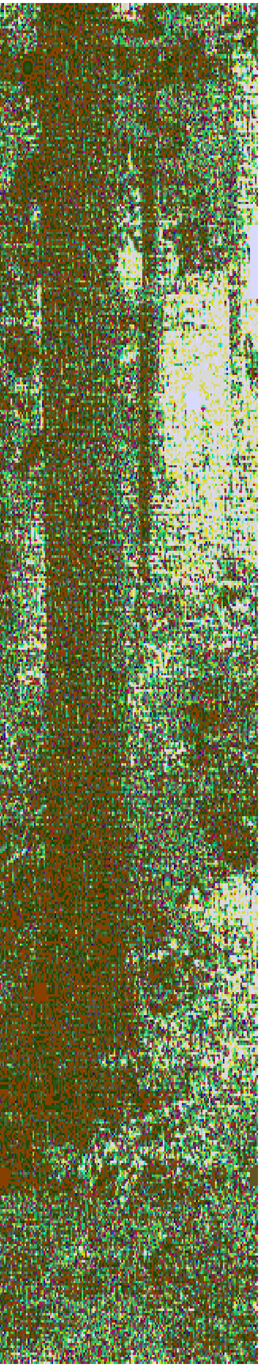
Stability ⟷ Vitality

3.1 Tree structure and function

Key concept

Partitioning of assimilates by the tree

1. Minimal growth (maintenance of division tissues and their respiration
2. Limited growth (mutually correlated growth of branches and roots = primary growth)
3. Un-limited growth (deposition of excess assimilates no longer utilizable by the growing tree = secondary growth)



3.1 Tree structure and function

Key concept

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

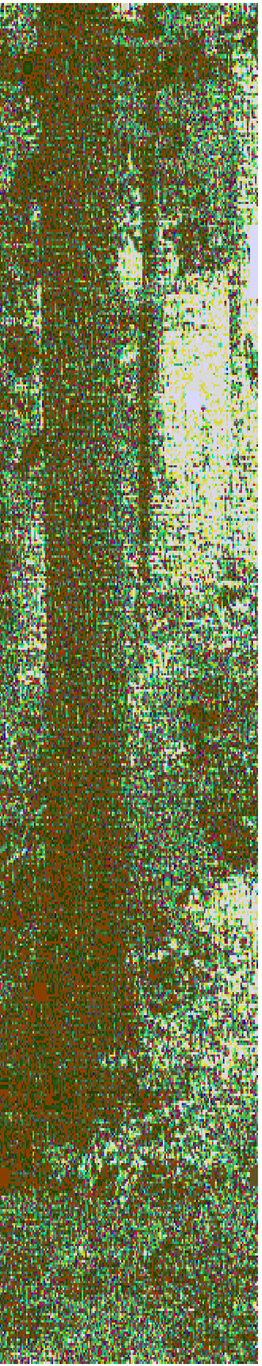
This type of mechanism is called **adaptive growth** – trees are compromise structures that have to meet a number of different and opposing mechanical requirements.

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.

3.1 Tree structure and function

Conclusion



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.

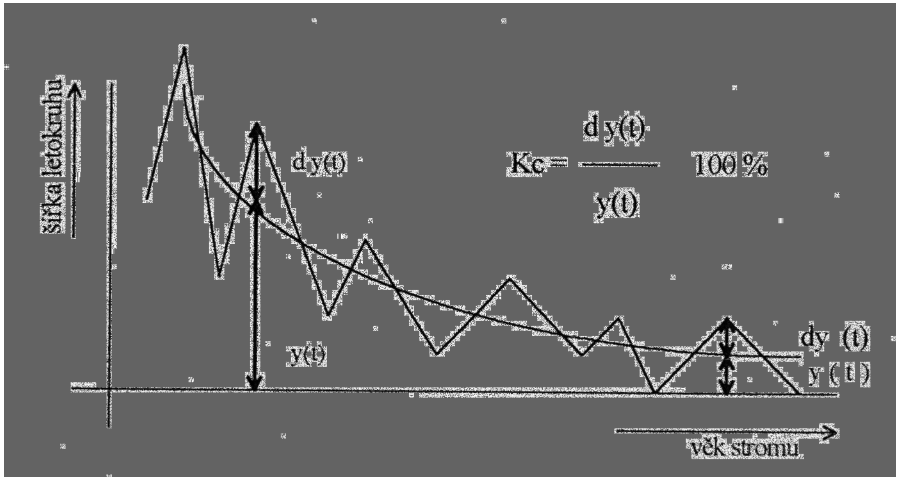
The tree-ring structure is the result of a complex of factors that affect the site, and it is also an expression, both quantitative and qualitative as well, of these prevalent conditions on the site.

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

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

3.2 Tree growth and ontogeny

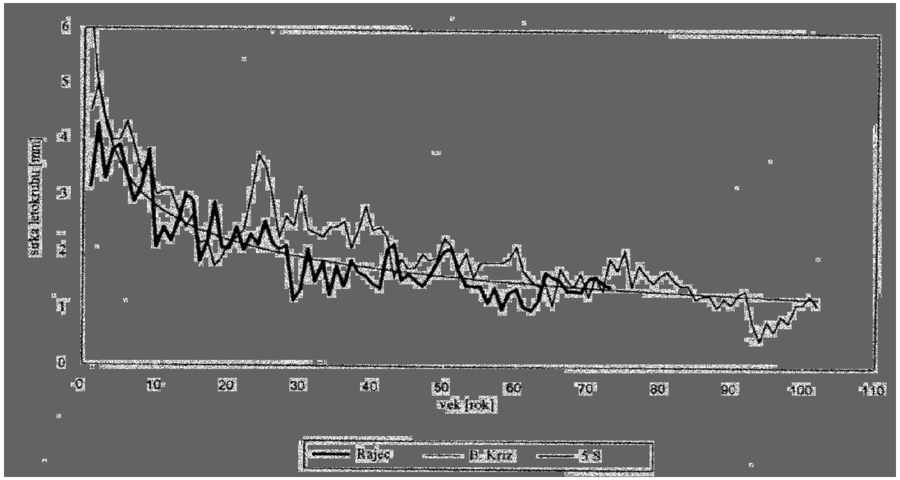
Young cambium, whether at the apex of old trees or at the base of young individuals, features fewer changes and is less susceptible than at an older age.



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



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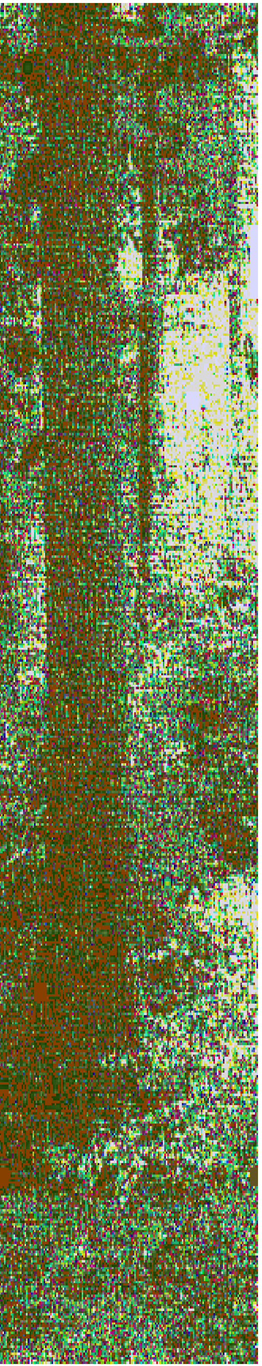
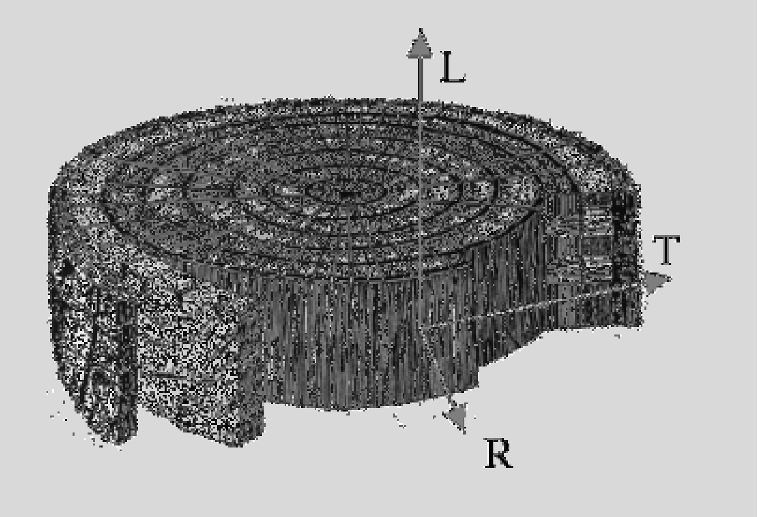


3.3 Intro to wood science

Objectives

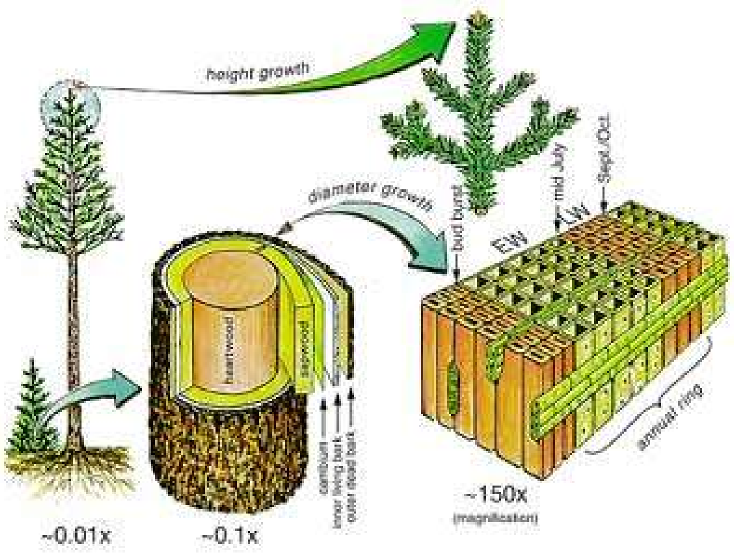
1. Wood – victory or loss ?
2. How does wood structure limit wood properties ?
3. Why mechanical properties are determined by wood structure ?
4. Wood is hierarchical structure, unfortunately very complicated – true or false ?
5. Wood is optimised compromise structure – how to apply it in tree biomechanics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

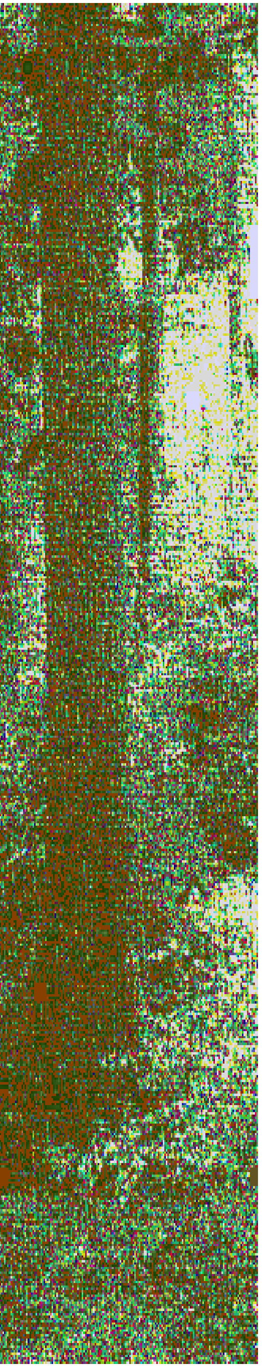


3.3 Intro to wood science

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

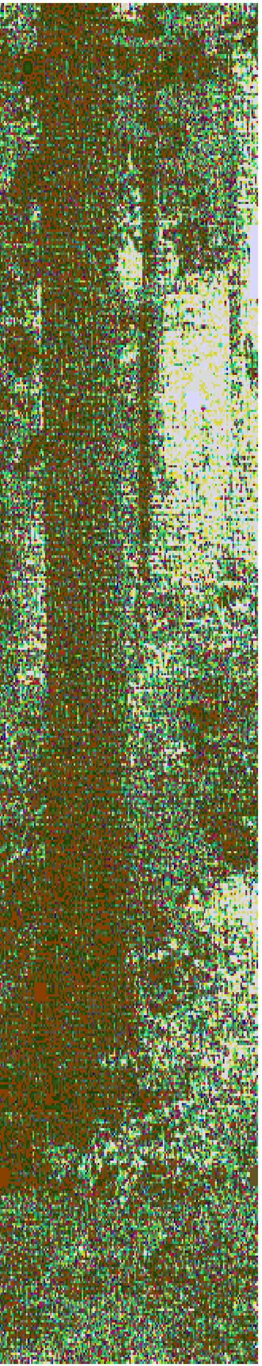
2. Mechanical properties represented as „strength“ properties – maximum (ultimate) stress = resistence to failure

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) and the *wood properties* is to be determined



3.3 Intro to wood science

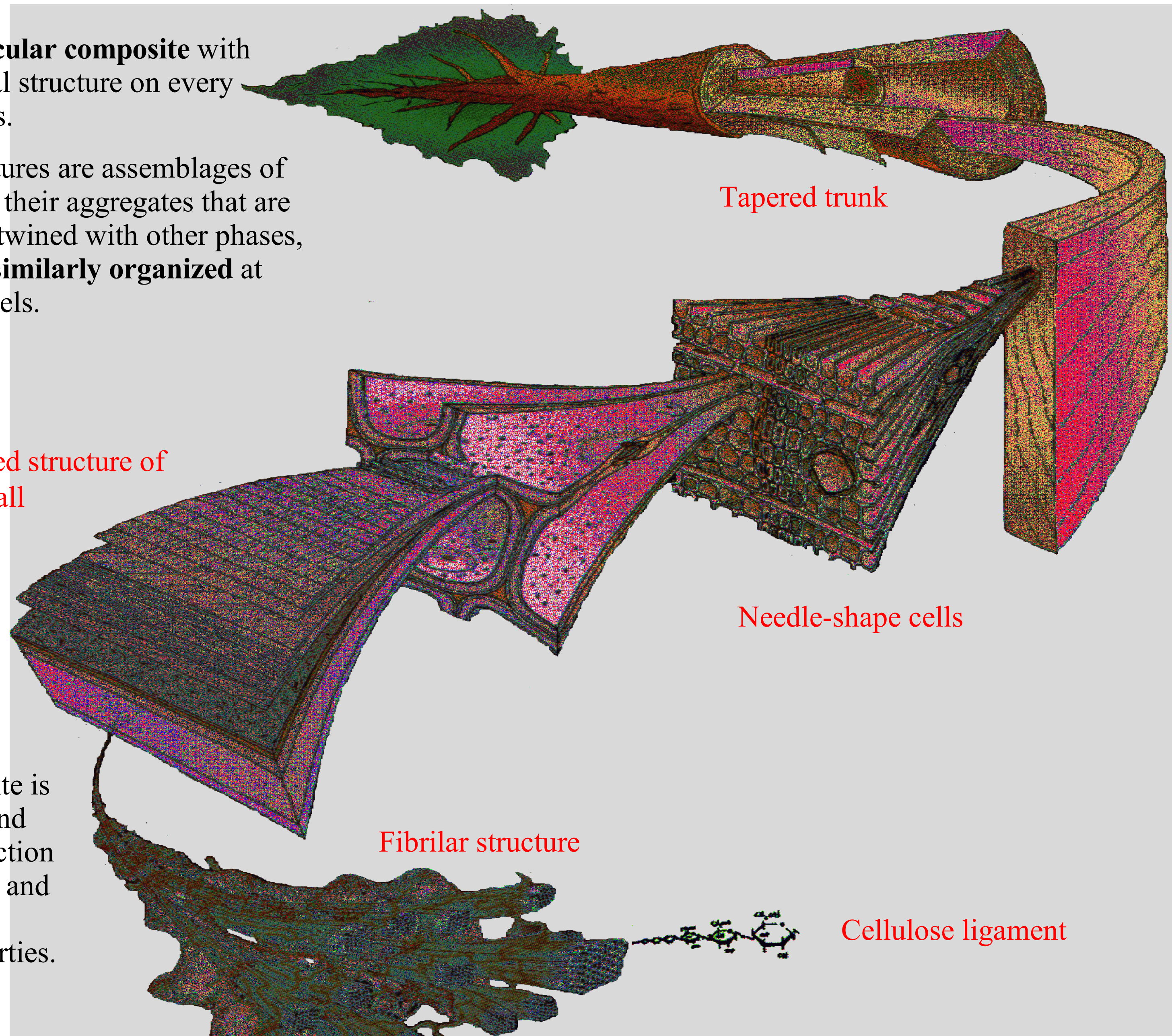
Wood as material

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

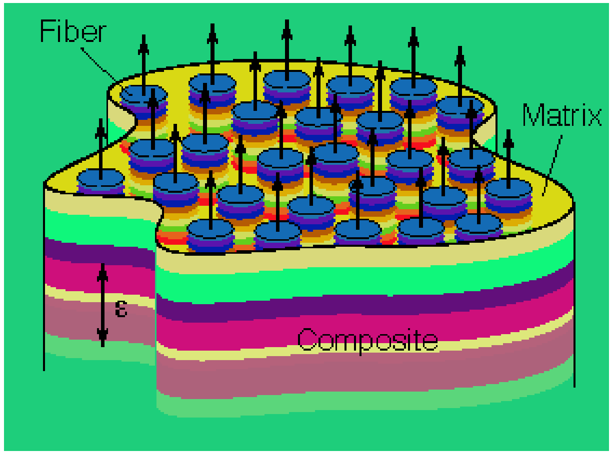
- Wood as **biomolecular composite** with similar hierarchical structure on every organization levels.
- Hierarchical structures are assemblages of molecular units or their aggregates that are embedded or intertwined with other phases, which in turn are **similarly organized** at increasing size levels.



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

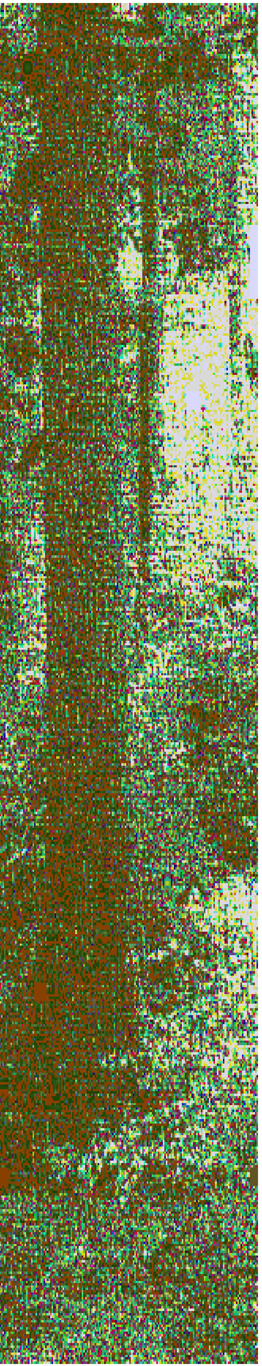
3.3 Intro to wood science

Wood as bio-composite – chemical composition



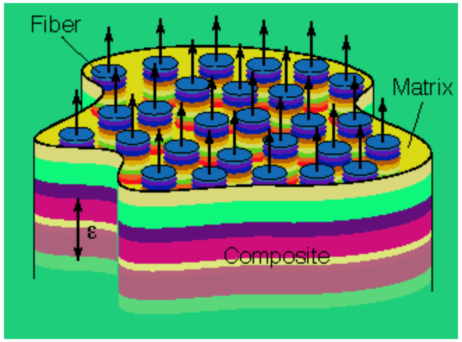
Wood = **F**iber-**R**einforced **C**omposite

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



3.3 Intro to wood science

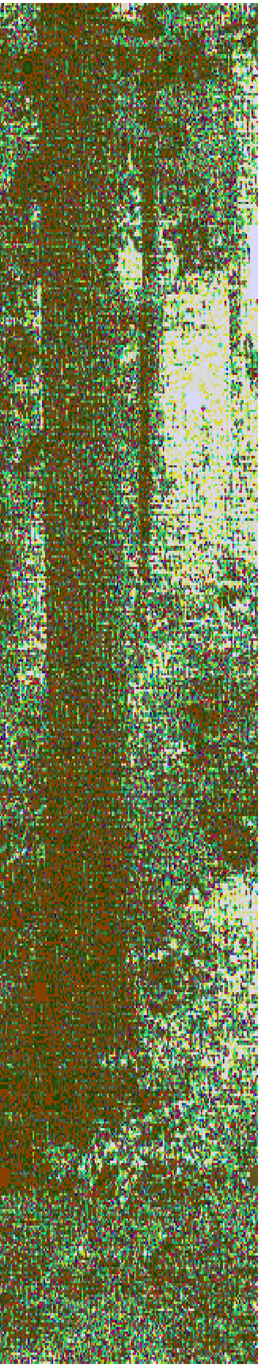
Wood as bio-composite – chemical composition



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

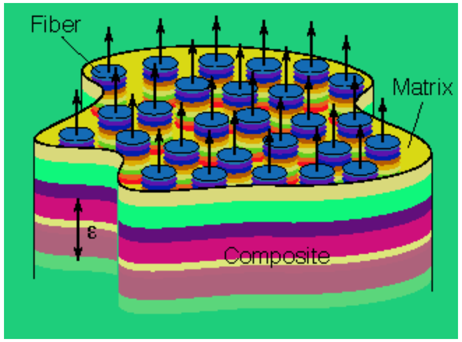
Cellulose

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



3.3 Intro to wood science

Wood as bio-composite – chemical composition



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

Cellulose

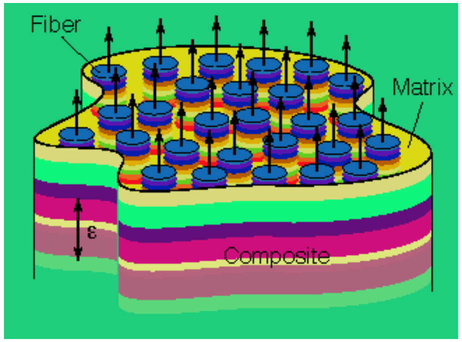
- is responsible for elasticity
- behaves as brittle matter
- provides stiffness and restricted deformation

Lignin

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

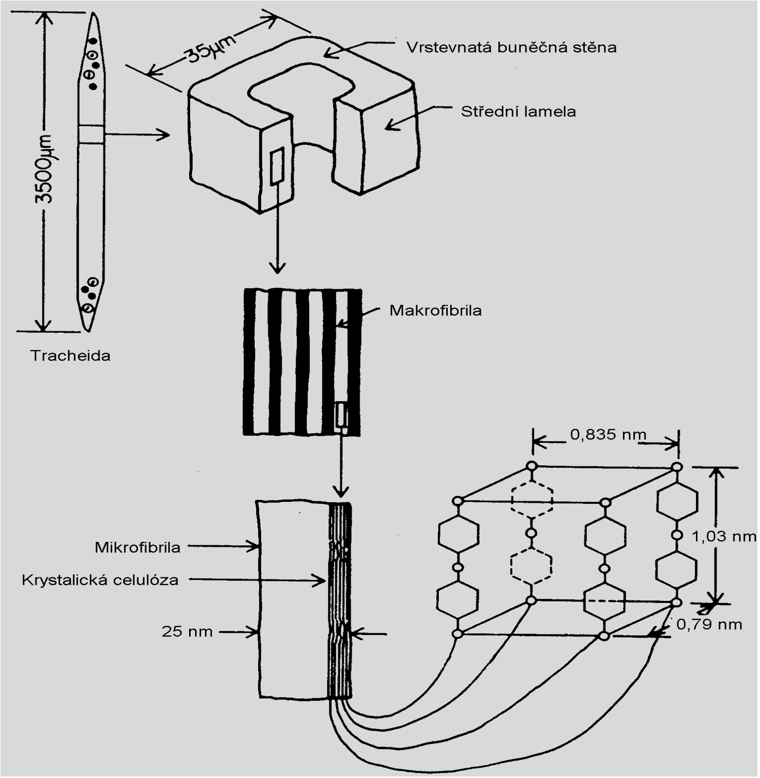
3.3 Intro to wood science

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

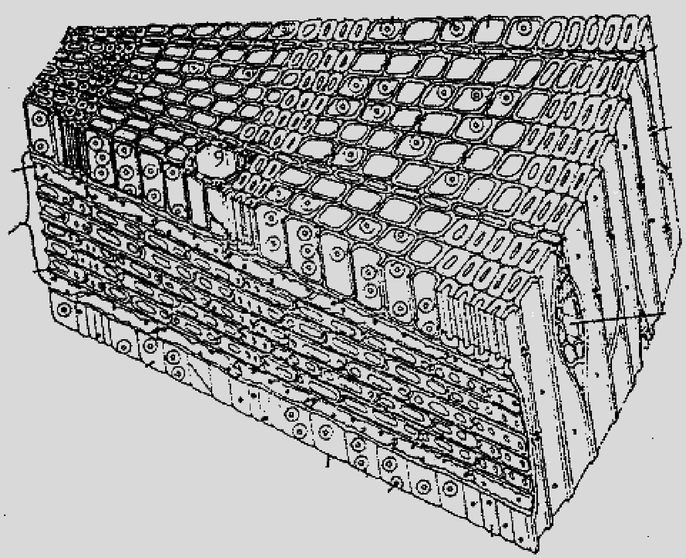


3.3 Intro to wood science

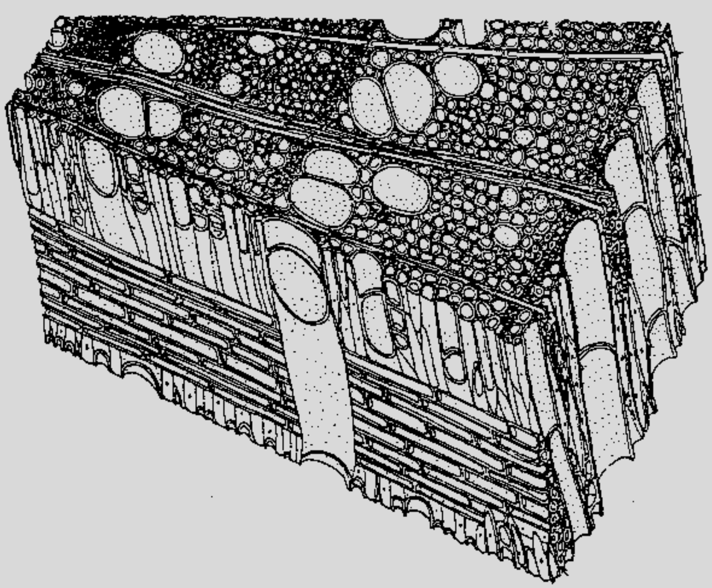
Wood as bio-composite – anatomical structure

What is important for tree biomechanics ?

Softwoods



Hardwoods

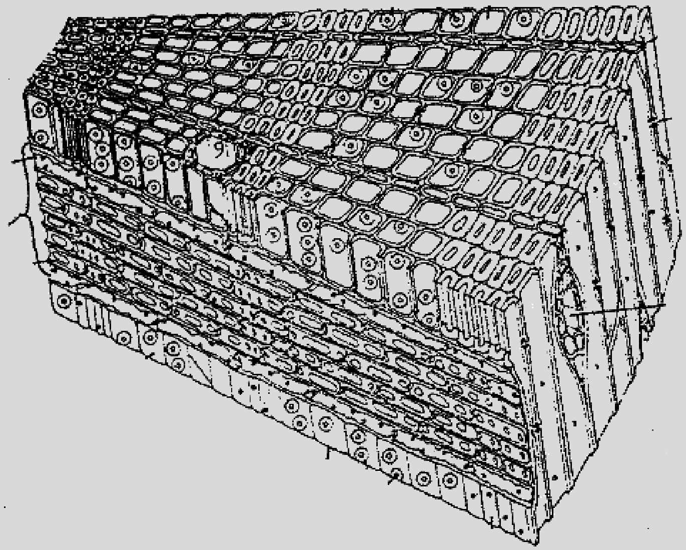


3.3 Intro to wood science

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

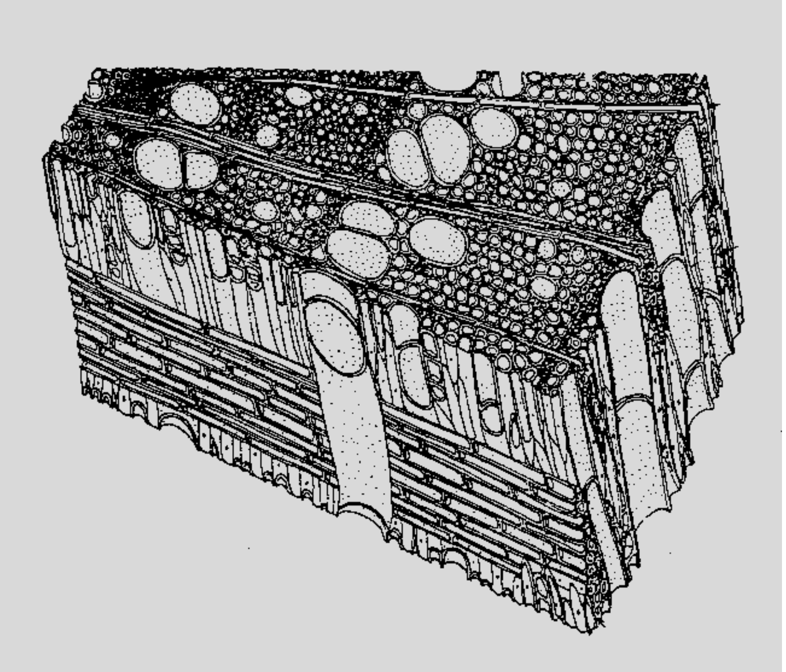
3.3 Intro to wood science

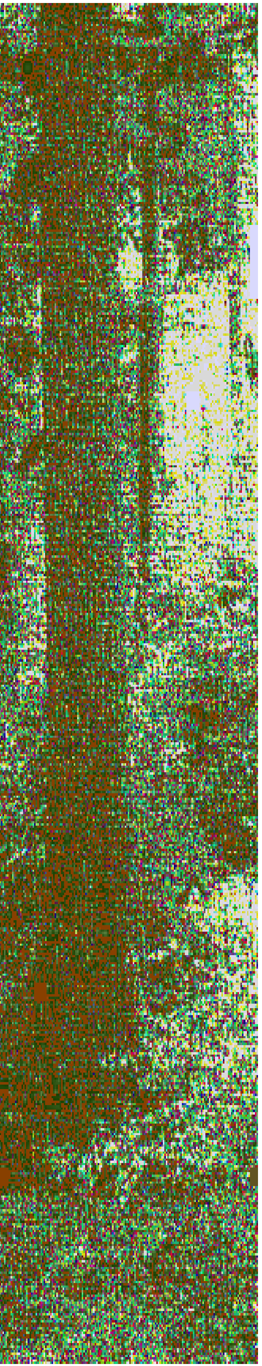
Wood as bio-composite – anatomical structure

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

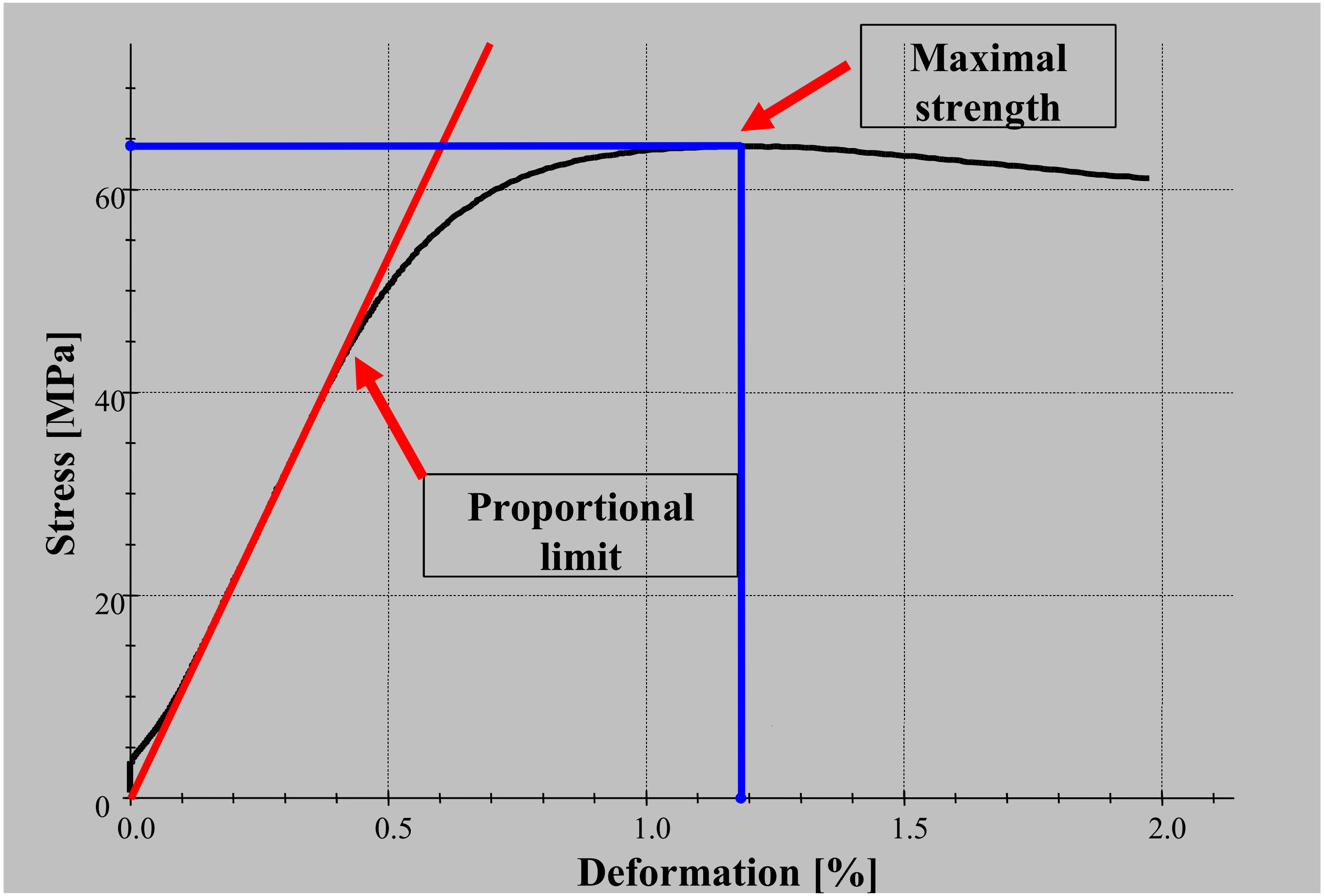
Wood as bio-composite – mechanical properties

- 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

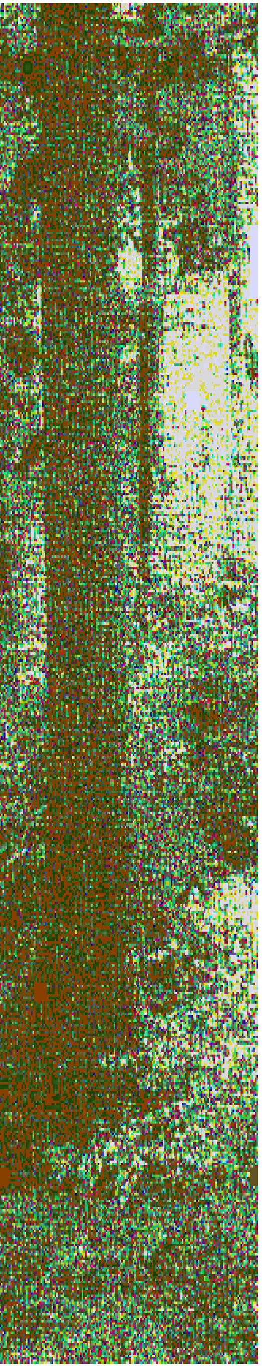
How get to know your material – Stress-Strain Diagram

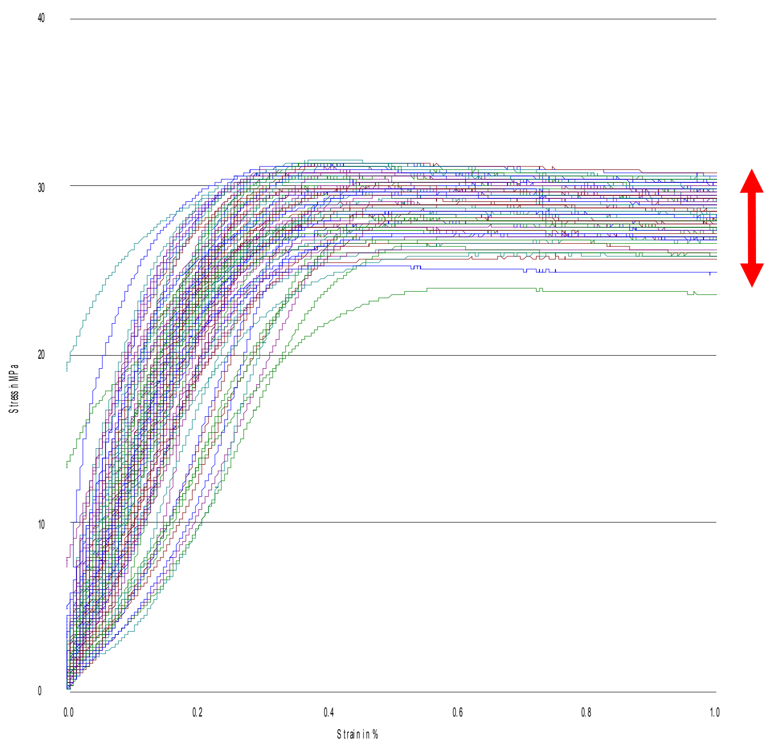


3.3 Intro to wood science

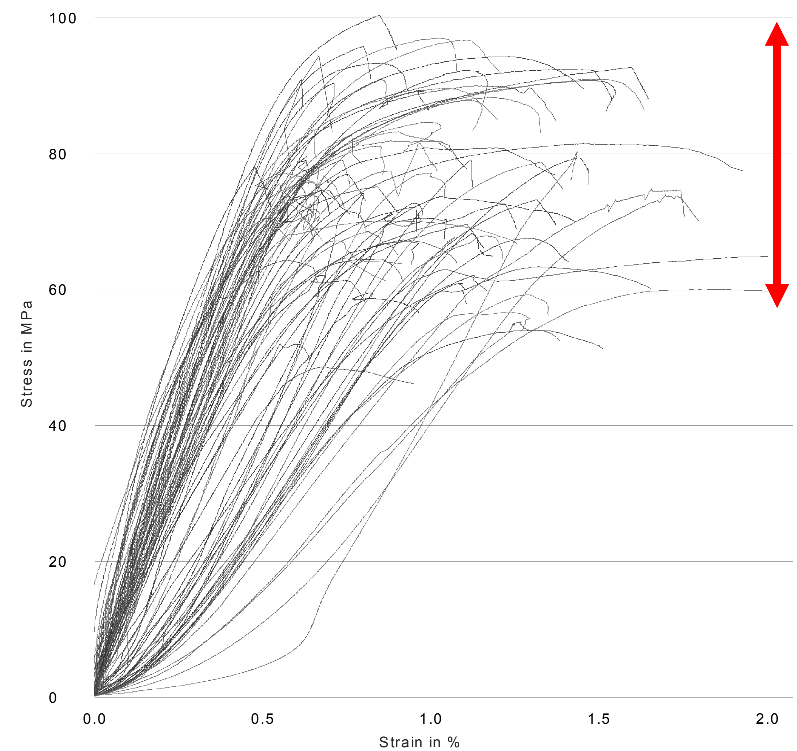
Wood as bio-composite – mechanical properties

An example: Maple wood (*Acer platanoides*)





Green wood



Dry wood

3.3 Intro to wood science

Wood as bio-composite – mechanical properties

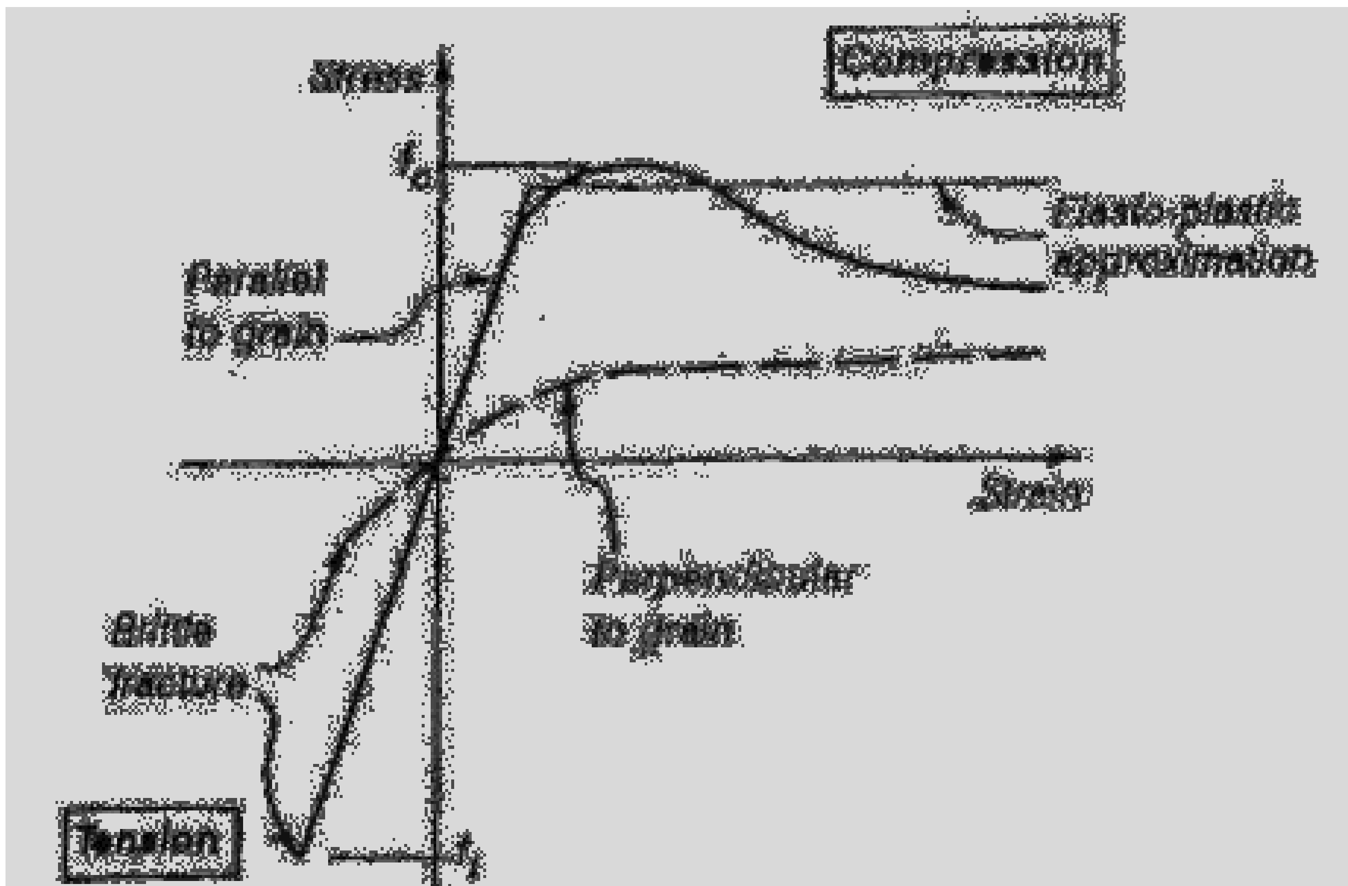
What is the stress-strain diagram providing us?

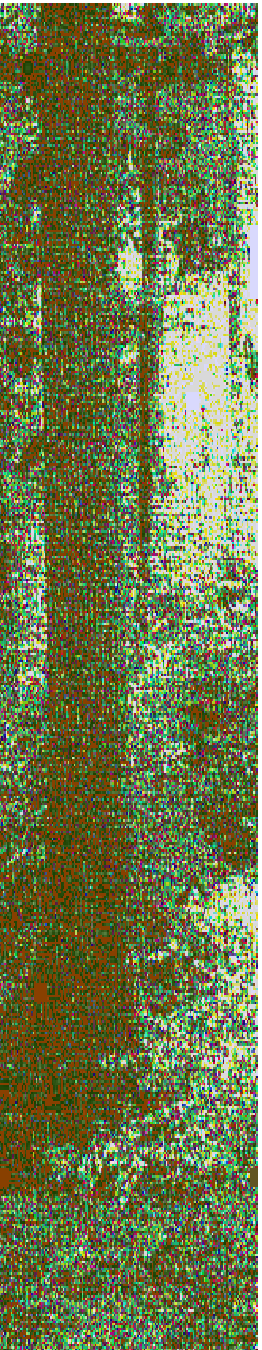
- Character of material (will be discussed immediatelly)
- Important values (could be measured only)
  - Modulus of elasticity
  - Strength
  - Proportional limit
  - Deformation
  - Energy saved

3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Stress-strain diagrams all in one

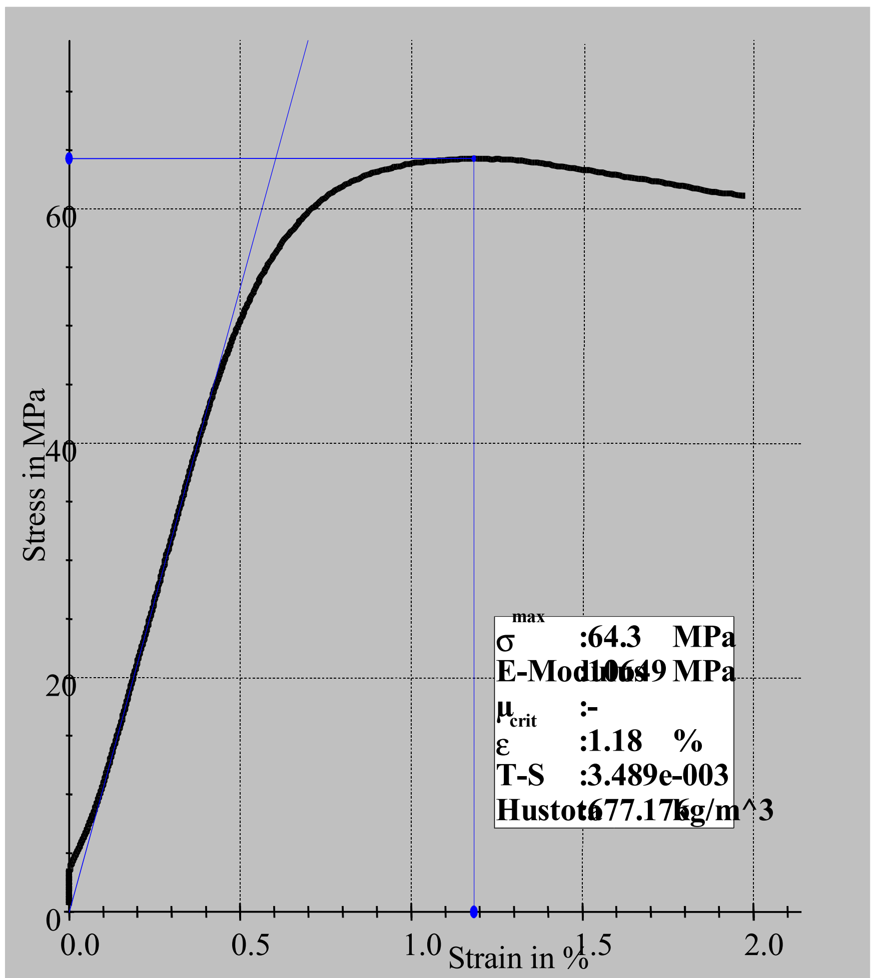




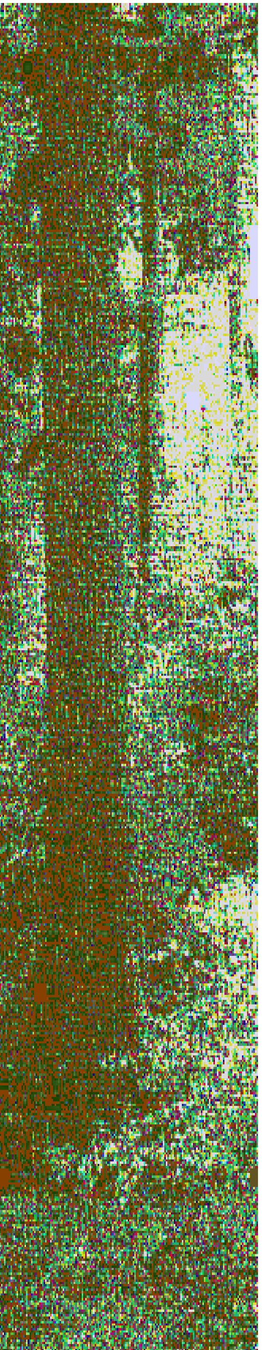
3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Compression parallel to grains



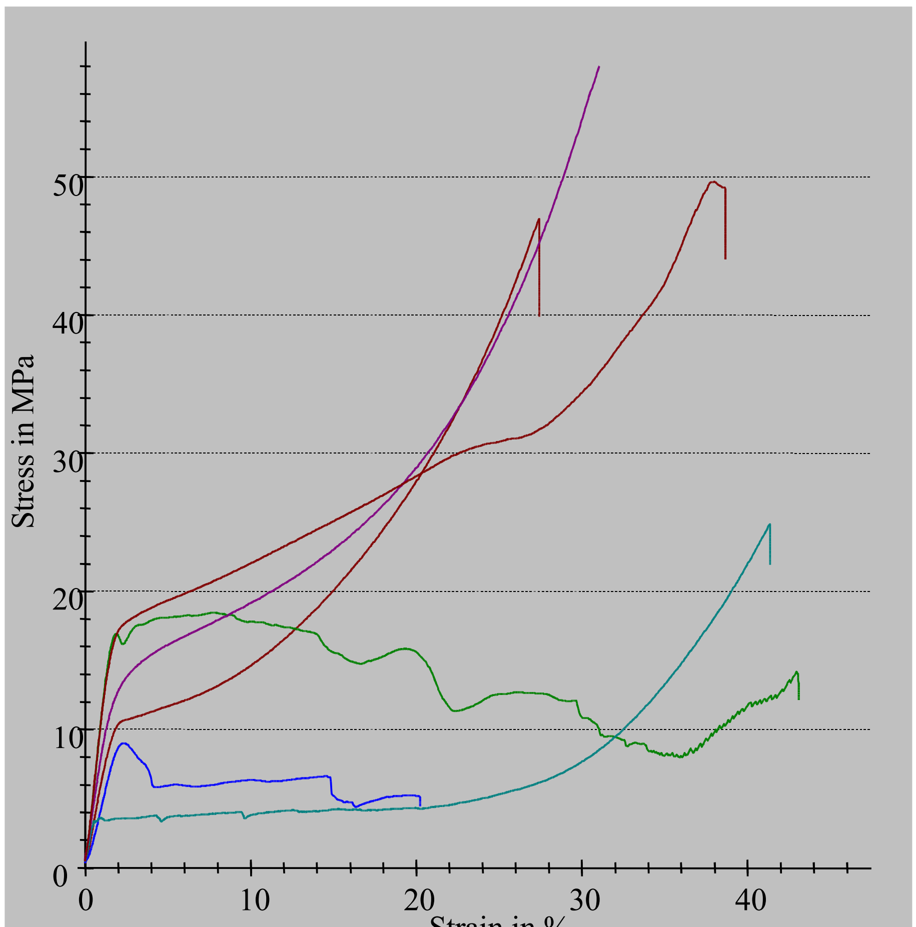
- Viscoelastic behaviour
- High stiffness
- High strength
- Deformation about 1 %
- High amount of saved energy
- “No failure”- **good** way of loading



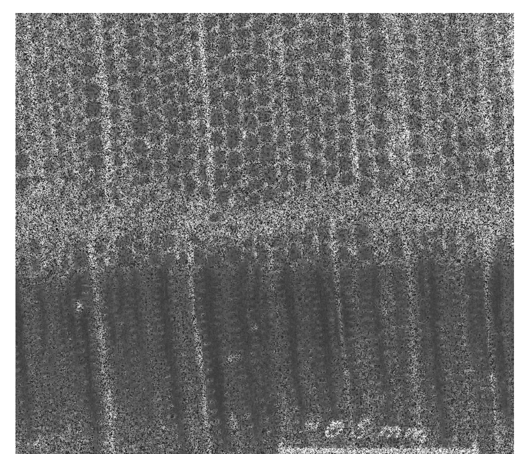
3.3 Intro to wood science

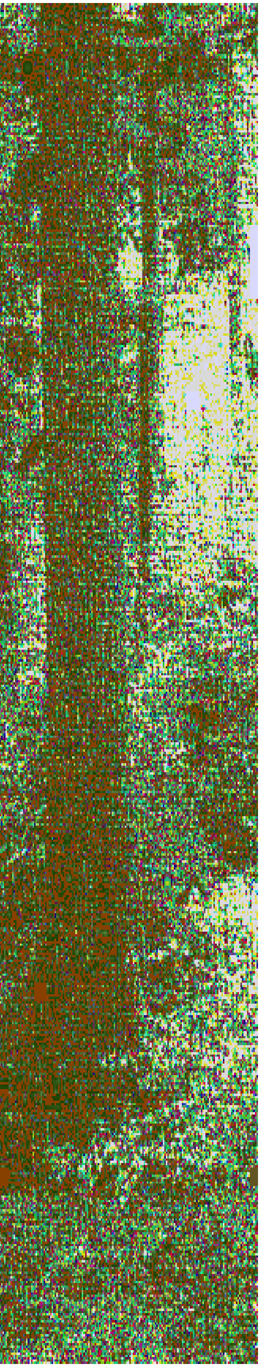
Wood as bio-composite – mechanical properties

Compression perpendicular to grains



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

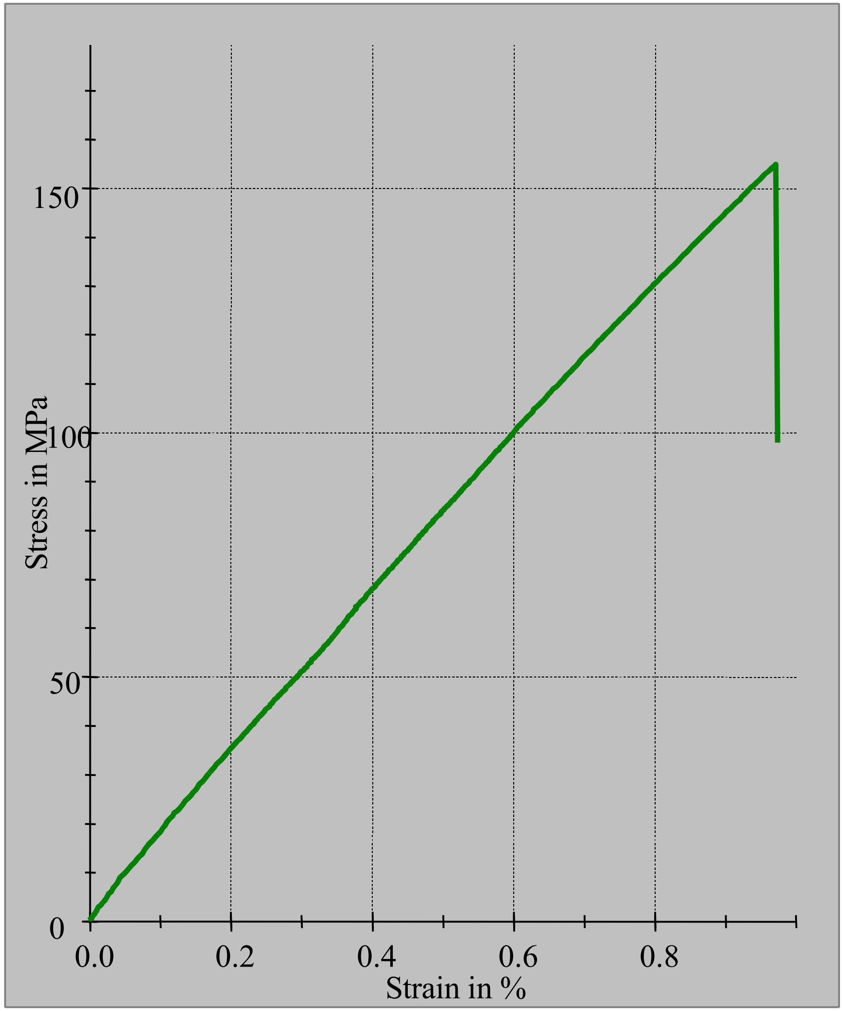




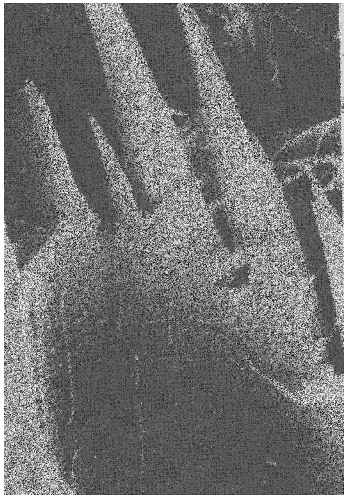
3.3 Intro to wood science

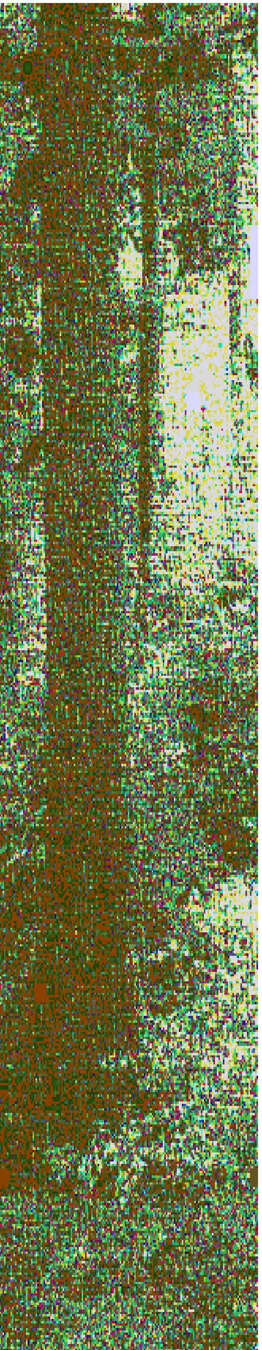
Wood as bio-composite – mechanical properties

Tension parallel to grains



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

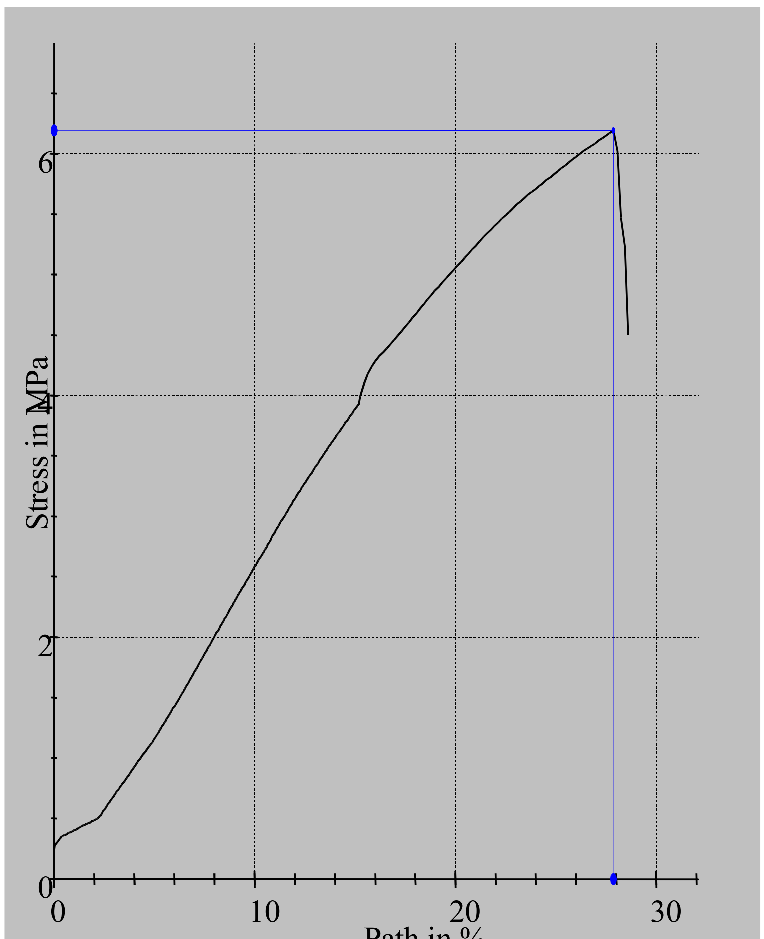




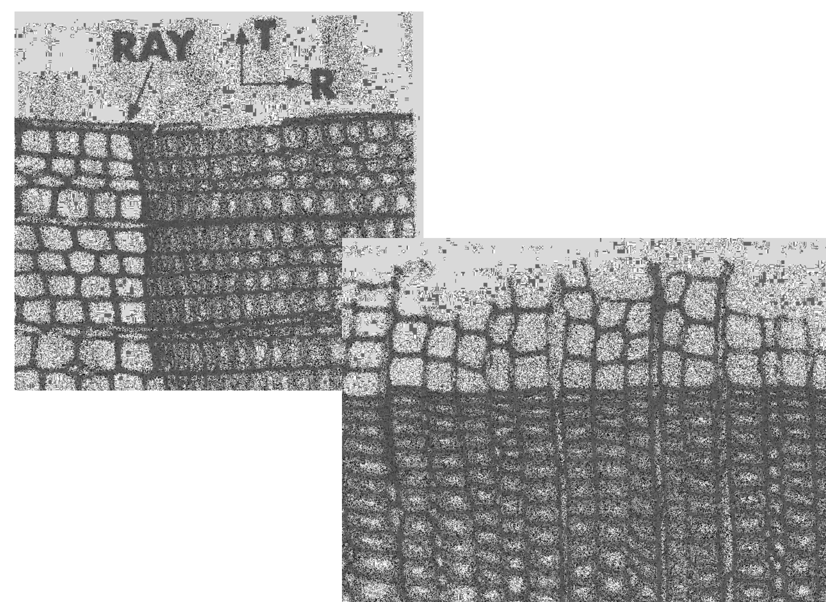
3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Tension perpendicular to grains

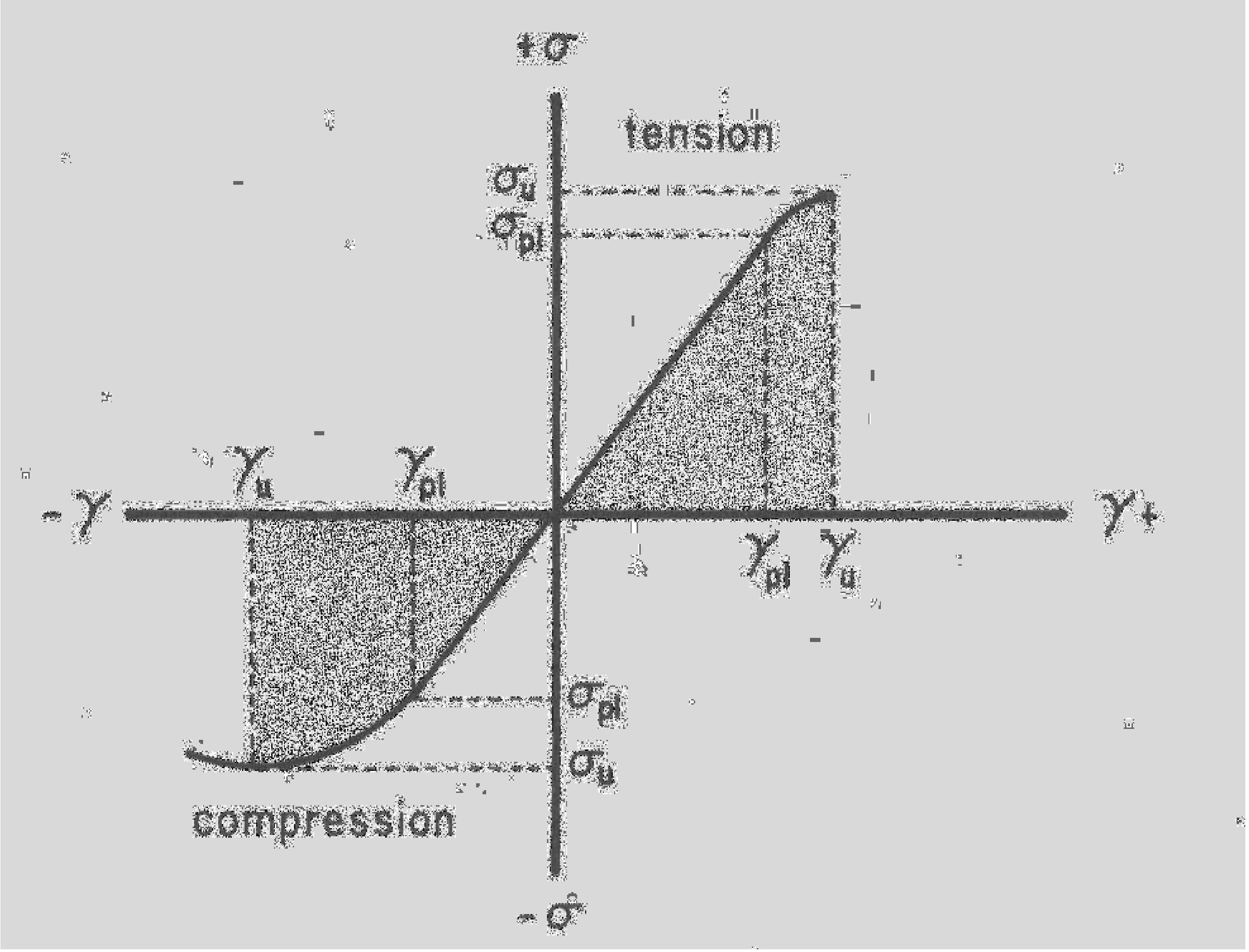


- Brittle material
- Very low strength and stiffness
- The **worst** way of loading
- Fails by tearing



3.3 Intro to wood science

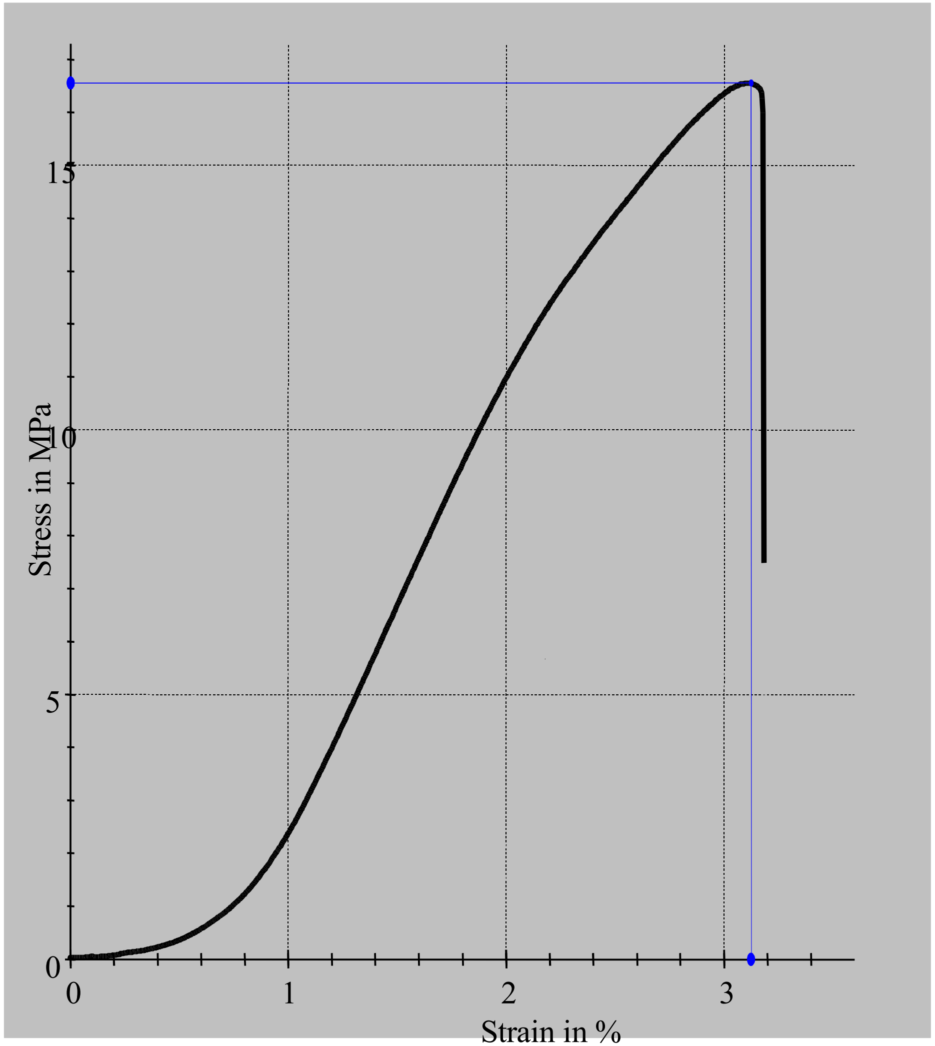
Wood as bio-composite – mechanical properties



3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Shear

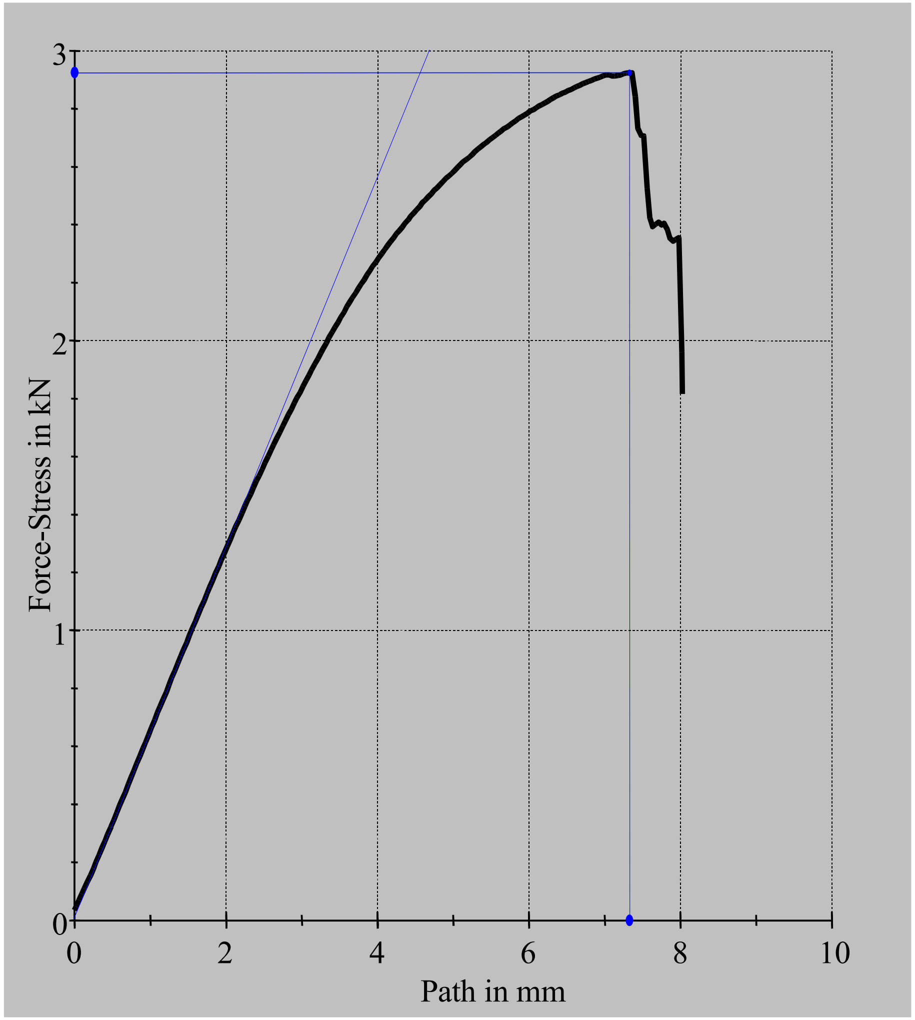


- Viscoelastic behaviour
- Low strength and stiffness (one exception)
- Fails by shearing
- **Bad** way of loading

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 miantenance of loading
  - Water content
  - Temperature of wood

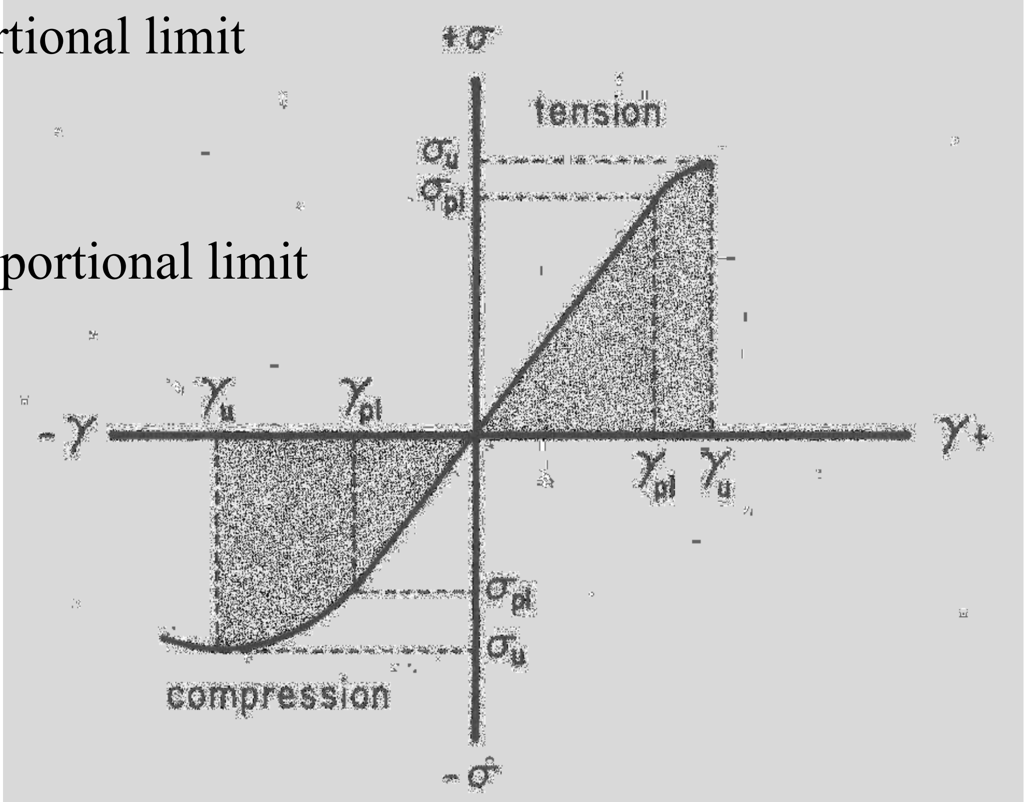
- Wood can behave like:
  - Plastic – viscoelastic – elastic matter
  - Ductile – brittle

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
  - deformatio at the proportional limit

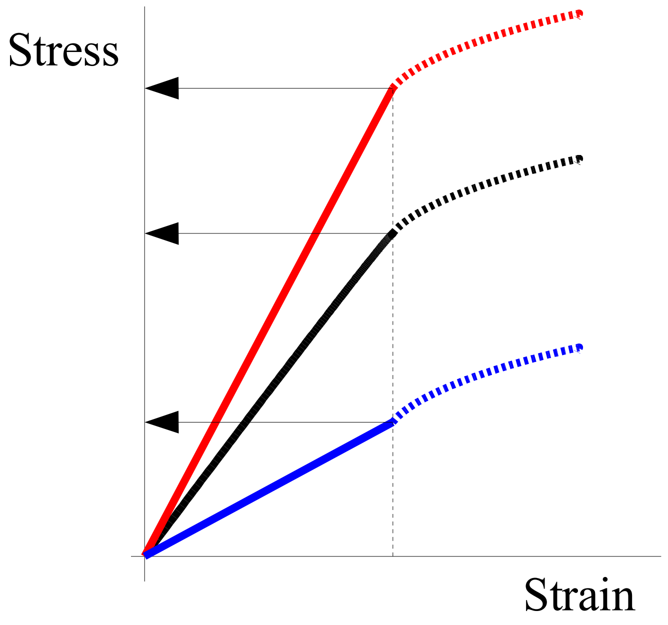


3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Modulus of elasticity

- 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 elongation of the material [MPa, kN/cm2].



3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Modulus of elasticity (stiffness)

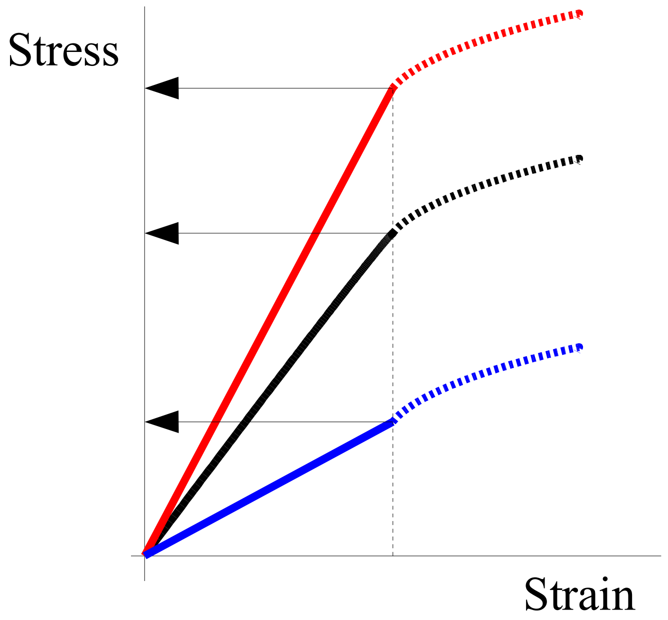
Taxon	Moisture (%)	Density (kg.m-3)	E (MPa)	G (MPa)
Spruce	**Green**	**497**	**7 300**	**400**
Picea abies	12	350	9 500	500
Beech	**Green**	**833**	**9 800**	**800**
Fagus sylvatica	12	600	12 600	1 100
Oak	**Green**	**833**	**8 300**	**-**
Quercus sp.	12	689	10100	-

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)
- True x nominal stress
- True x nominal strength



3.3 Intro to wood science

Wood as bio-composite – mechanical properties

Strength of wood

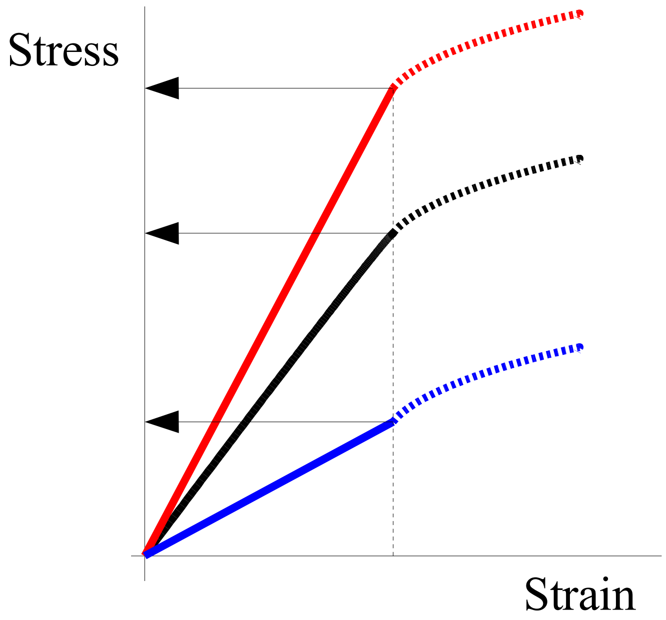
Taxon	Moisture (%)	Density (kg.m-3)	MOR (MPa)	Comp. ǁ (MPa)	Tension ǁ (MPa)	Shear (MPa)
Spruce	**Green**	**497**	**36**	**17**		**5**
Picea abies	12	400	66	35	84	9
Beech	**Green**	**833**	**65**	**28**		**9**
Fagus sylvatica	12	689	110	54	130	16
Oak	**Green**	**833**	**59**	**28**		**9**
Quercus sp.	12	689	97	52	132	14

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
- Poisson's number



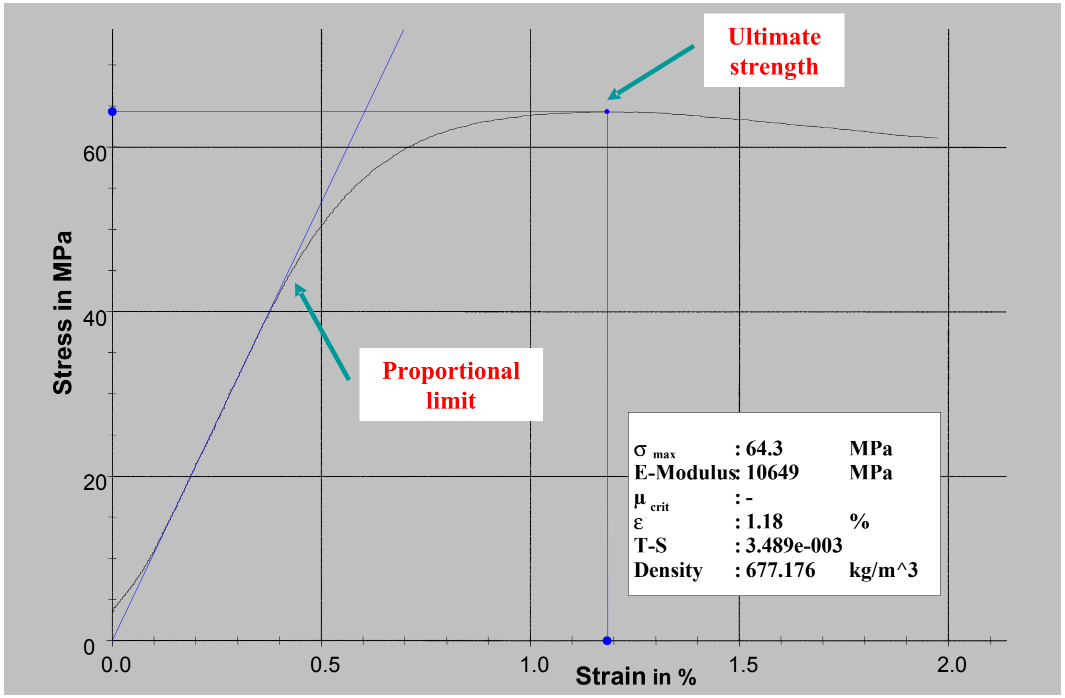
3.3 Intro to wood science

Relation between stress and strain

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

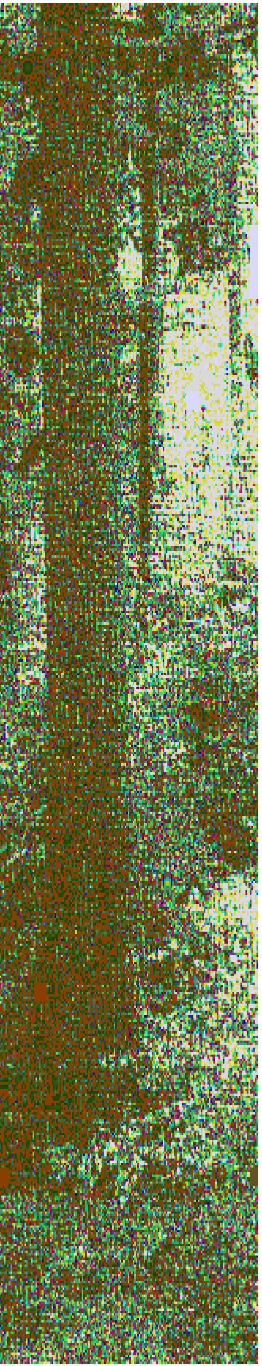
E-modulus – only material **constatnt** ever known (the criterion of the stiffness) because of the wood nature (chemical constitution and anatomical structure)

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



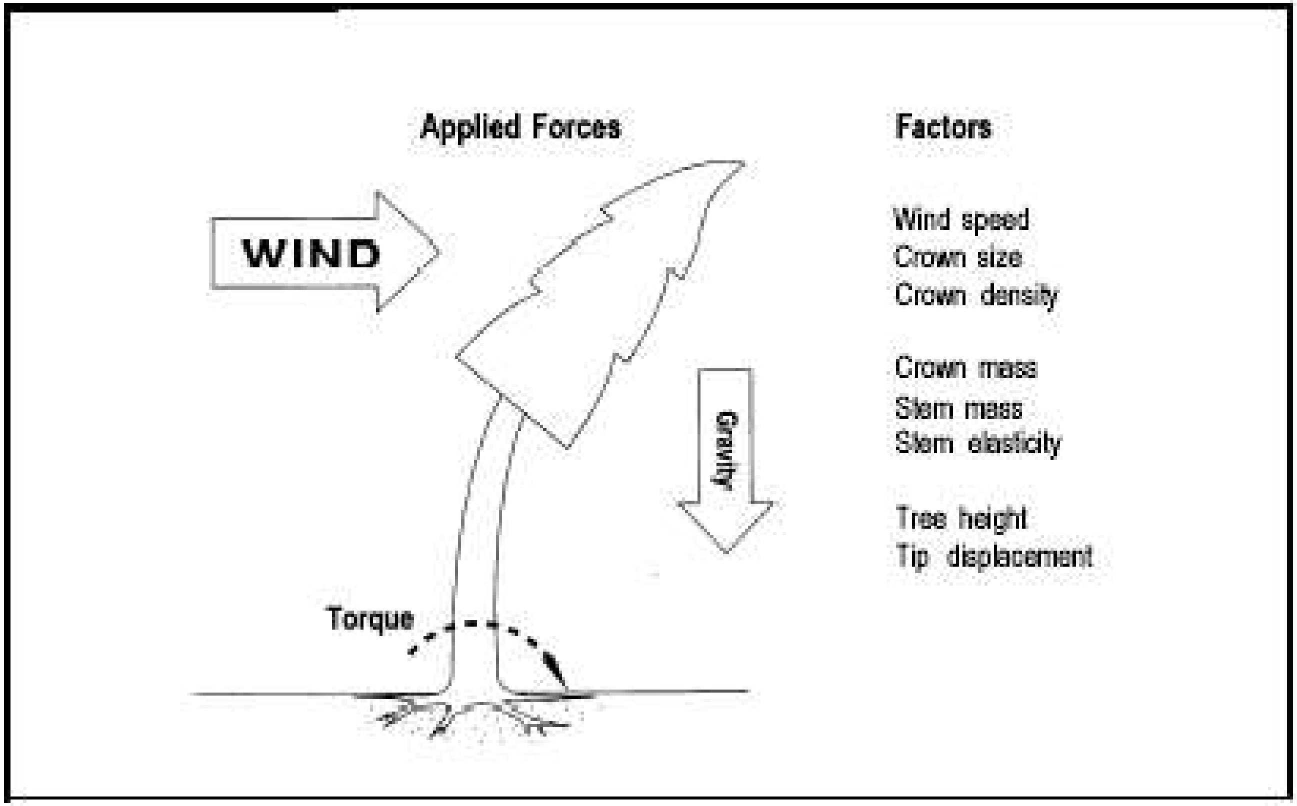
Conclusion

4. Components of Tree Stability

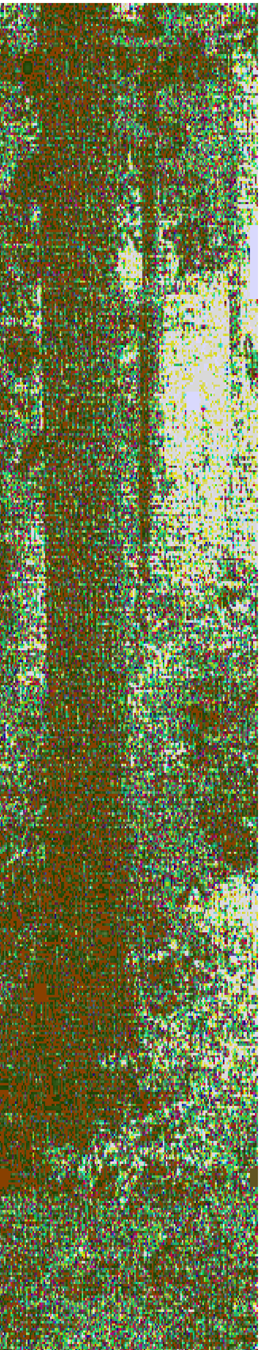


4.1 Tree geometry

- 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).



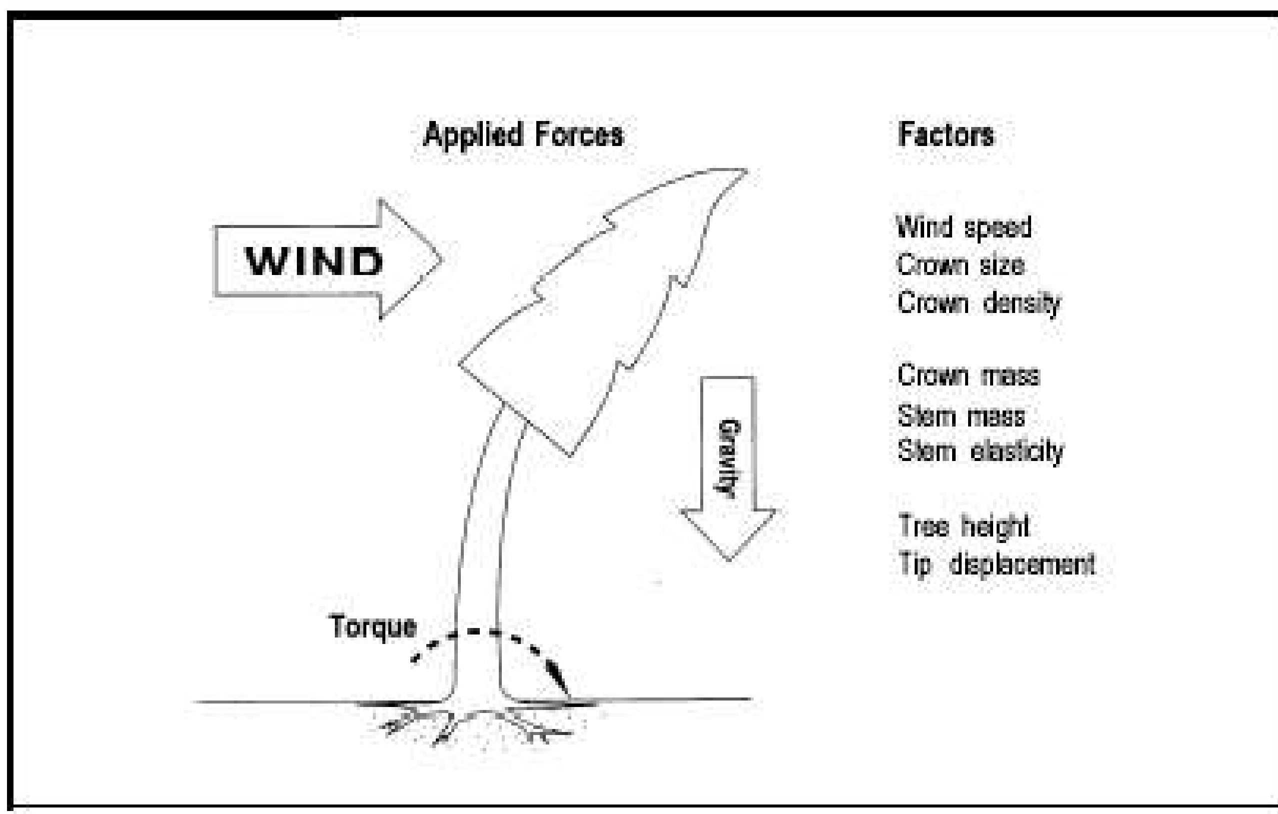
4. Components of Tree Stability



4.1 Tree geometry

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.



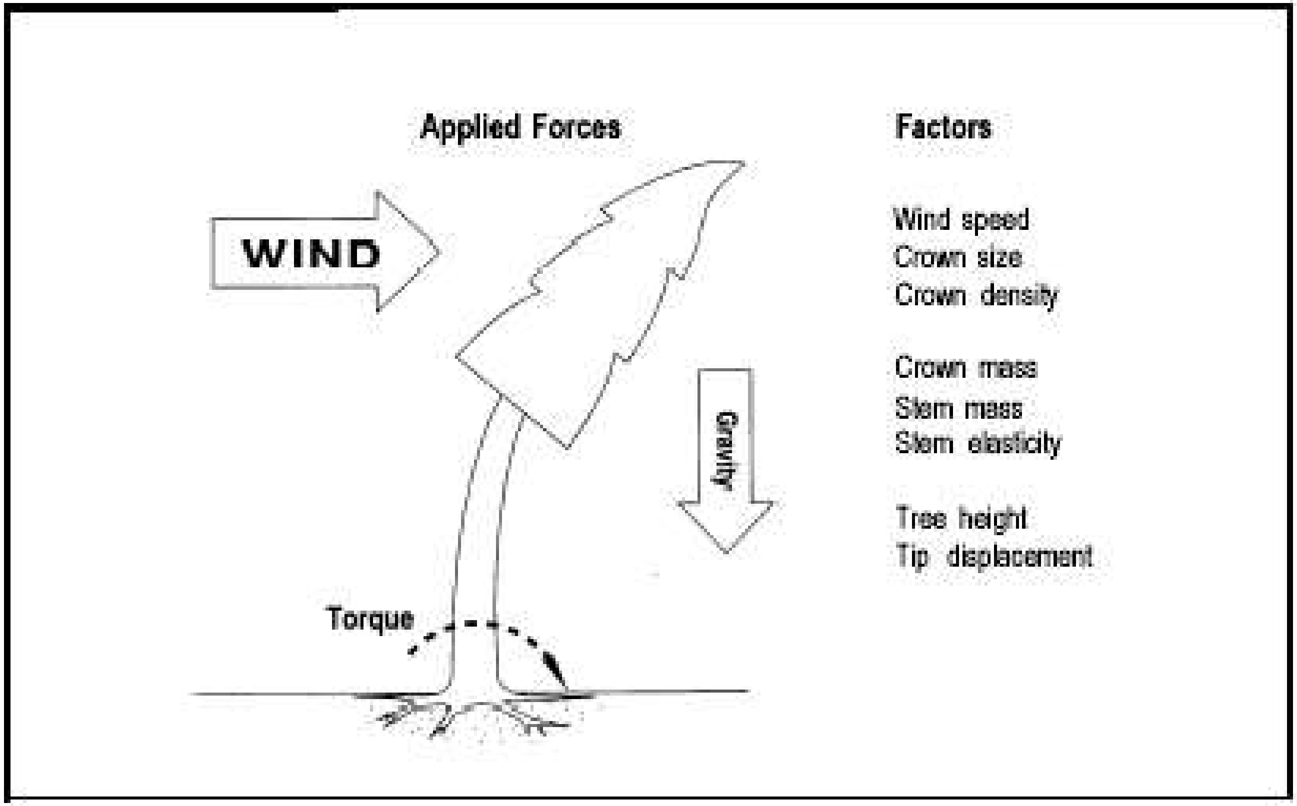
4. Components of Tree Stability

4.1 Tree geometry

4.2 Wood properties

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

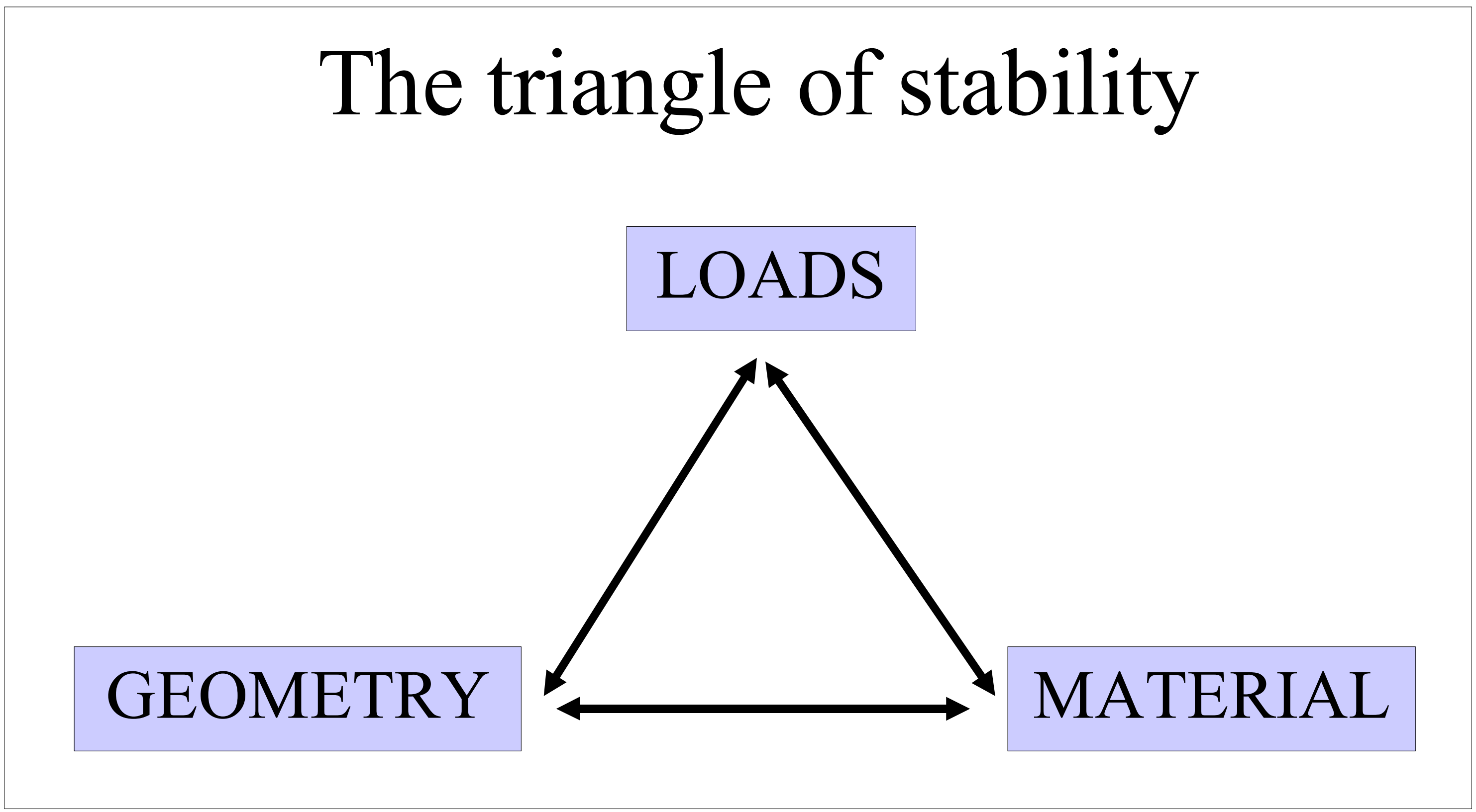


4. Components of Tree Stability

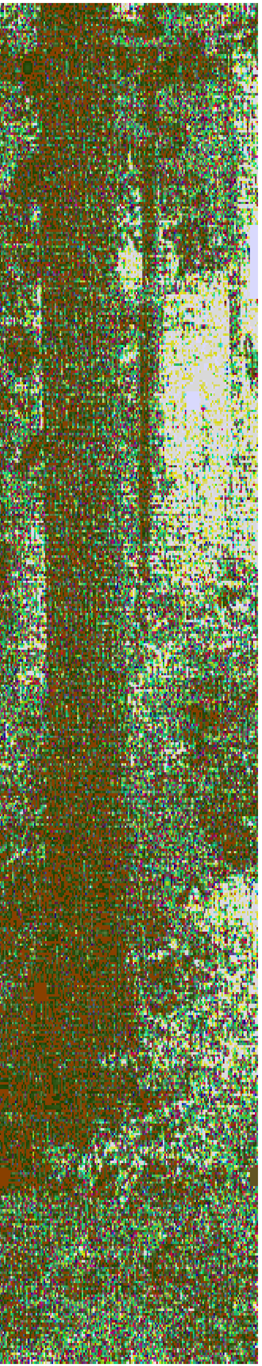
4.1 Tree geometry

4.2 Wood properties

4.3 Loads applied to tree



4. Components of Tree Stability



4.1 Tree geometry

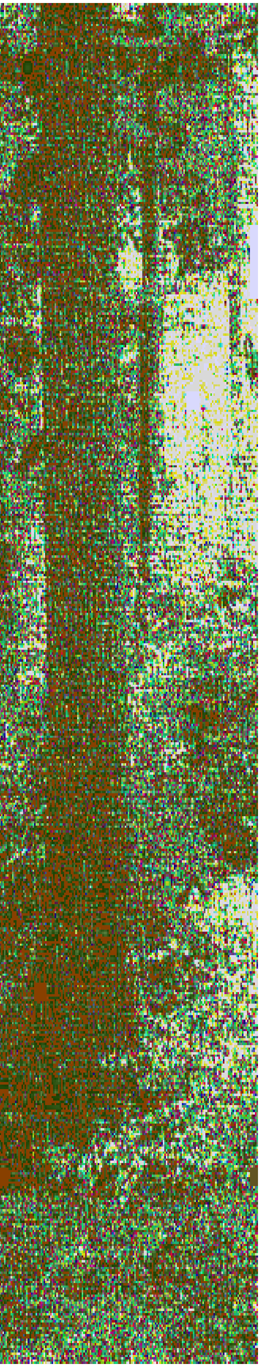
Objectives

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

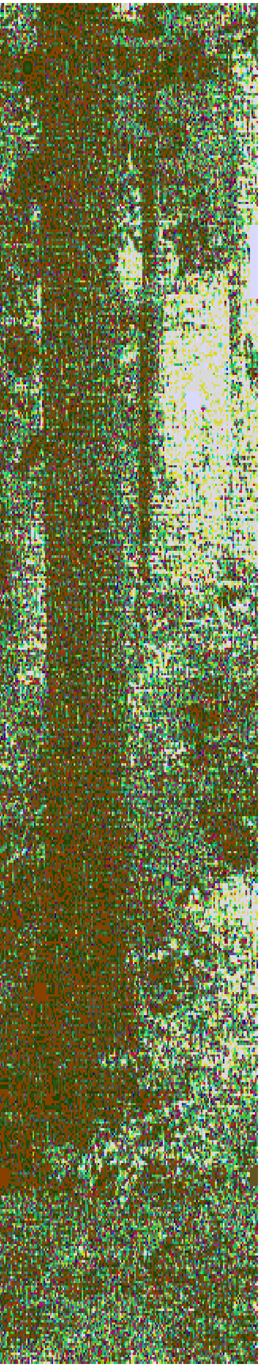
Key concepts

Basic idea of constructional morphology is the principal 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).

4. Components of Tree Stability



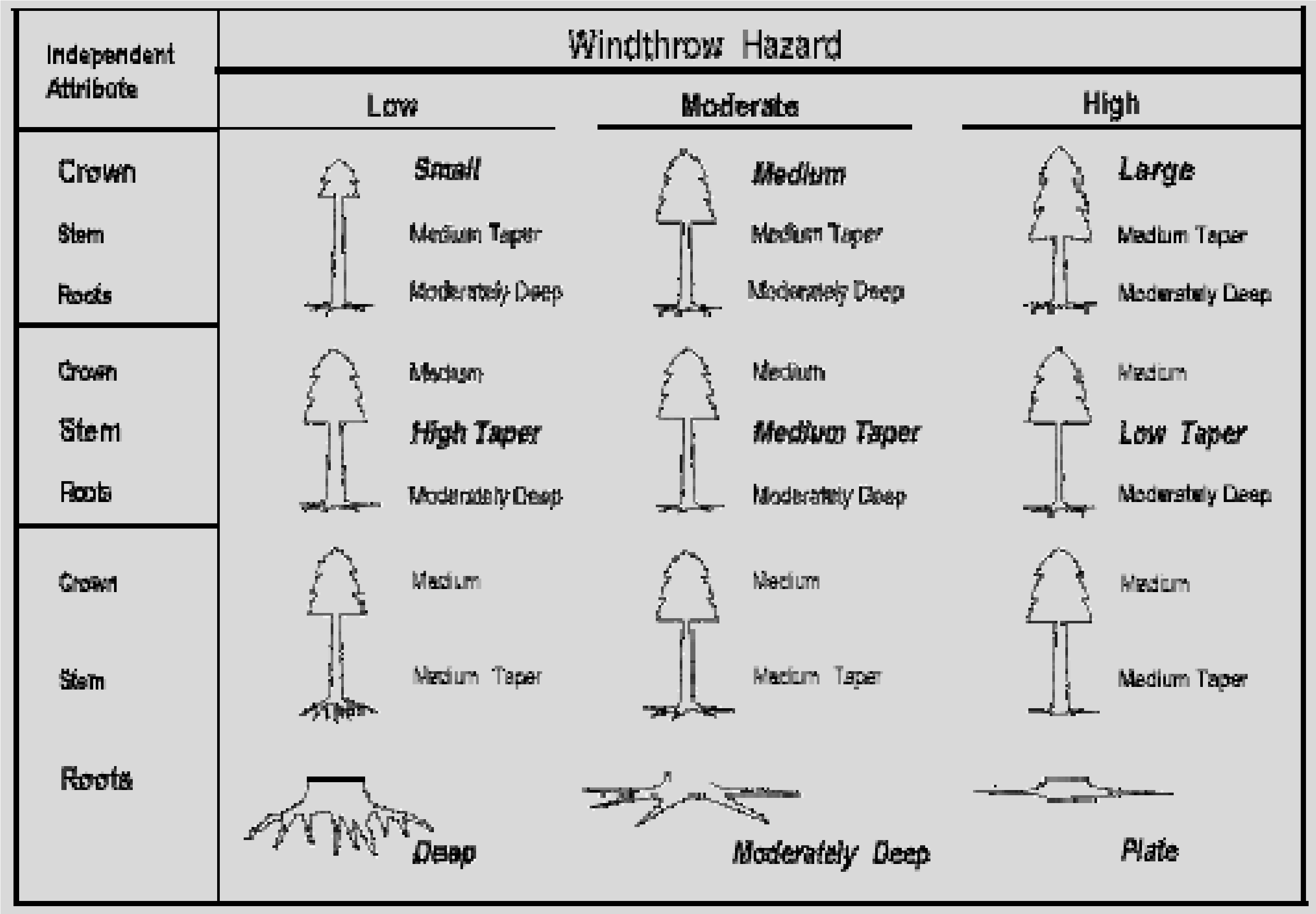
4.1 Tree geometry

Special cases

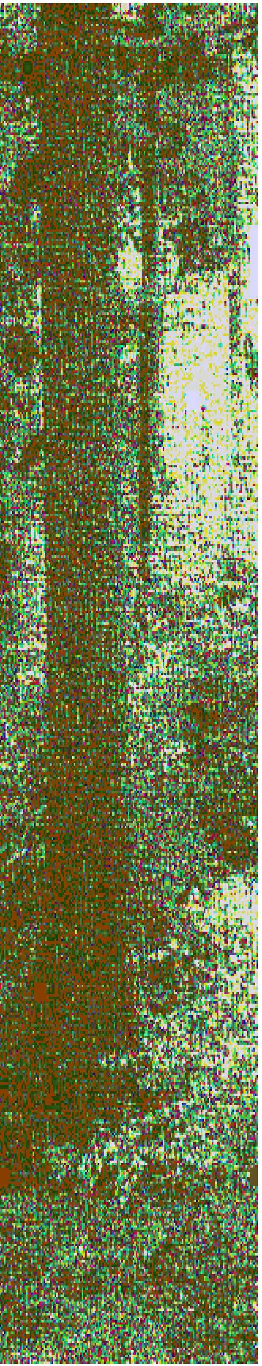
- Shape of the trunk
- Shape of the branches
- Shape of the single roots
- Shape of the whole root system

4.1 Tree geometry

Special cases



Independent Attribute	Windthrow Hazard: Low	Windthrow Hazard: Moderate	Windthrow Hazard: 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

1. Shape of the trunk

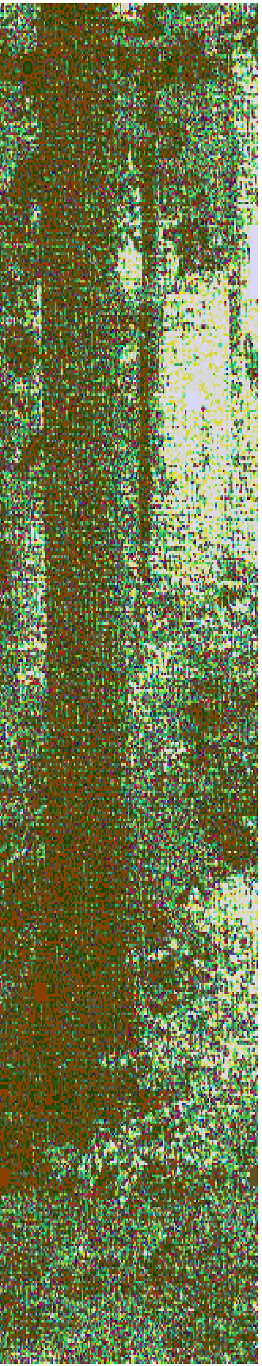
The trunk of the tree is a **nonprismatic** tapered cantilever beam.

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.



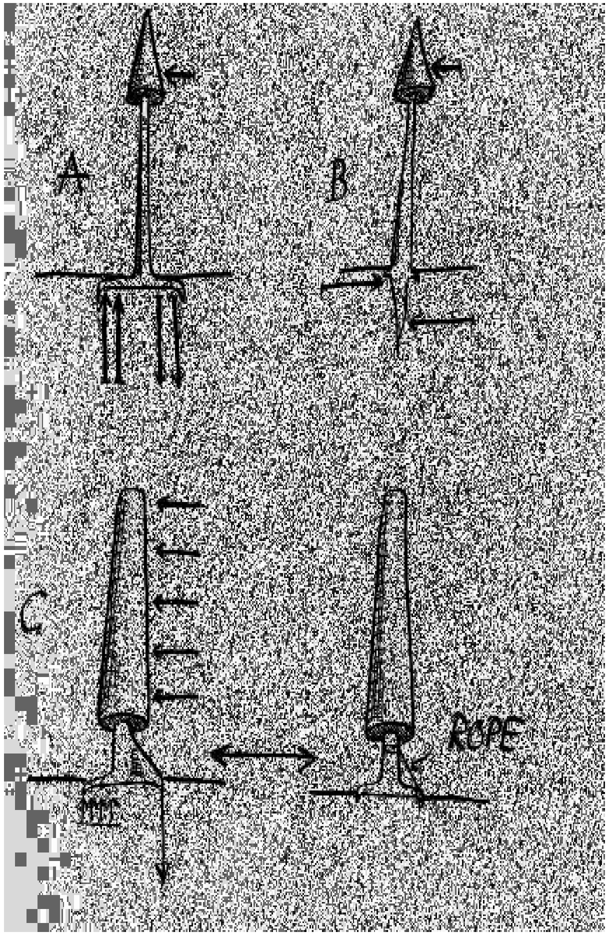
4.1 Tree geometry

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



4.1 Tree geometry

1. Shape of the trunk – Stem cross-section

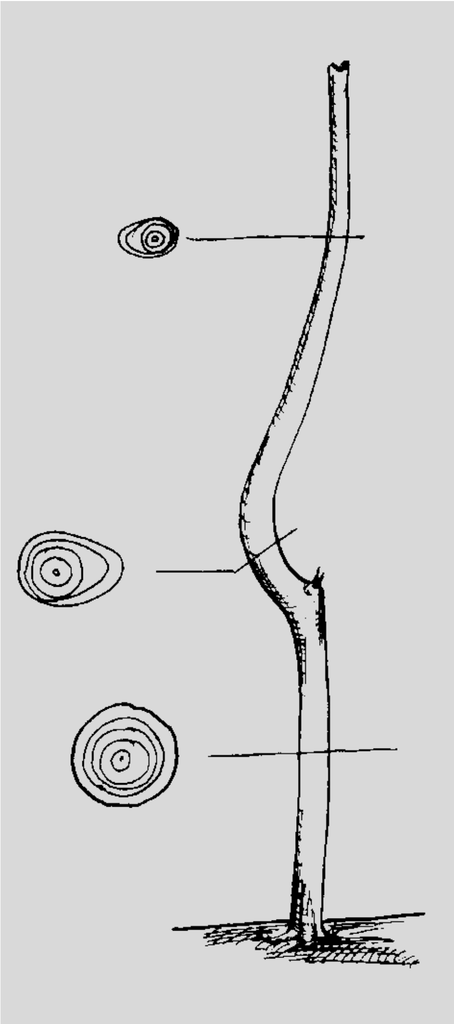
The stem have round cross-section. This is more advantageous from the mechanical point of view.

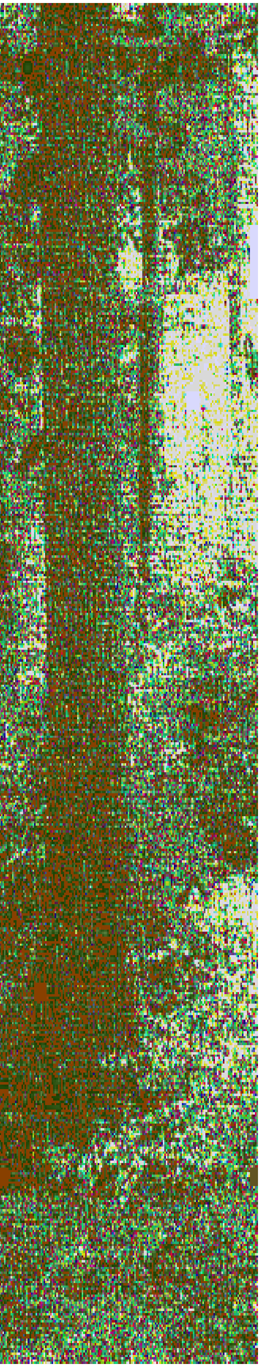
The cross-section can be hollow. It is necessary to remember, that the hollowness of the trunk is not disadvantage.

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.





4.1 Tree geometry

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.

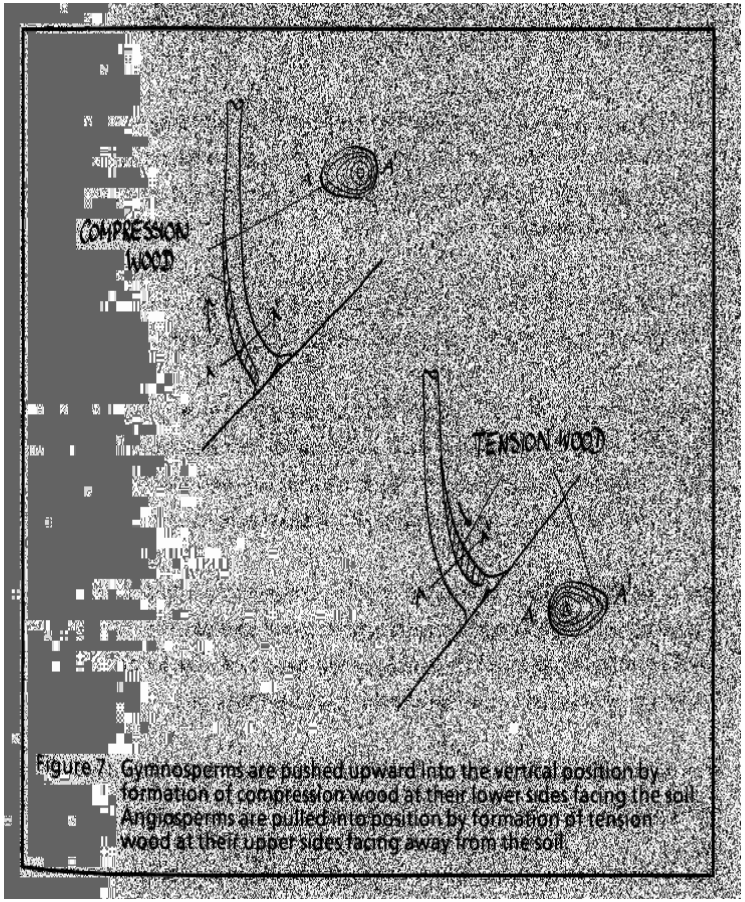
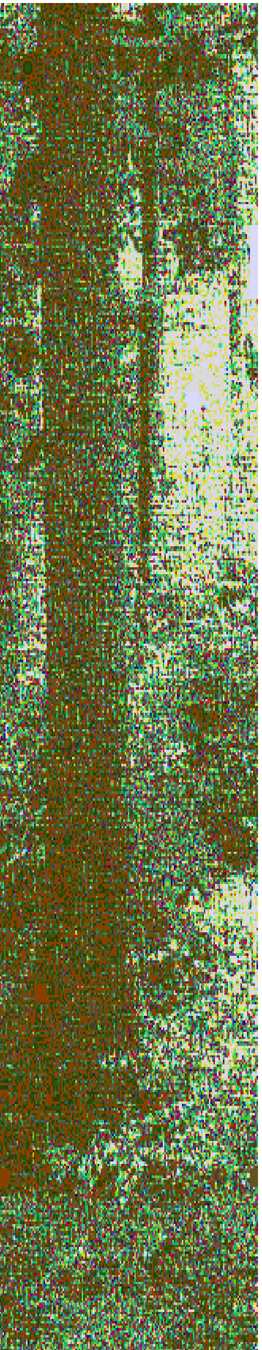


Figure 7: Gymnosperms are pushed upward into the vertical position by formation of compression wood at their lower sides facing the soil. Angiosperms are pulled into position by formation of tension wood at their upper sides facing away from the soil.

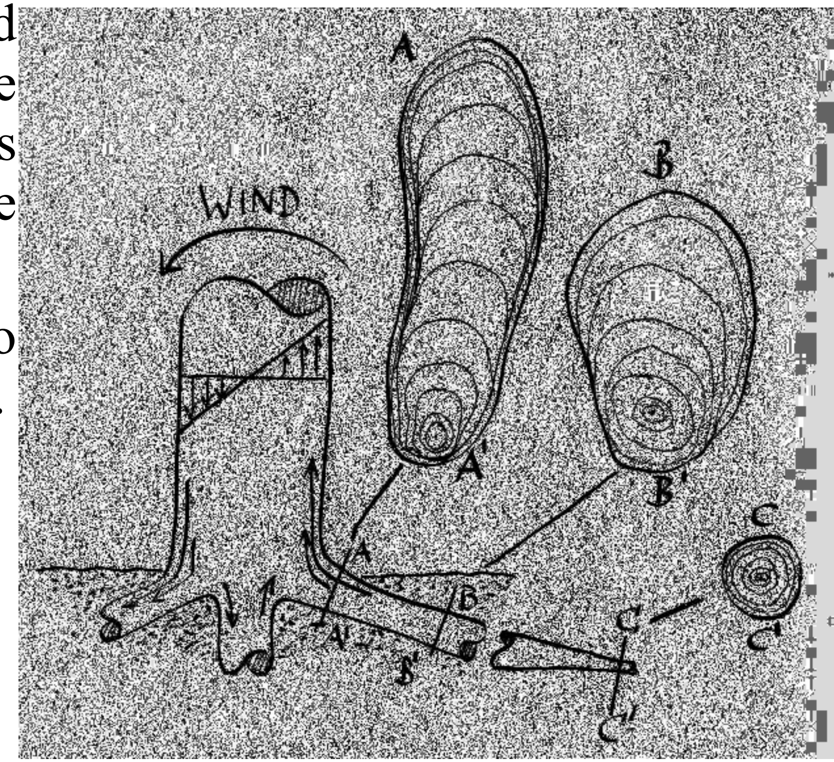


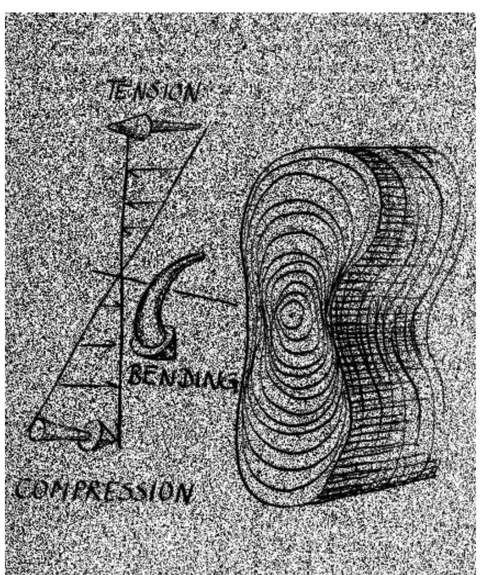
4.1 Tree geometry

3. Shape of roots

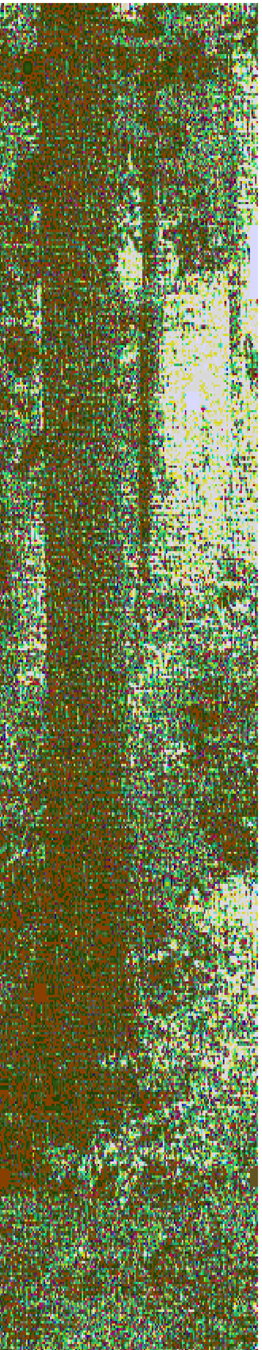
The roots have to transmit the forces and stresses arising in the crown and the trunk to the soil. There are these forces spread out by the friction between the roots and soil.

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





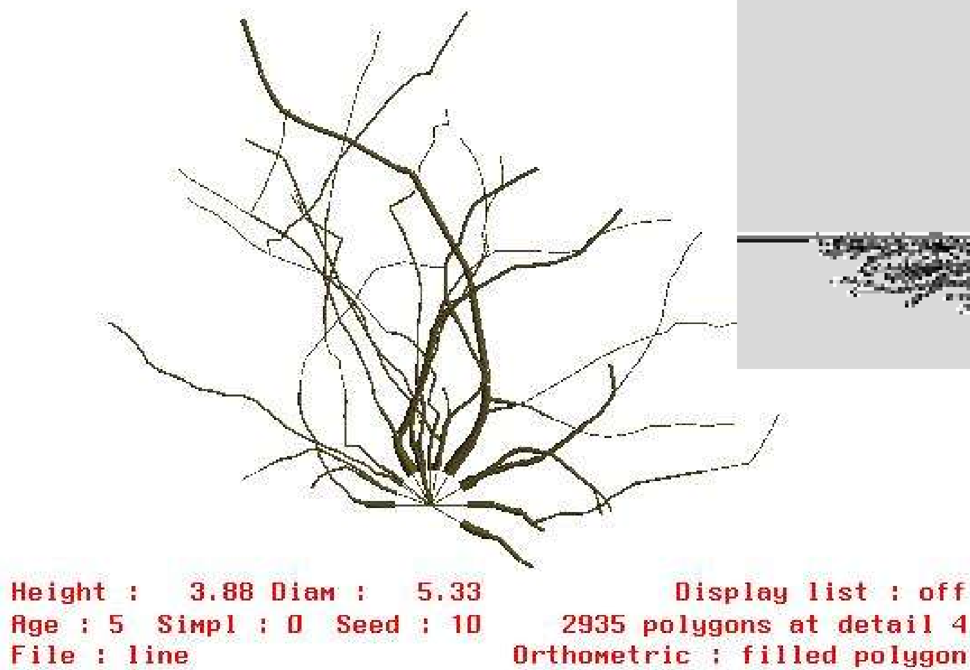
Wood is formed in accordance with the dominant force flow both axially and circumferentially.

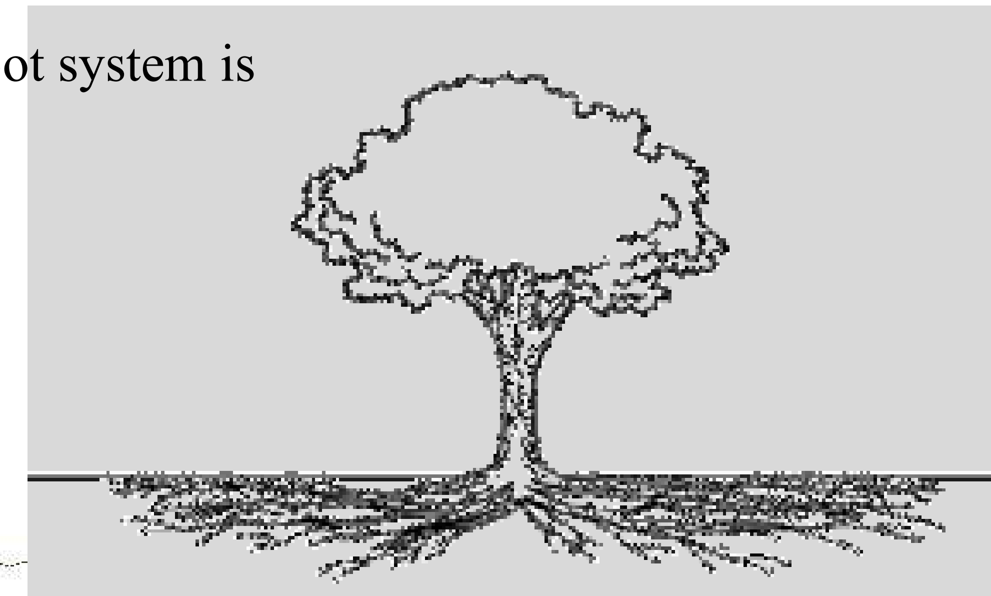


4.1 Tree geometry

4. Shape of root system

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





4. Components of Tree Stability

4.1 Tree geometry

Conclusion

- The trees are optimised construction, the biological load carriers, which self-optimize by adaptive growth.
- If the optimum state is disturbed, it is restored by the tree through the attachment of more material at points of maximum stresses.
- The tree reacts to any change in its loading or stress distribution by an adaptive growth response, which modifies its shape.
- Any deviations of the tree shape from optimal taper design represent either internal or external problems with the stability and/or vitality of the tree.

4. Components of Tree Stability

4.2 Wood properties

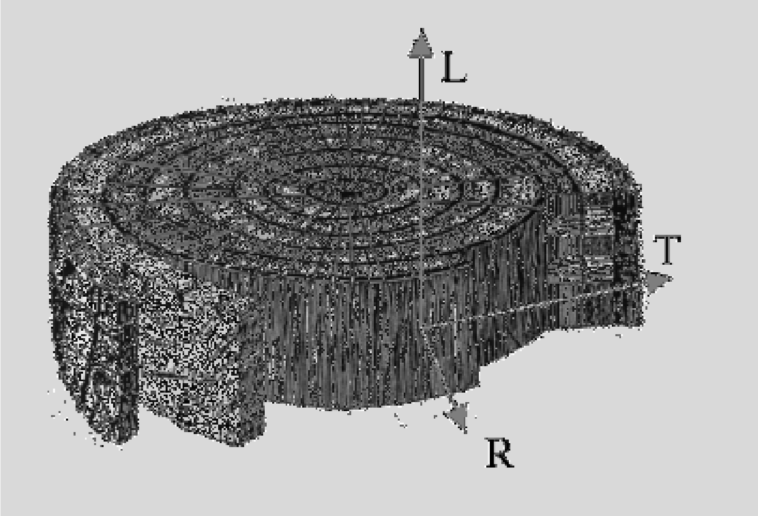
Objectives

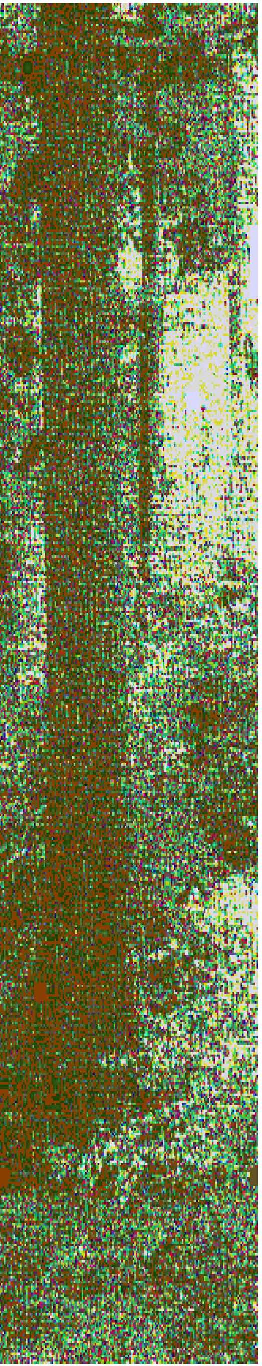
1. Methodological issues
    1.1 Wood at different moisture and physiological activies
    1.2 Dimensions of standard specimens for determination of properties
    1.3 Statistical processing of data
    1.4 Determining of modulus of elasticity and stress at proportional limit

2. Mechanical properties of wood

3. Relationship between properties from static and dynamic material tests

4. Items needed to be address

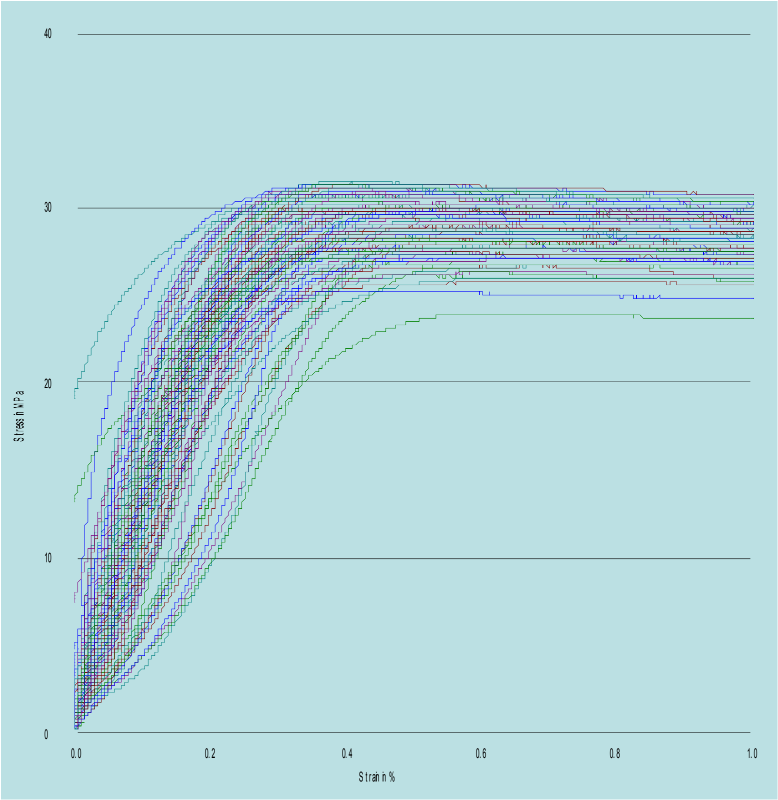




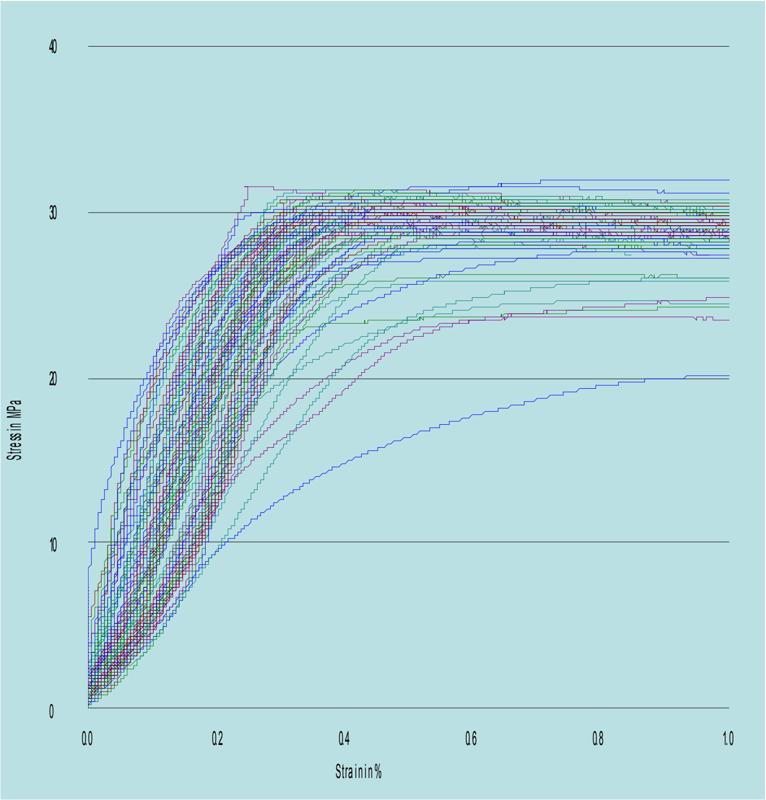
4.2 Wood properties

Methodological issues

Wood at different moisture and physiological activies

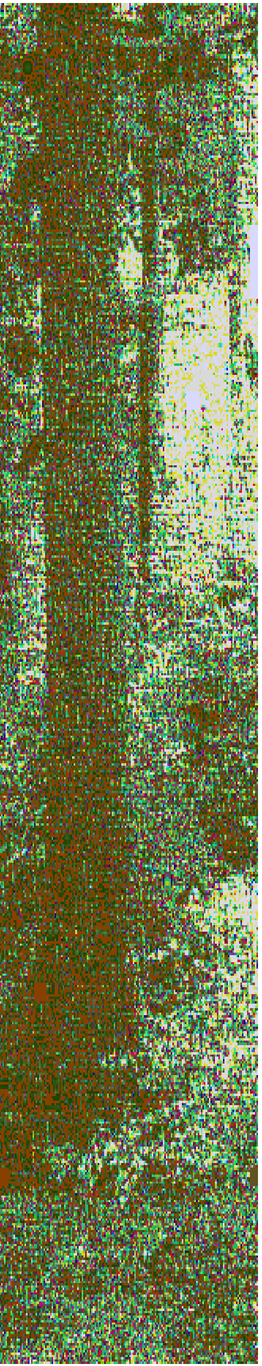


Stress-strain diagrams for green specimens „dead wet“



Stress-strain diagrams for green specimens physiological active, “living”

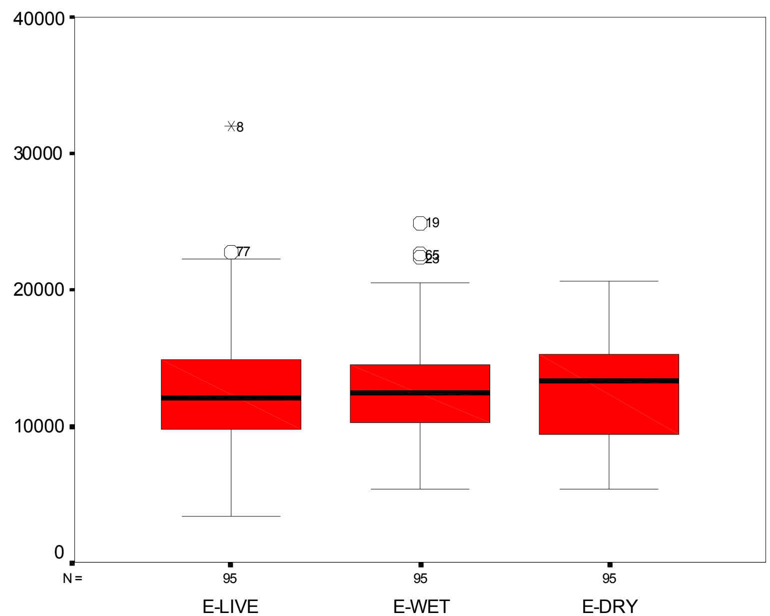
The **compression test** of the small clear specimens from wood of the **Norway maple** – *Acer platanoides* parallel to the grains



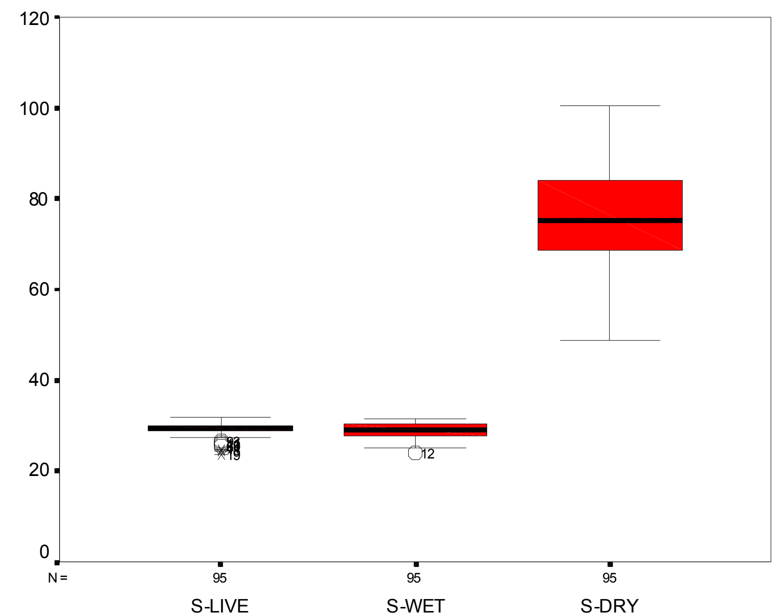
4.2 Wood properties

Methodological issues

Wood at different moisture and physiological activies

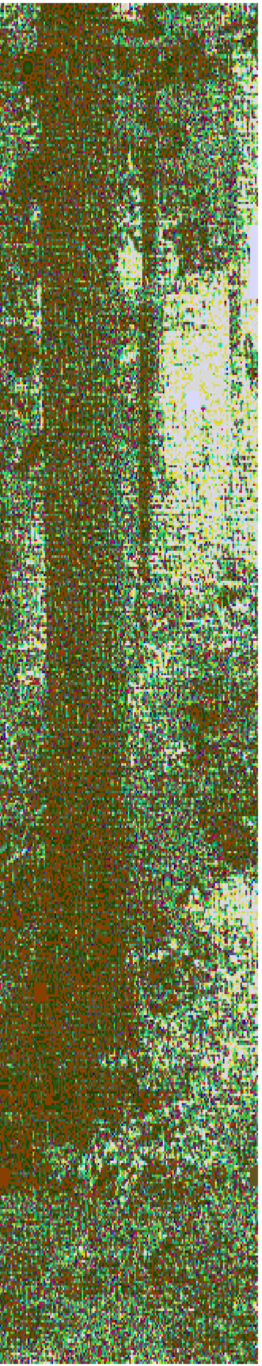


Modulus of elasticity



Compression ultimate strength

The ultimate strength and modulus of elasticity of „live“ and “wet” specimens have been statistically proofed **not to be different**.

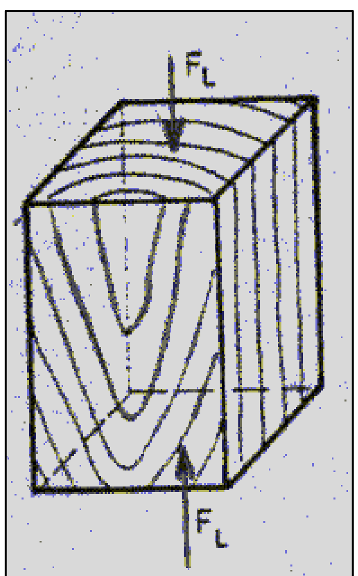


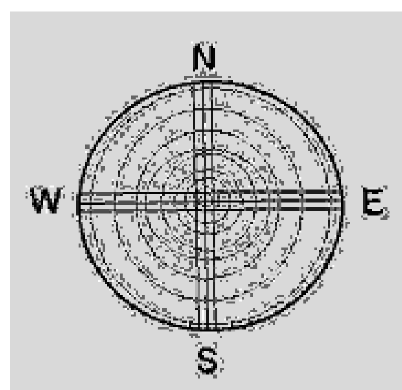
4.2 Wood properties

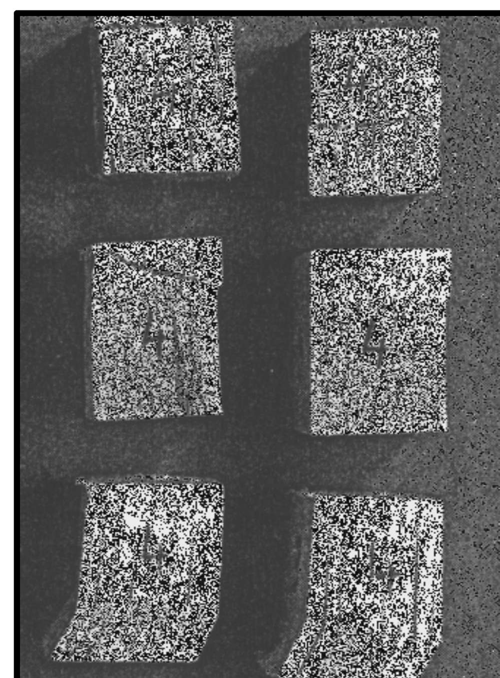
Methodological issues

Dimensions of standard specimens for determination of properties

Specimen dimension (cm)	USA		Germany	France	U.K.
	A	B			
Compression parallel to grains	5x5x20	2,5x2,5x10	2x2x3	2x2x6	2x2x6
Density	5x5x15		2x2x2,5	2x2x2	2x2x3



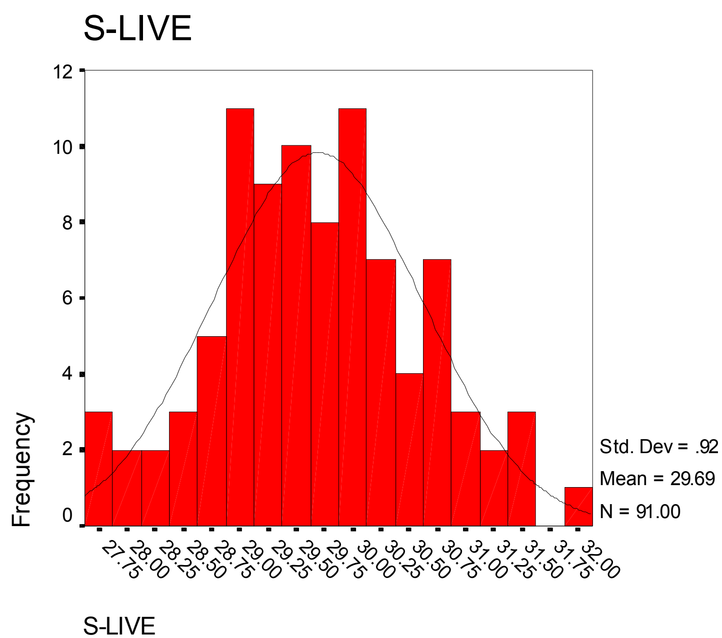


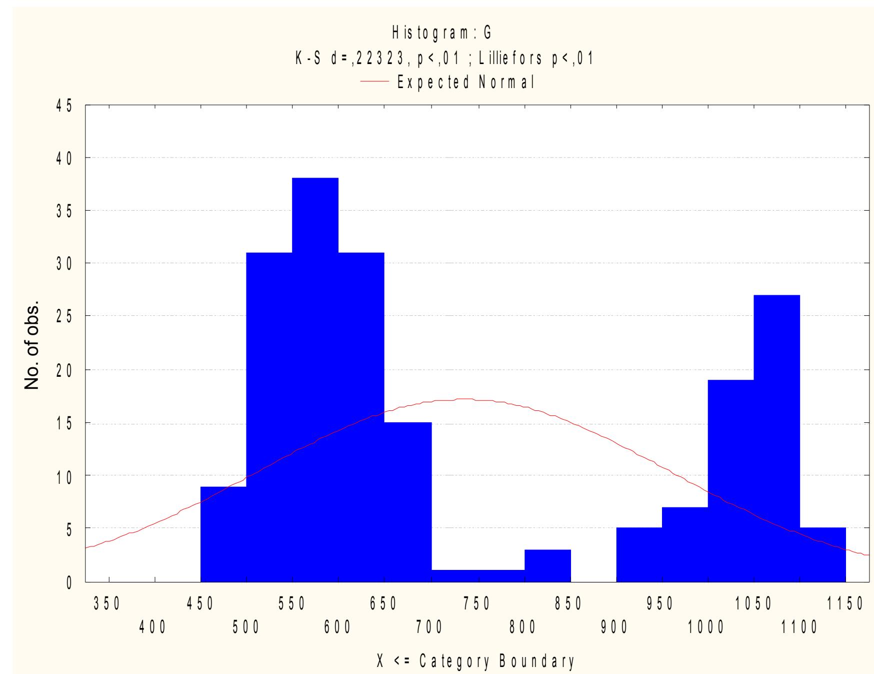


4.2 Wood properties

Methodological issues

Statistical processing of data



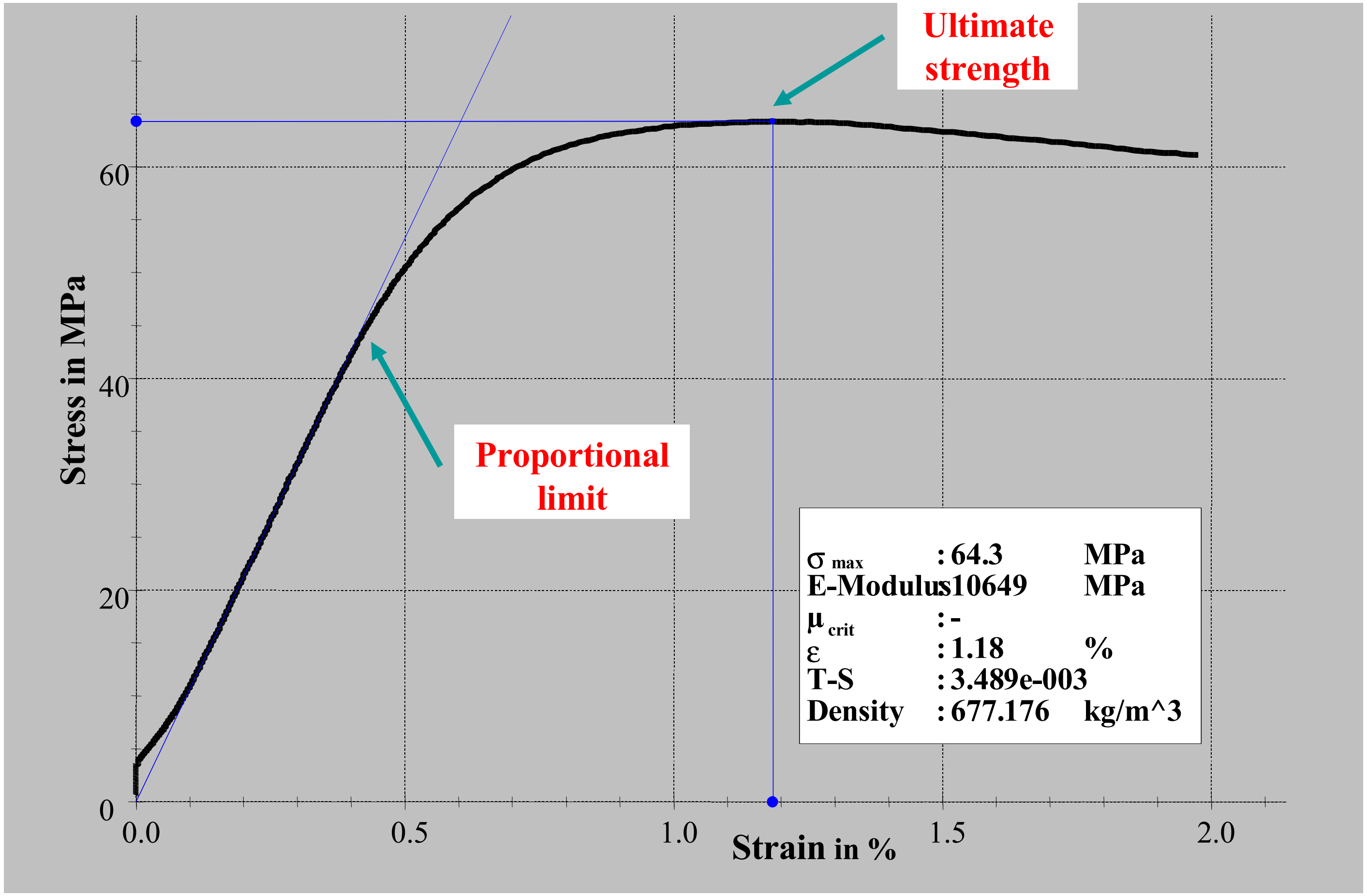


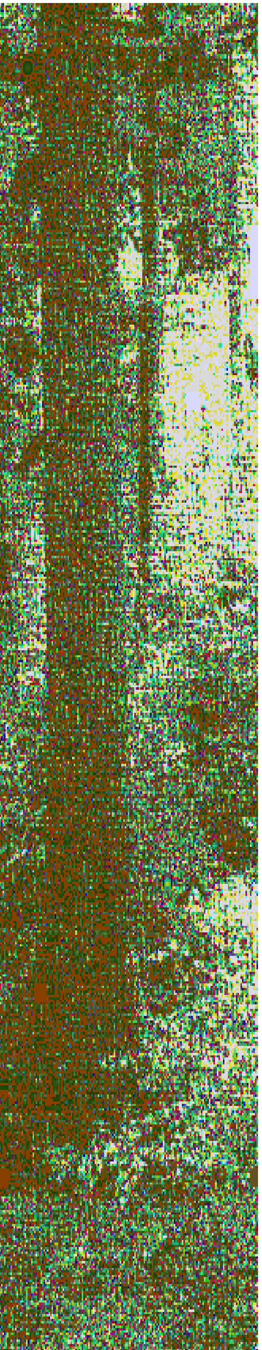
		Valid N	Mean	Median	Minimum	Maximum	Std.Dev.	Var.Coef.	Percentile 5%
E-modulus	N.mm-2	204	10544	10369	5031	17416	1810	17,2	7759
Stress proportional limit	N.mm-2	204	27,3	27,4	12,8	34,8	3,5	12,7	22,0
Strain proportional limit	%	204	0,26	0,26	0,116	0,42	0,048	18,1	0,19
Density	kg.m-3	204	925	927	753	1018	38	4,1	873

4.2 Wood properties

Methodological issues

Determining of modulus of elasticity and stress at proportional limit

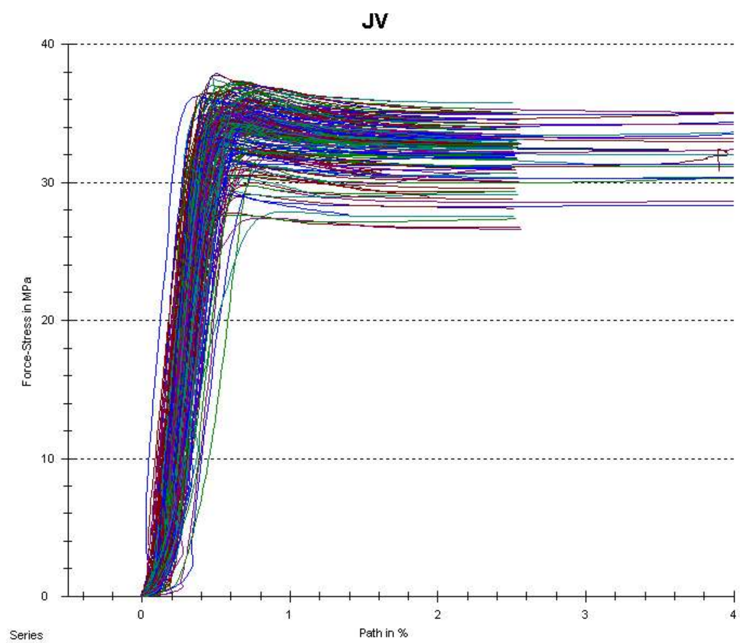




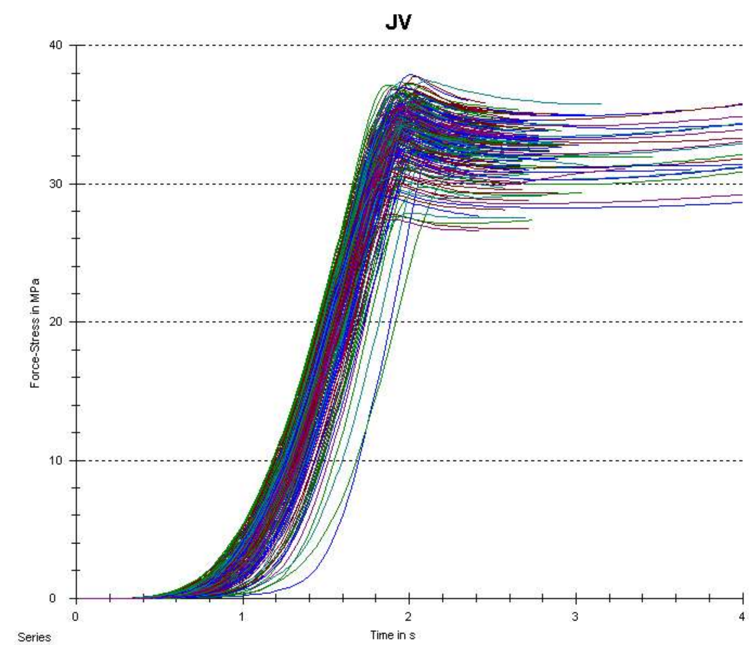
4.2 Wood properties

Norway maple *(Acer platanoides)*

		Valid N	Mean	Median	Minimum	Maximum	Std.Dev.	Var.Coef.	Percentile 5%
E-modulus	N.mm-2	204	10544	10369	5031	17416	1810	17,2	7759
Stress proportional limit	N.mm-2	204	27,3	27,4	12,8	34,8	3,5	12,7	22,0
Strain proportional limit	%	204	0,26	0,26	0,116	0,42	0,048	18,1	0,19
Density	kg.m-3	204	925	927	753	1018	38	4,1	873



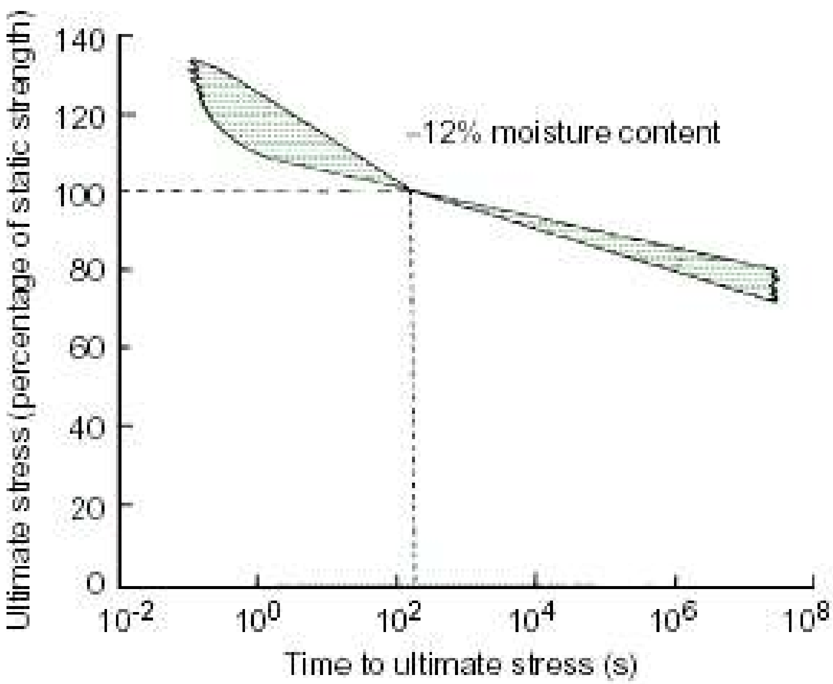
Stress-strain diagram



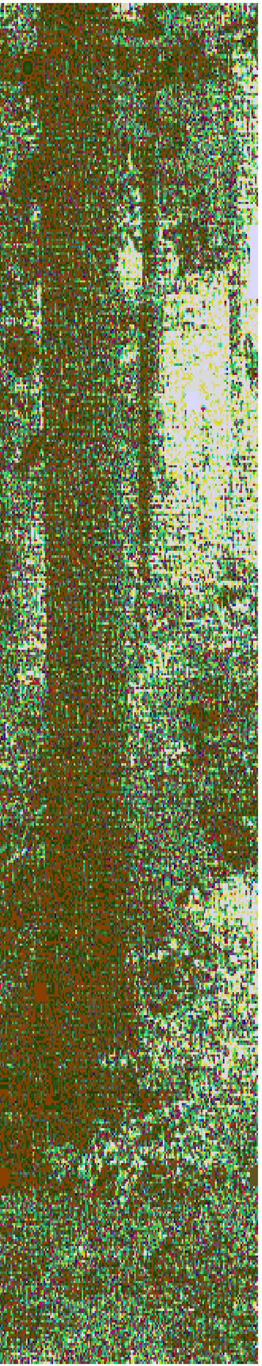
Stress against time

4.2 Wood properties

Relationship between properties from static and dynamic material tests



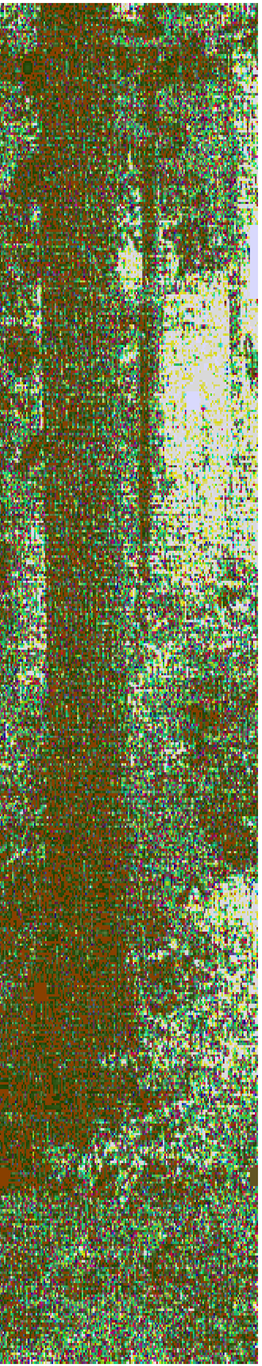
- Relationship of ultimate stress at short-time loading to that at 5 min loading, based on composite of results from rate-of-load studies on bending, compression, and shear parallel to grain.
- Variability in reported trends is indicated by width of band (Forest Products Laboratory 1999).



4.2 Wood properties

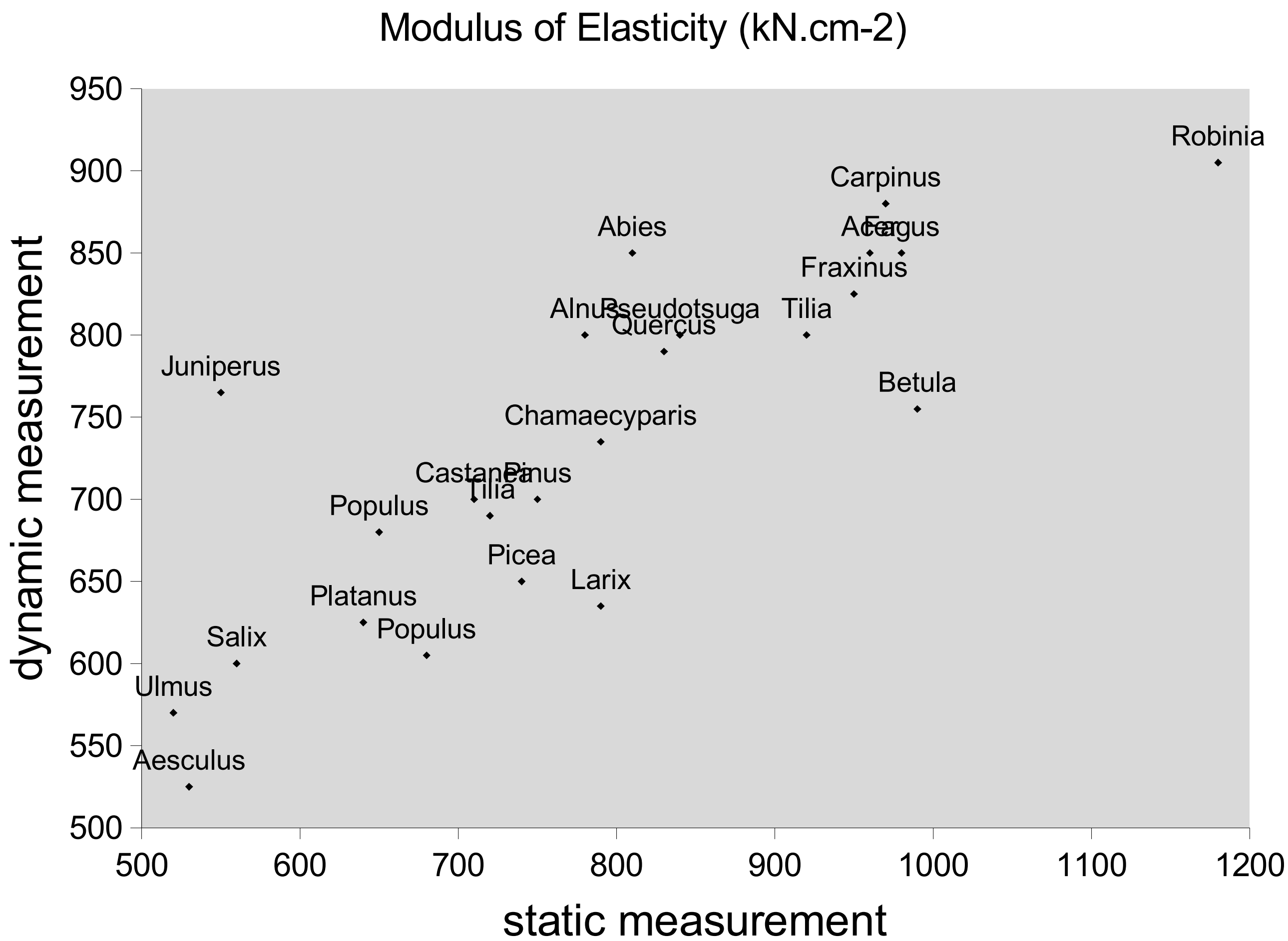
Stuttgart Material Properties of Wood

Common species names	Specific gravity	Modulus of elasticity	Deformation prop. limit	Compression prop. limit	Modulus of elasticity	Compression prop. limit
	green wood, dynamic measurement (1 Hz)				green wood, static measurement	
	-	kN/cm2	%	kN/cm2	kN/cm2	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		
willow (Salix)	0,82	700	0,23	1,6	560	1,5



4.2 Wood properties

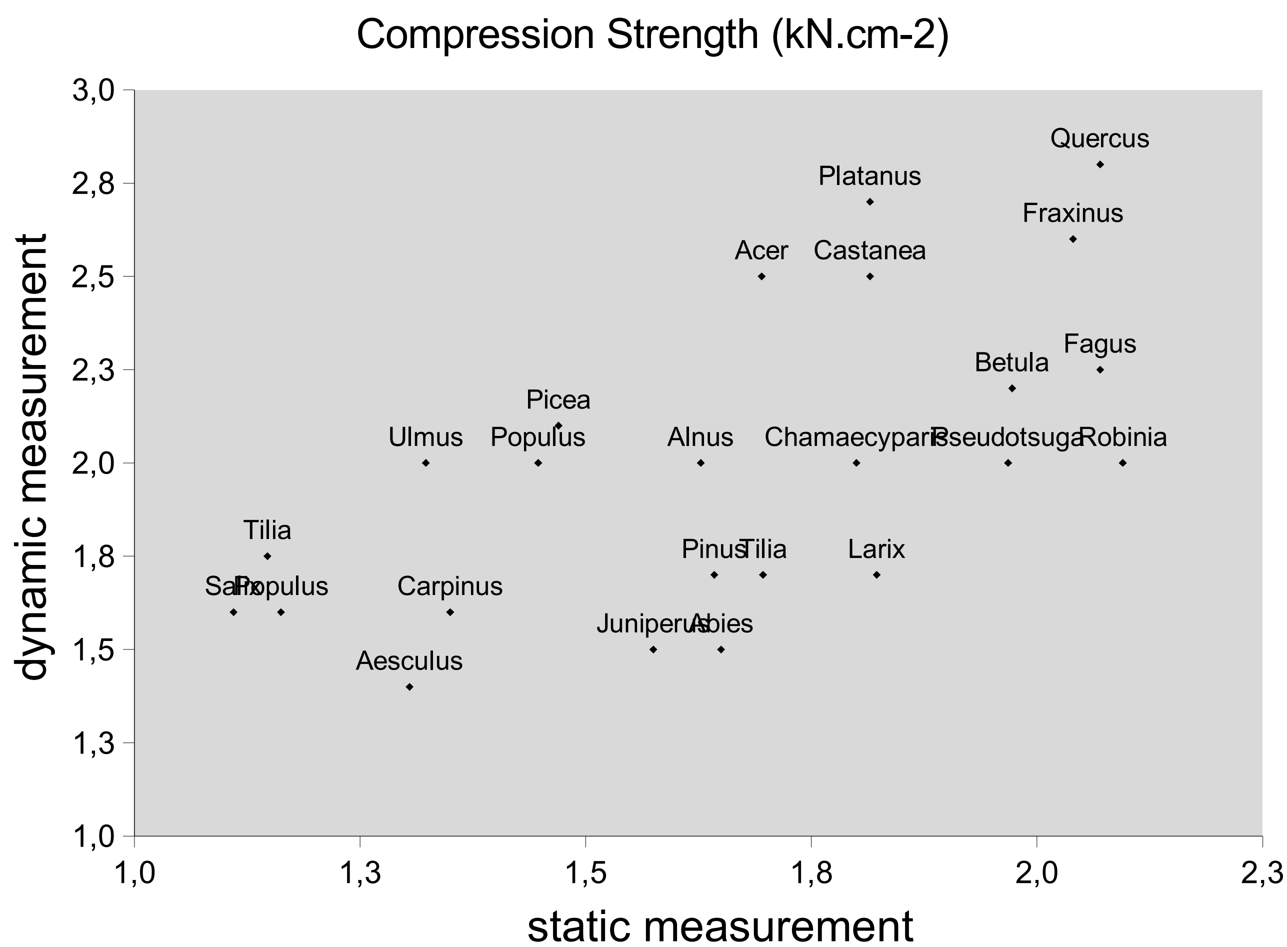
Relationship between properties from static and dynamic material tests



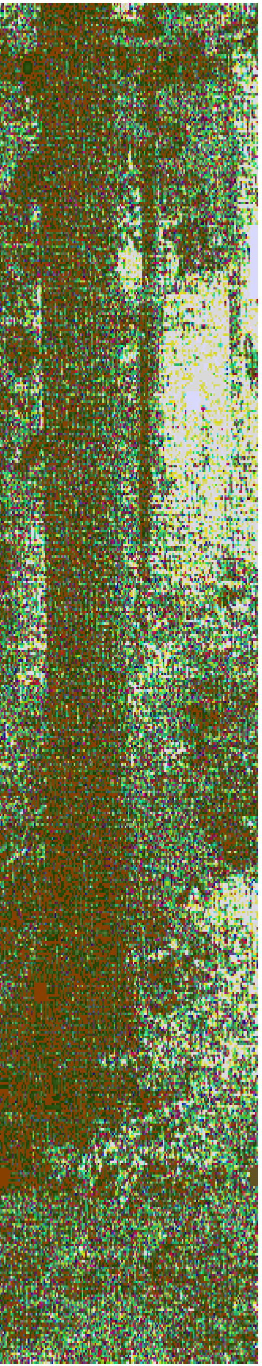
Relationship between static and dynamic measurement of modulus of elasticity in green condition.

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.

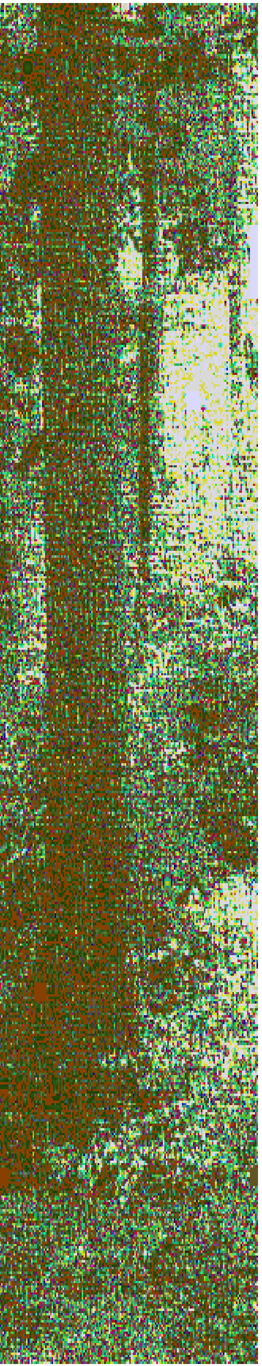


4.2 Wood properties

Conclusion (items needed to be address)

- Interpretation of Stuttgart Catalog of Wood Material Properties
- Statistical processing of measured data – 5% percentile, determination of modulus of elasticity and proportional limit
- Wood properties at regional level – influence of ecological conditions
- Relationship between properties obtained by static and dynamic tests
- Modelling of mechanical behaviour of the tree – not only the stem, but main branches as well

4. Components of Tree Stability

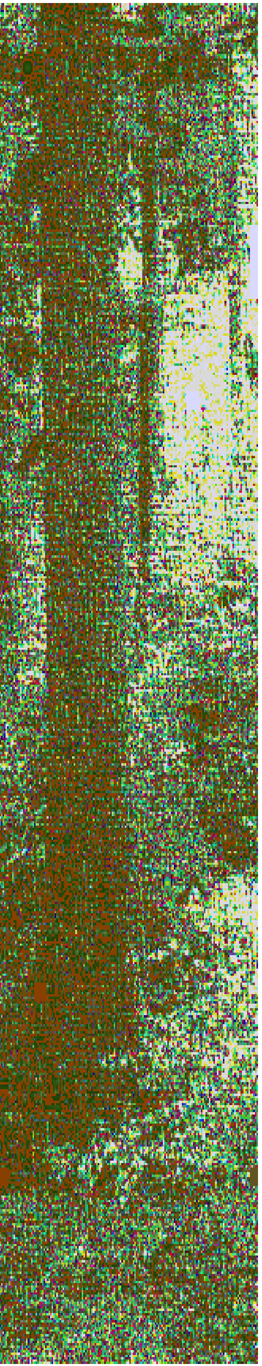


4.3 Loads applied to tree

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.

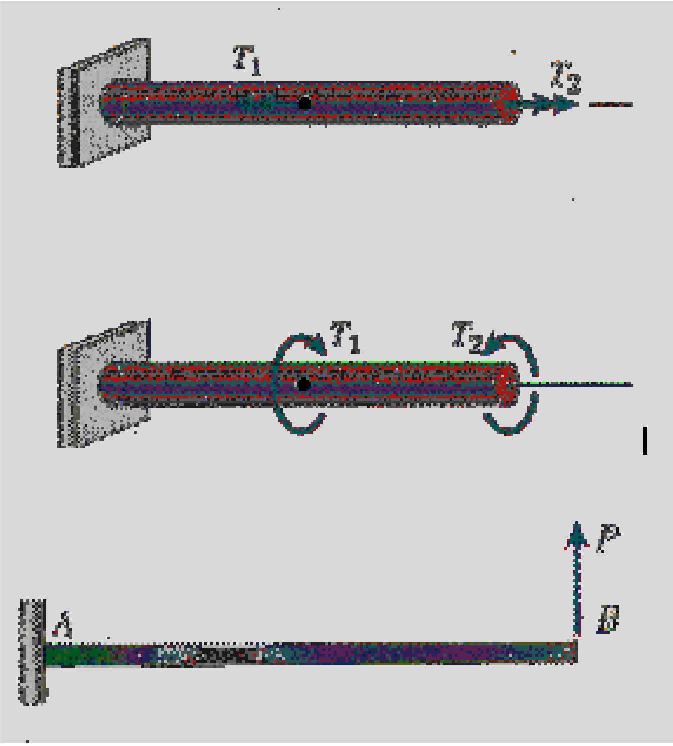
4. Components of Tree Stability



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. Components of Tree Stability

4.3 Loads applied to tree

Summary of mechanical stresses acting in trees

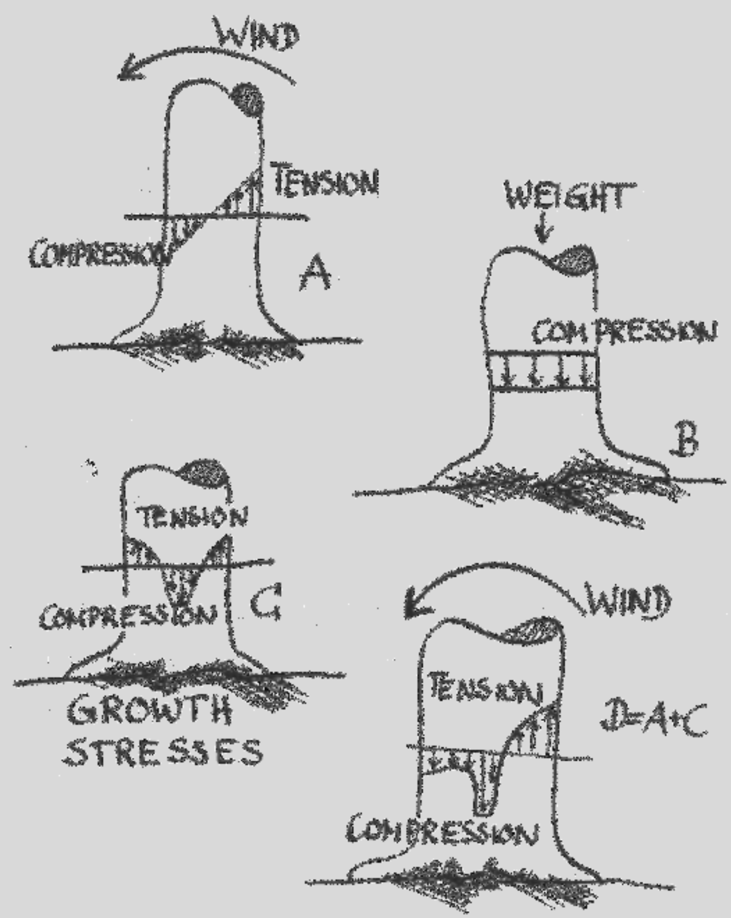
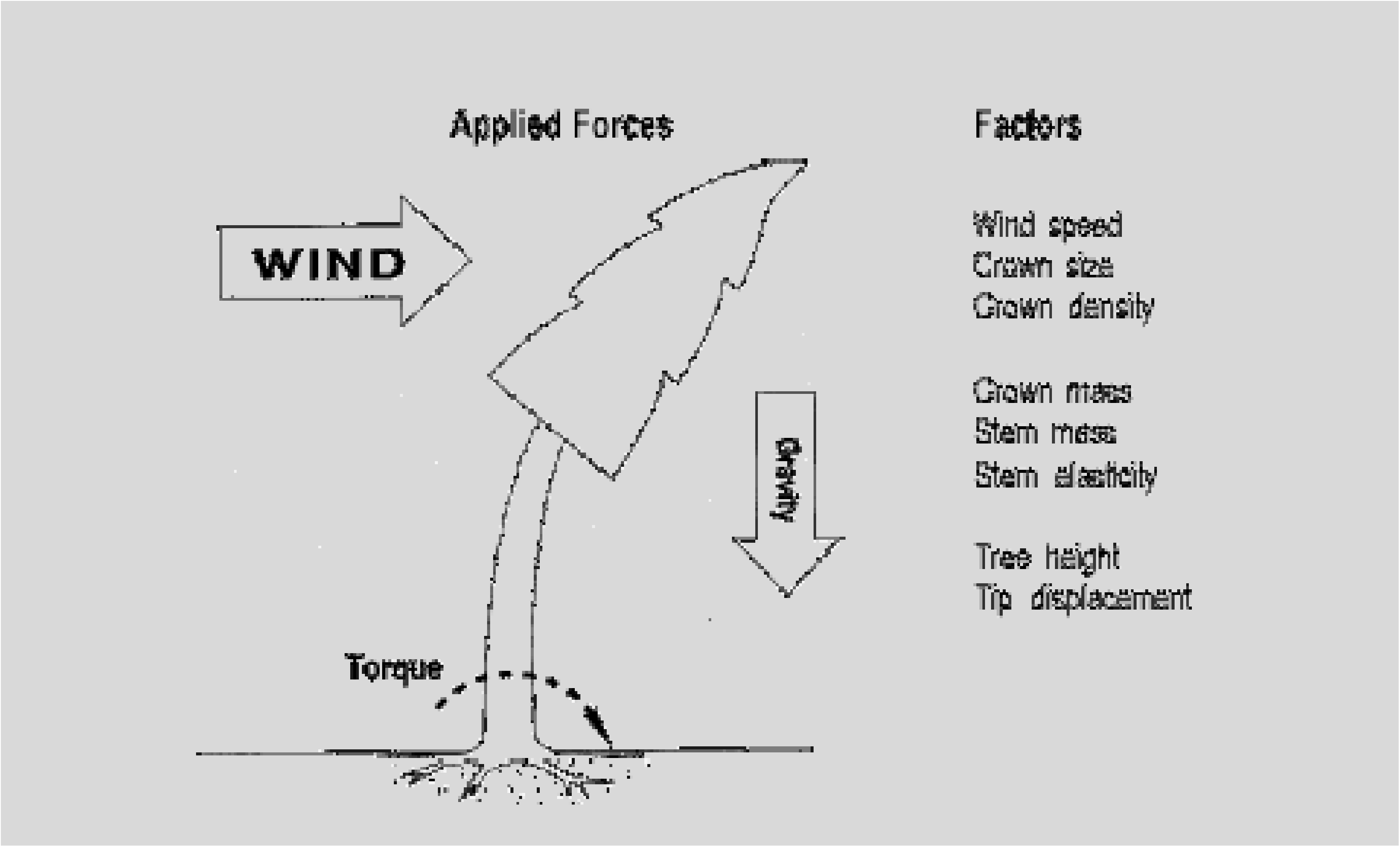


Figure 9: Main sources and effects of mechanical stresses acting in trees

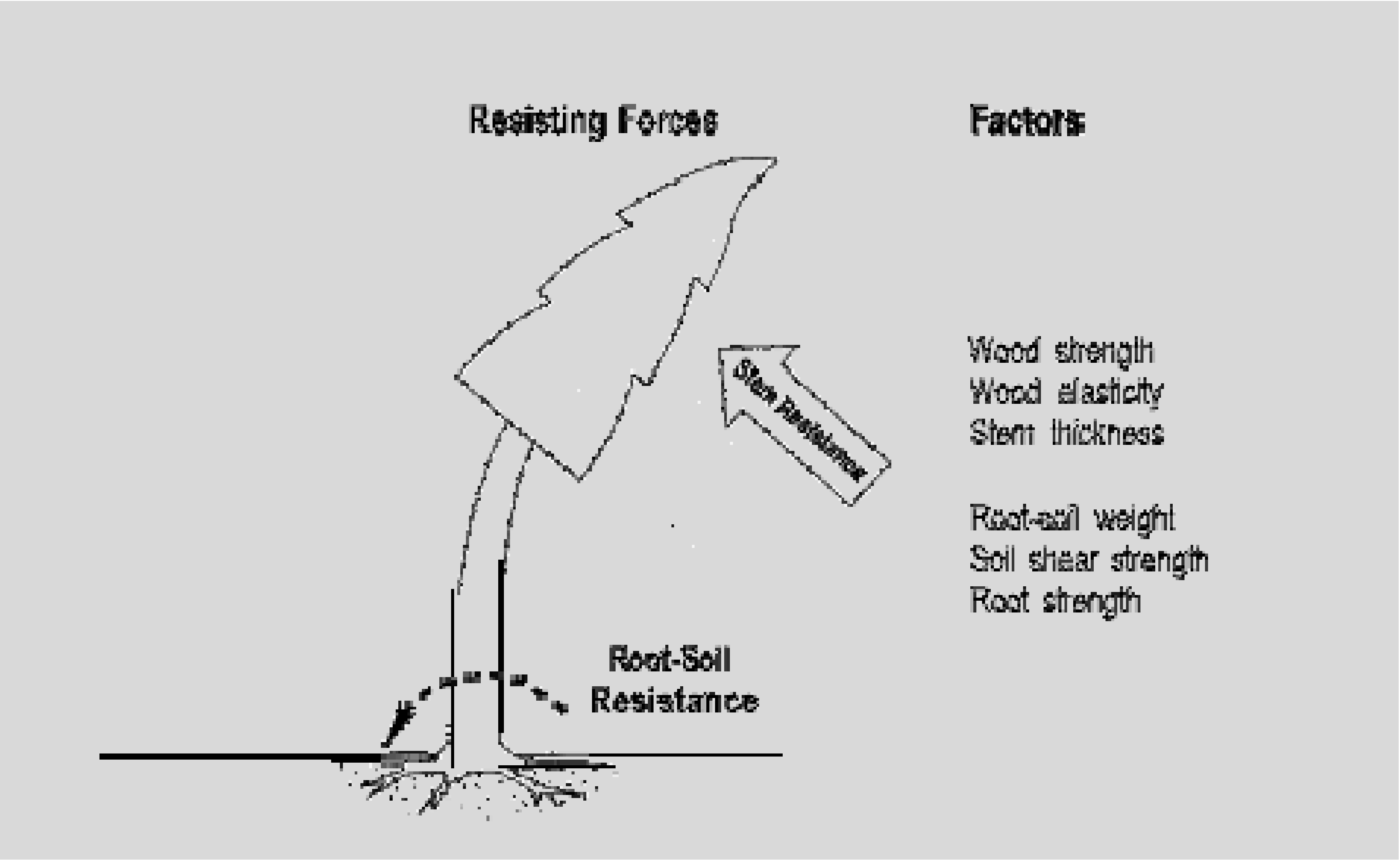
4.3 Loads applied to tree

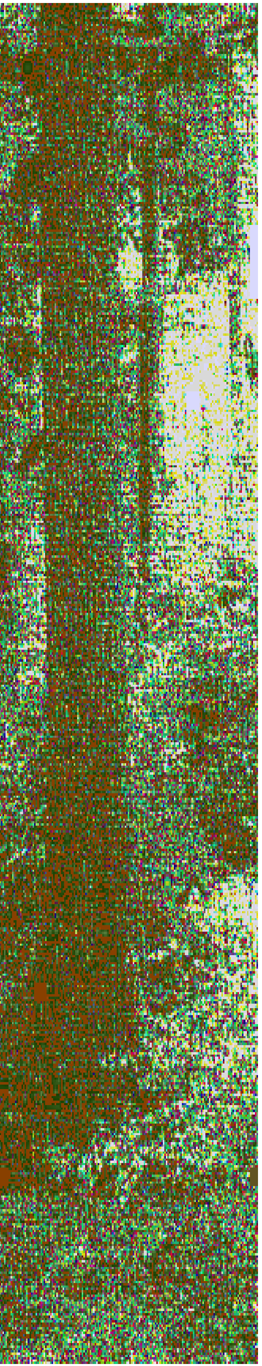
Factors affecting wind and gravitational forces acting on a tree.



4.3 Loads applied to tree

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





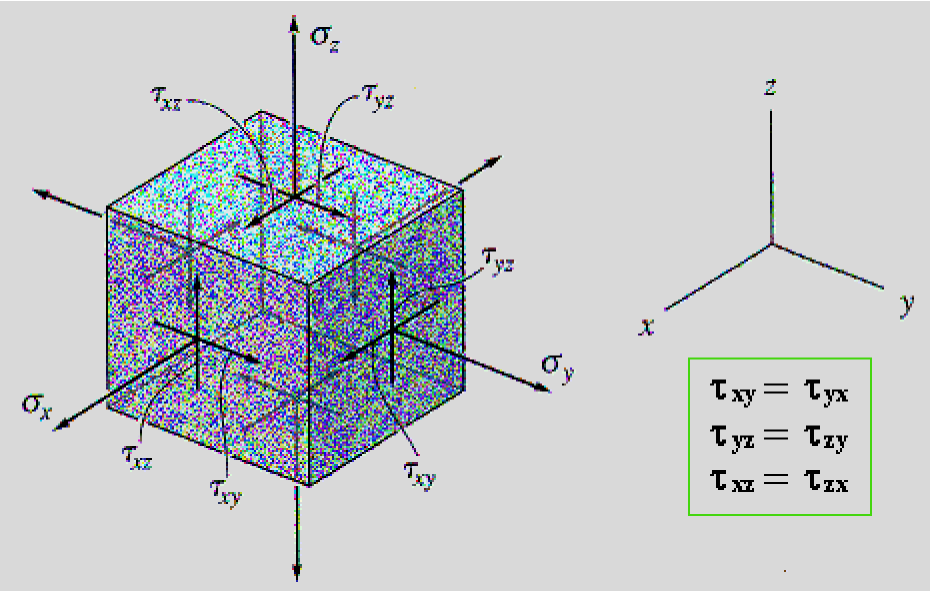
Conclusion

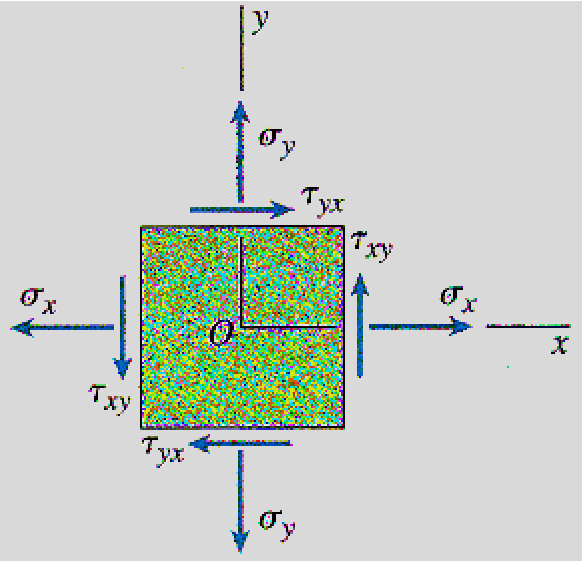
- Trees adapt their stem and root growth in response to the wind loading to which they are subjected in order to resist breakage or overturning.
- By understanding the behaviour of trees in strong winds and the mechanisms of root anchorage it has become possible to develop mechanistic models that predict
    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.

Origin dates back to Galileo in the 17th century.





5. Biomechanics of Tree

5.1 Application of mechanics of materials

5.2 Stability and failure of tree

Failure occurs when the horizontal forces on a tree are transmitted down the trunk to create a stress that exceeds the resistance to breaking or turning of the root/soil system.

5. Biomechanics of Tree

5.1 Application of mechanics of materials

5.2 Stability and failure of tree

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. Biomechanics of Tree

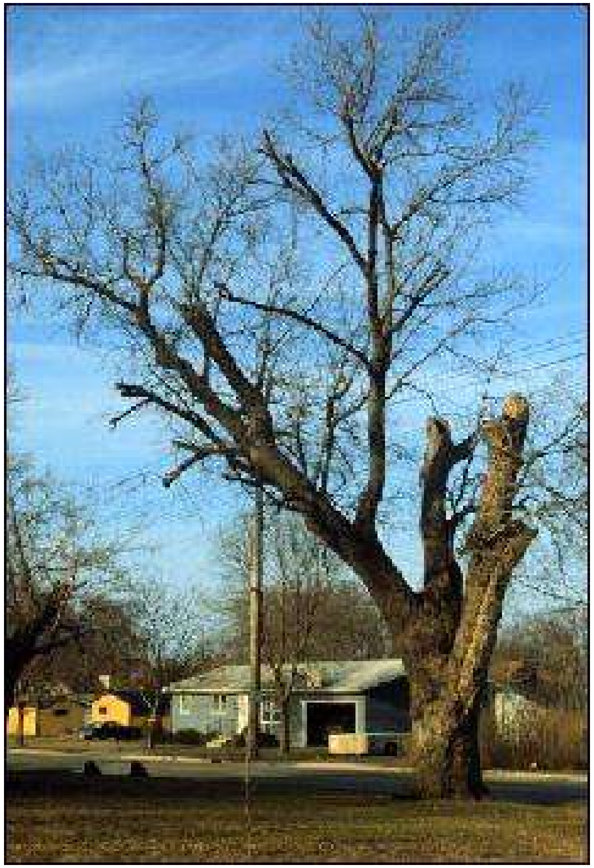
5.1 Application of mechanics of materials

5.2 Stability and failure of tree

5.3 Factors influencing tree stability

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

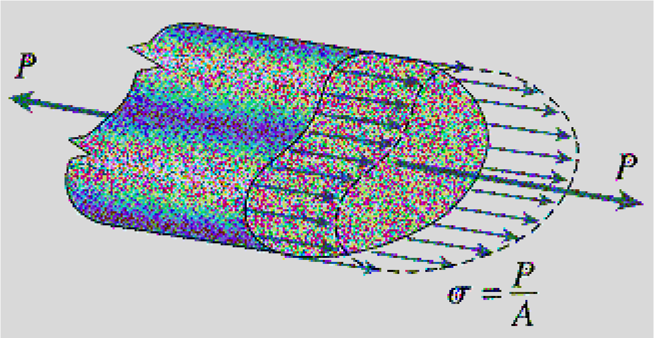
Objectives

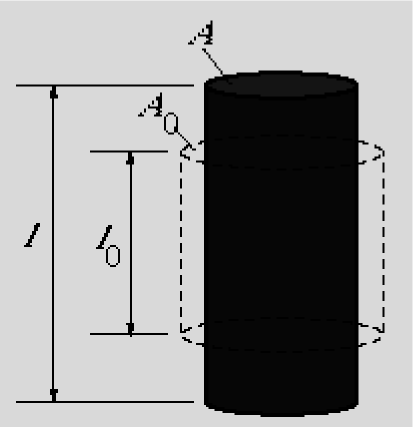
1. Understand the axial, shear, and bearing stresses associated with simple trunk design and analysis.
2. Understand the stress-strain and load-displacement relationships for axial members – *tree as column*.
3. Learn to calculate the stress, strain and displacement for beams under various loading conditions – *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.
6. Try to relate to the real world in a simplified idealistic manner that gives usable results.

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)

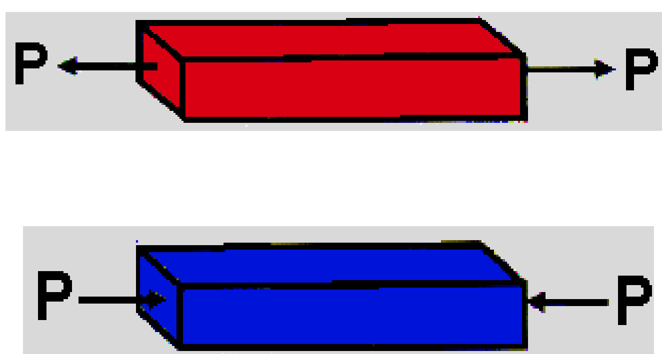


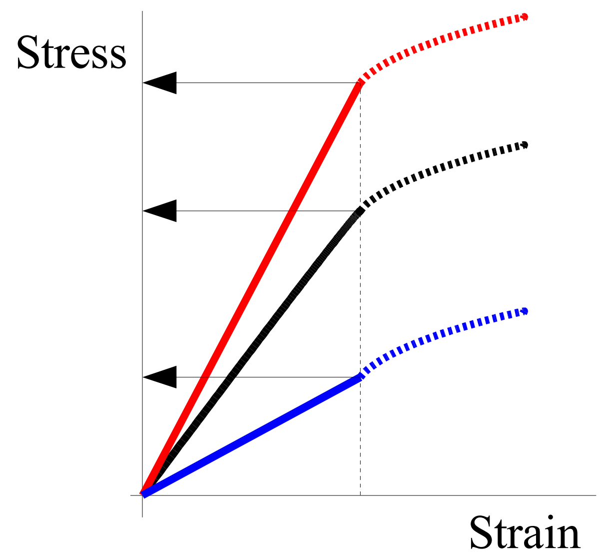


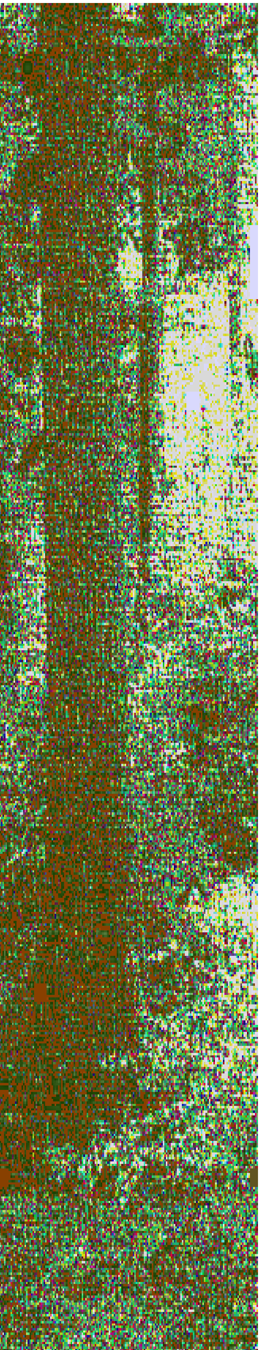
5.1 Application of mechanics of materials

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)







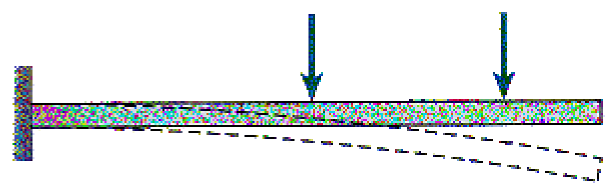
5.1 Application of mechanics of materials

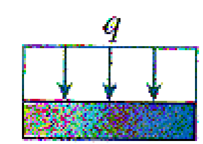
Key Terms

- 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. Biomechanics of Tree

5.1 Application of mechanics of materials

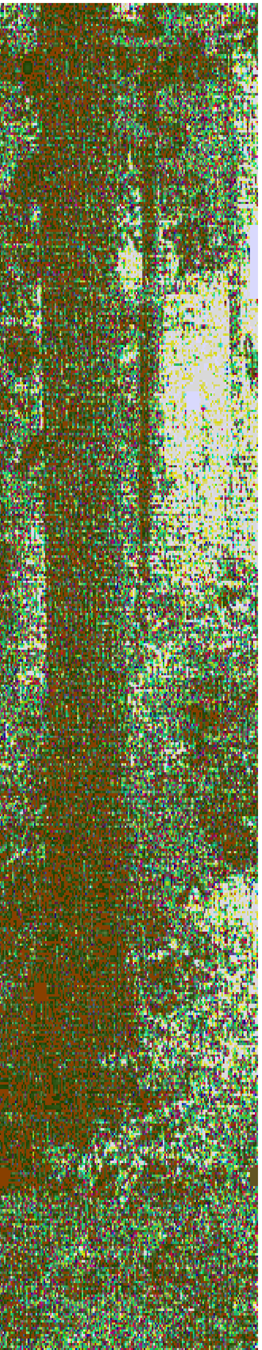
Key Terms

- 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 alterinative 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

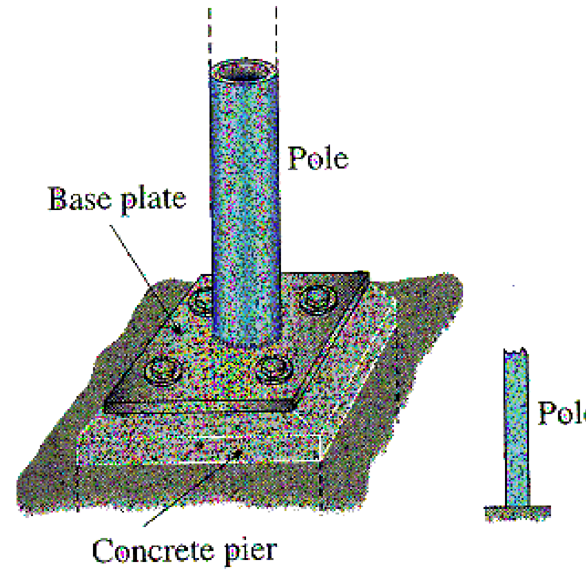
- Analysis - the *properties* of the structure are given and the *response* is to be determined
- Design - the desired *response* is given and the *properties* of the stucture are to be determined (usually a longer and more involved process)
- Stiffness - the ability of the structure to resist changes 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)

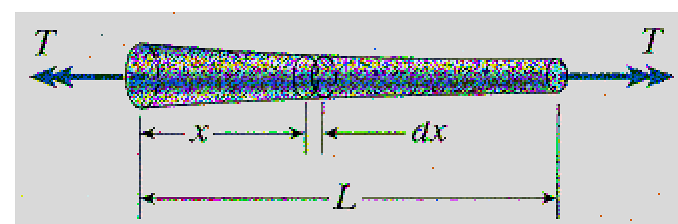


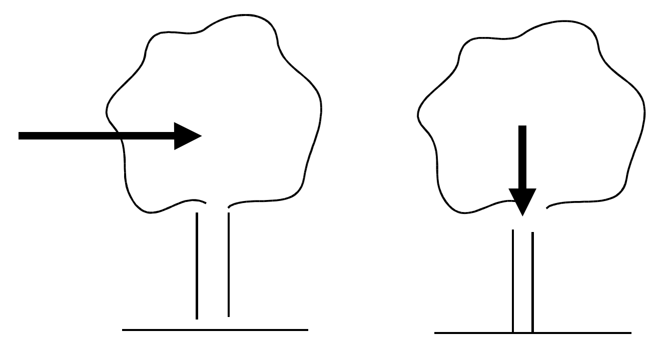
5.1 Application of mechanics of materials

Assumption / limitation

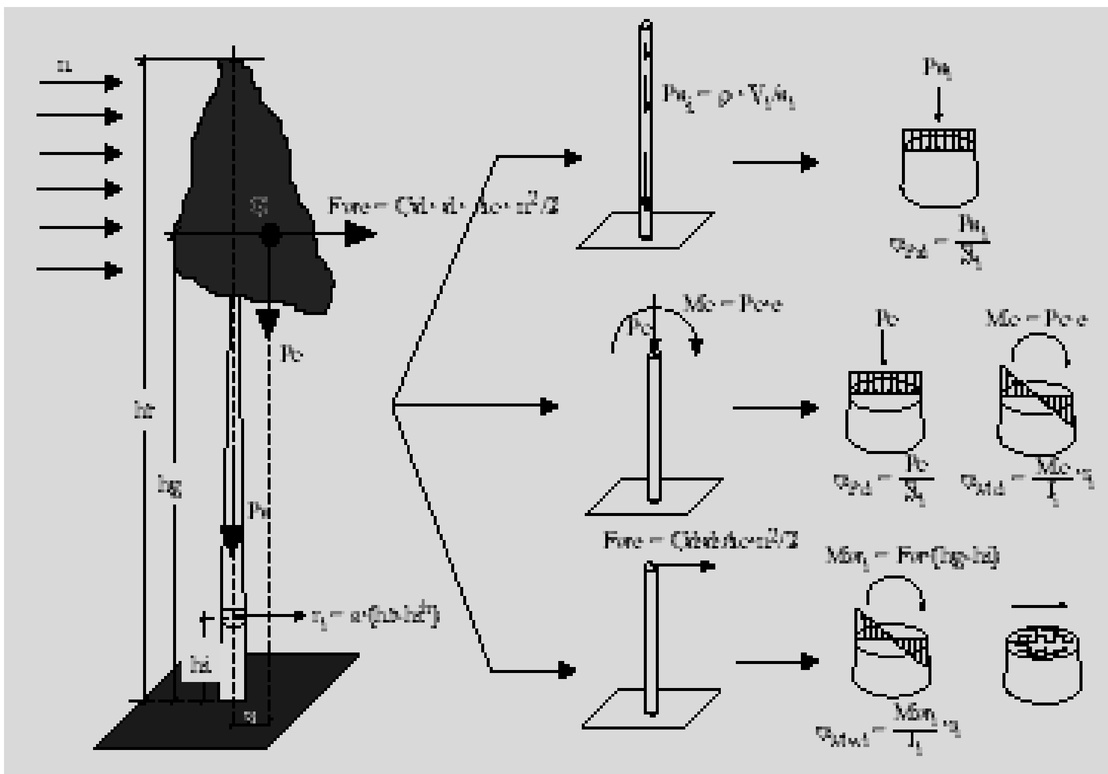
- elastic cantilever beam, rigidly fixed on one side and free on the other
- croos-section varies with height, and this non-uniform taper can be described by a mathematical function
- transverse section of the stem is considered with an area A and a section moduli W
- in order to calculate the self-weight 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

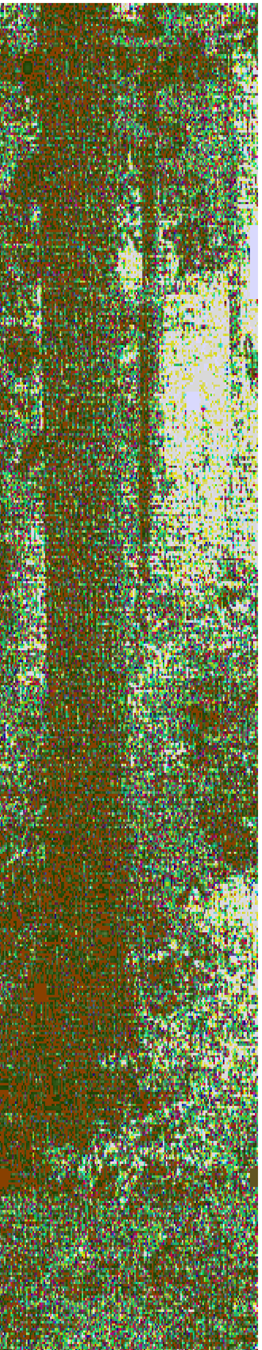




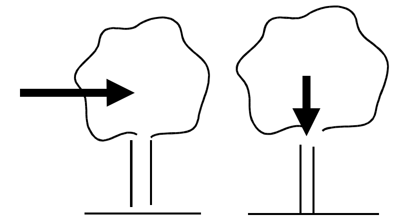


5.1 Application of mechanics of materials

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

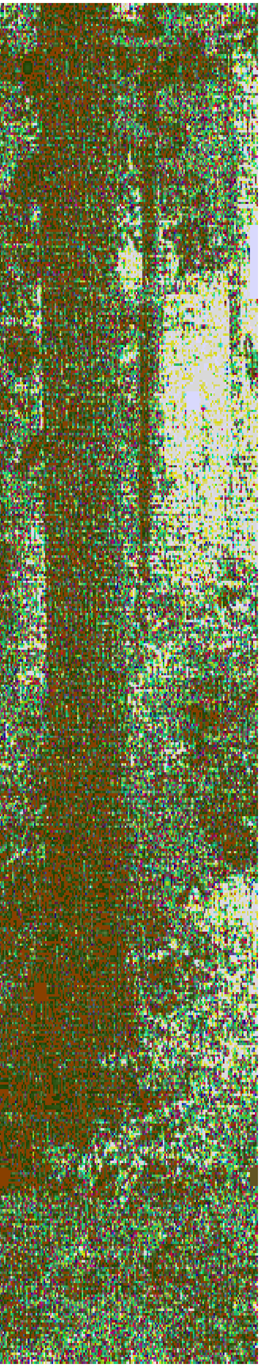
- The forces acting upon a tree are divided into

    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.

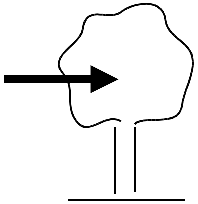
- Trees are assumed to

    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. Biomechanics of Tree



5.1 Application of mechanics of materials



1. Force due to wind (horizontal)

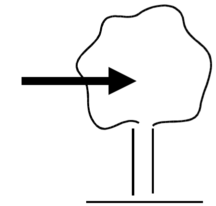
- There are a number of possible methods for calculating the wind loading on a tree. These include direct calculation from a knowledge of the drag coefficient and leaf area of the tree canopy (Jones, 1983), spectral methods using the approach pioneered by Davenport (1961) or an empirical approach using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

- The wind speed (*u*) over a forest s canopy is given by a logarithmic or power profile:

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

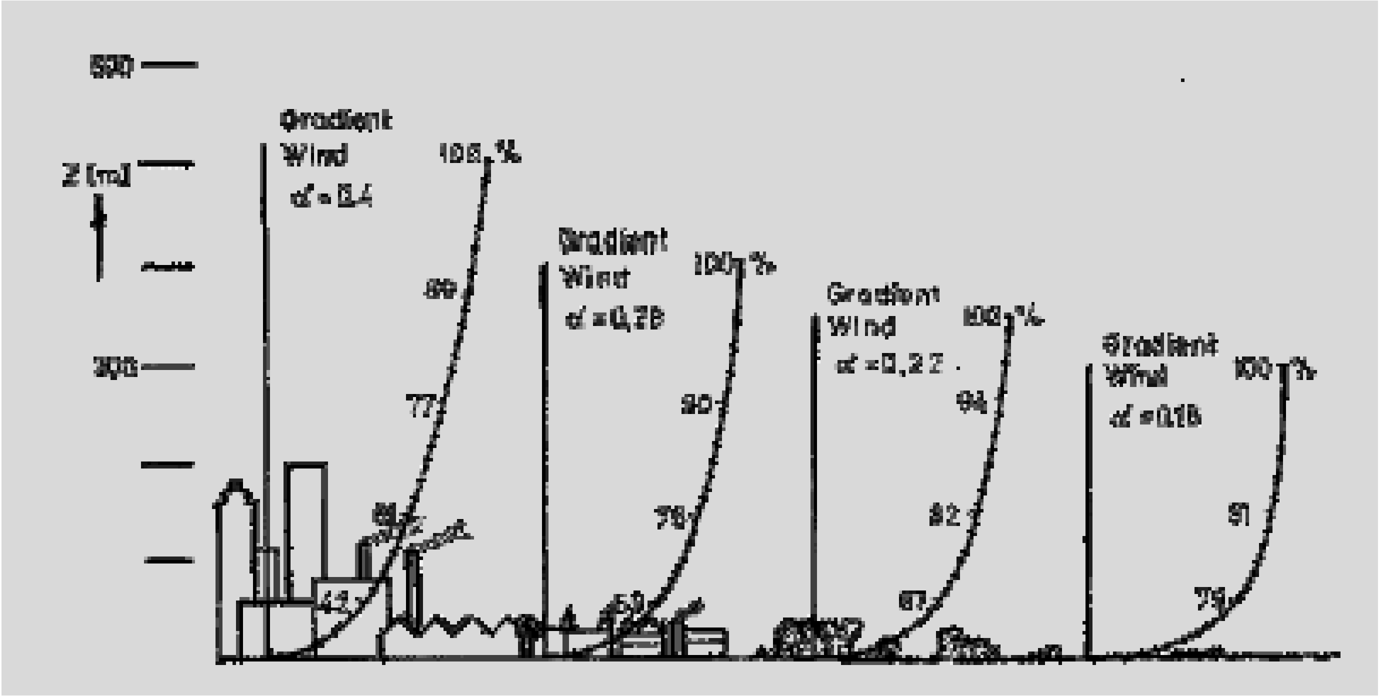
- The mean wind loading and gravity-based forces are calculated at each height in the canopy using a predicted wind profile and the vertical distribution of stem and crown weights.

5.1 Application of mechanics of materials

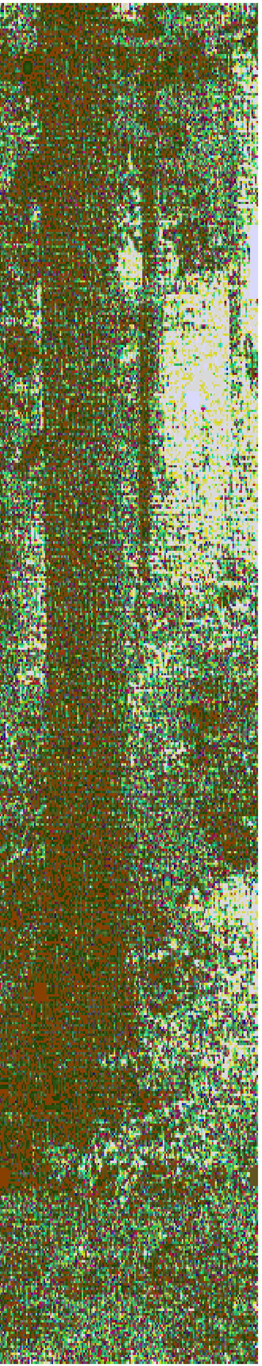


1. Force due to wind (horizontal)

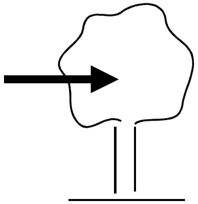
The new Eurocode 1 includes four terrain categories with different roughness-parameters and in addition to that there are special windmaps based on different mean wind velocities for different locations:



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



5.1 Application of mechanics of materials



1. Force due to wind (horizontal)

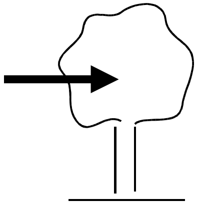
- The total mean wind-induced force is the sum of the wind forces acting at each point on the stem and crown that is given (Jones, 1983; Peltola et al., 1999) at height *z* by:

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

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. Biomechanics of Tree

5.1 Application of mechanics of materials



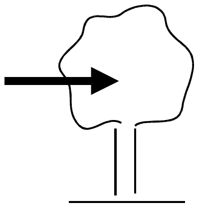
1. Force due to wind (horizontal)

- 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 $kg.m^{-3}$).

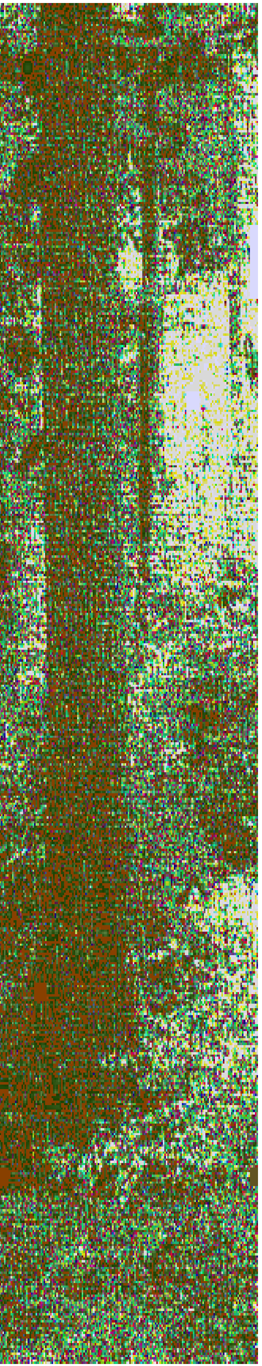
5. Biomechanics of Tree

5.1 Application of mechanics of materials

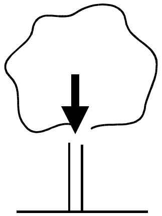


1. Force due to wind (horizontal)

- 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

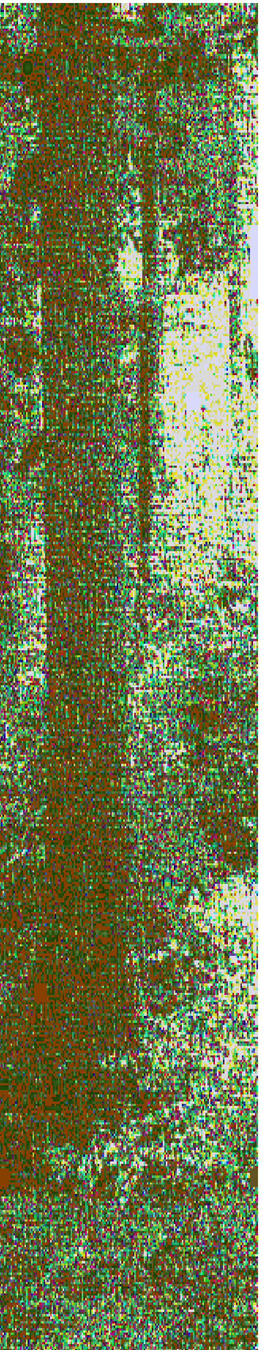
$$F_{stem} = V_{stem} G_{stem} g$$

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

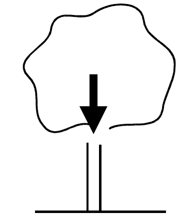
$$F_{crown} = m_{crown} g$$

Usually, the centre of gravity of the crown will be eccentric, and the distance to stem *e,* and height hcg can define its situation

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



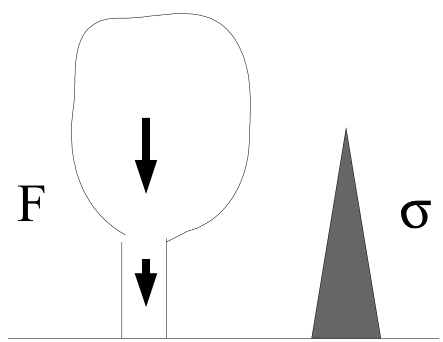
5.1 Application of mechanics of materials

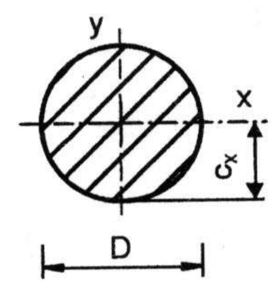


3. Axial stress (normal stress)

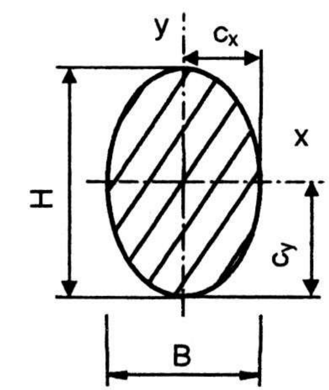
Axial stresses due to stem and crown mass loading vary along the stem with a maximum occurring at a position which depends on taper.

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

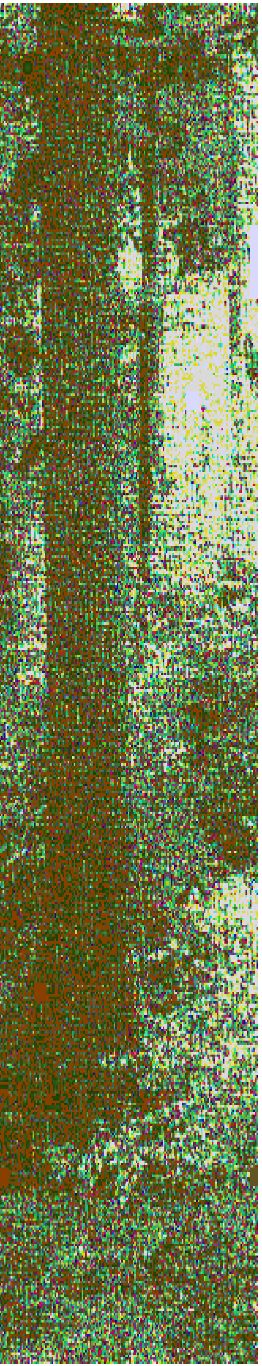




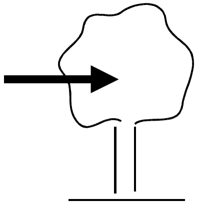
$$A = \frac{\pi}{4} D^2$$



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



5.1 Application of mechanics of materials

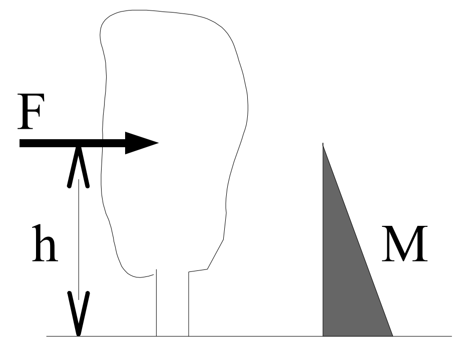


4. Flexure formula

a) bending moments

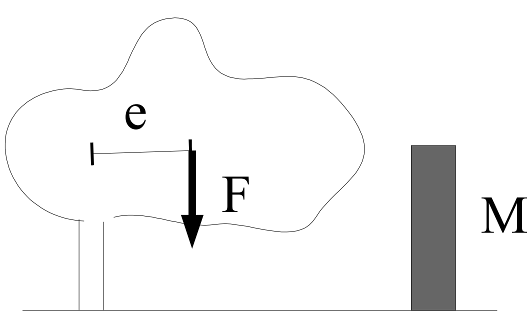
- bending – mean wind force acting on the crown centre and the height of center of gravity
- total maximum bending moment is at the base of the stem
- bending moment varies with the height

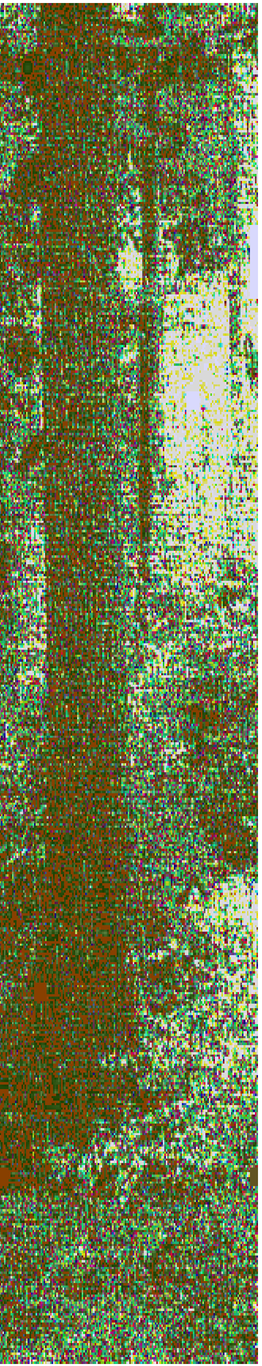
$$M_{wind} = F_{wind}\, h_{cg}$$



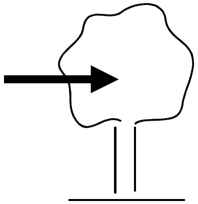
- the eccentric load induces a bending moment which is constant along the stem

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





5.1 Application of mechanics of materials

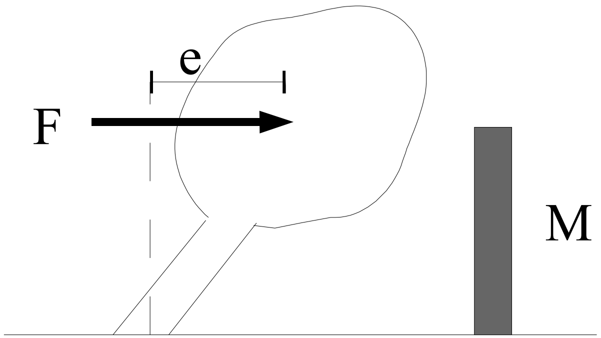


4. Flexure formula

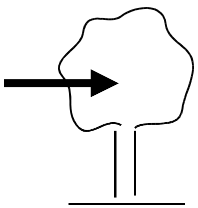
b) torsion moments

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

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



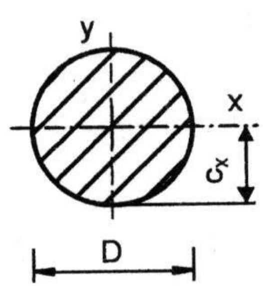
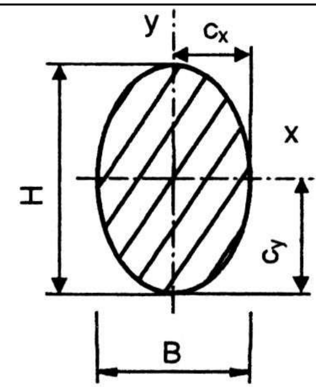
5.1 Application of mechanics of materials



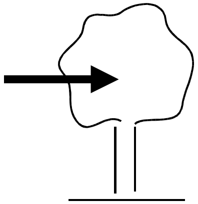
4. Flexure formula

c) section modulus

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

BENDING		TORQUE
		
$W = \frac{\pi D^3}{32}$	$W_x = \frac{\pi}{32} H^2 B$	$W_T = 2W$
	$W_y = \frac{\pi}{32} H B^2$	

5.1 Application of mechanics of materials

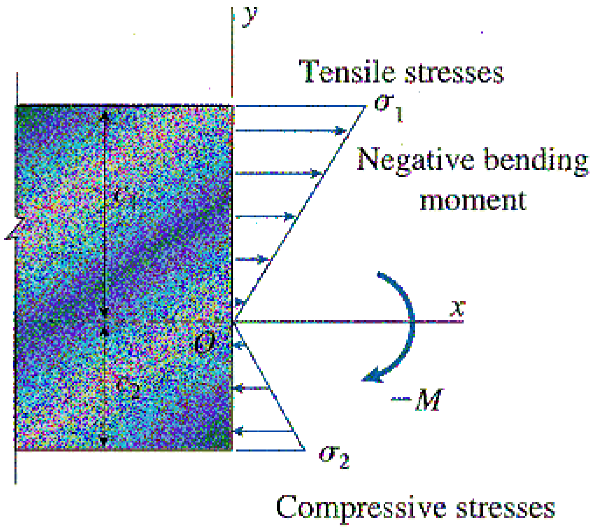


4. Flexure formula

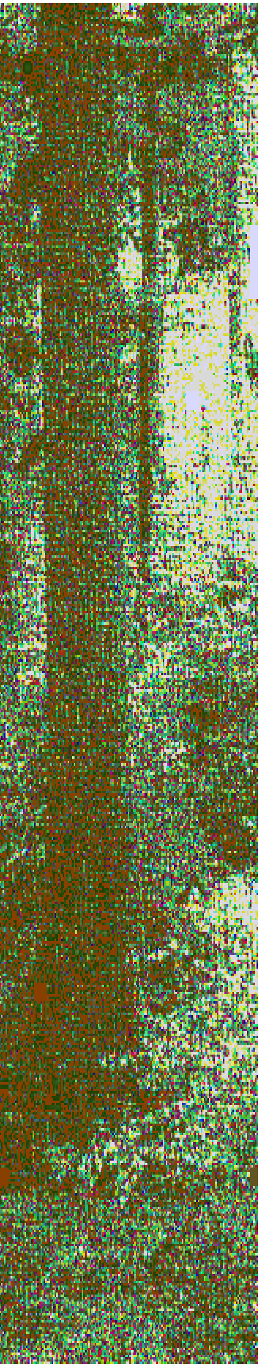
d) bending stress

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

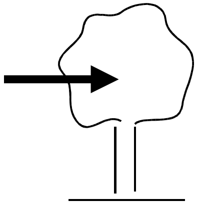
$$\sigma_{crown} = \frac{M_{crown}}{W}$$



- bending stress = RESISATNCE to BREAKAGE
- 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 stress at proportional limit – the stem will break.



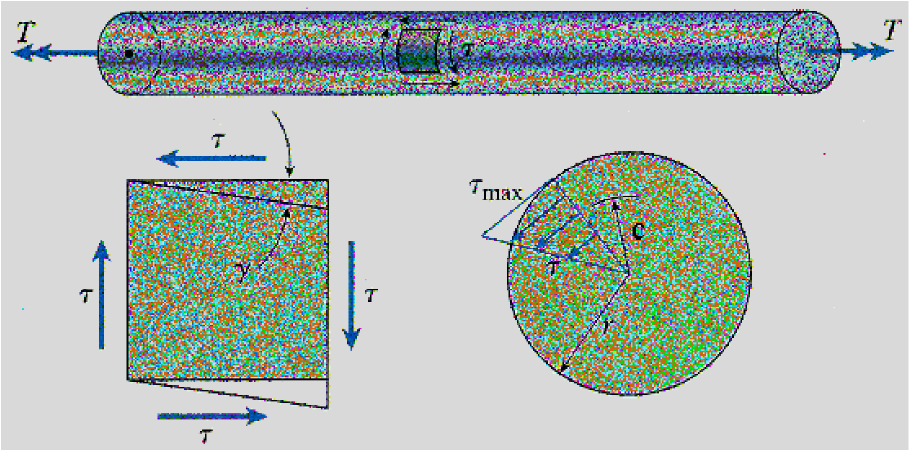
5.1 Application of mechanics of materials



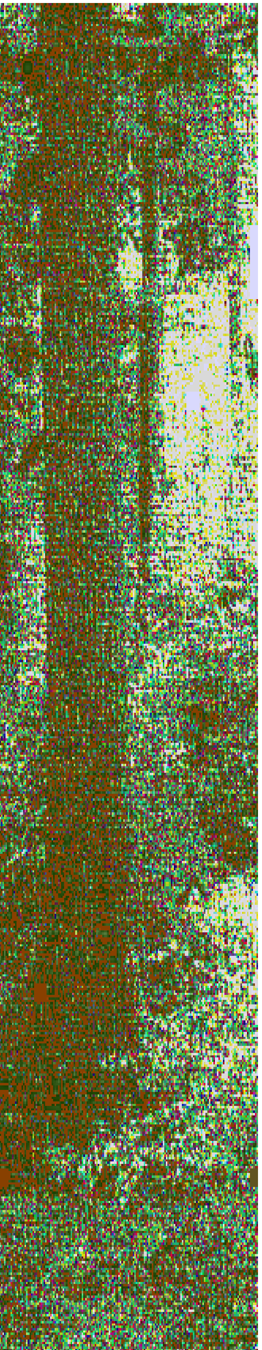
4. Flexure formula

e) torsion stress

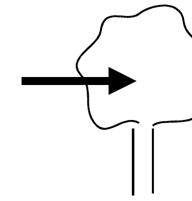
$$\tau_{wind} = \frac{T_{wind}}{W_T}$$



- torsion stress = RESISATNCE to BREAKAGE (TORQUE)
- 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 stress at proportional limit – the stem will break.



5.1 Application of mechanics of materials

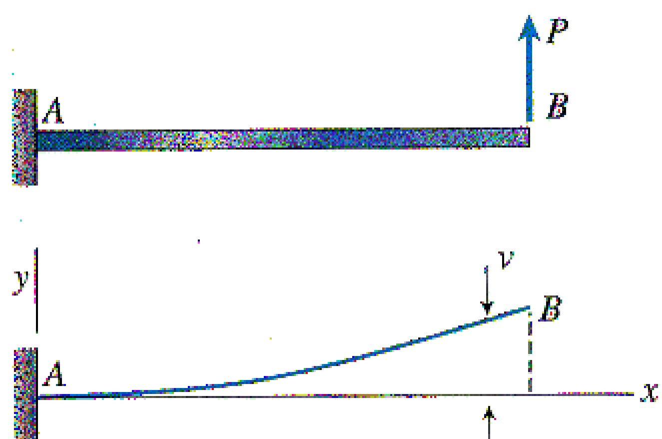


5. Deflection formula

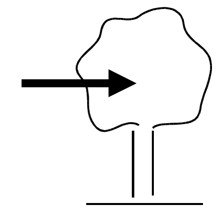
a) bending moment

- 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

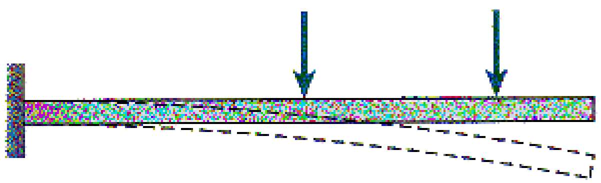
$$EI\frac{d^2v}{dx^2} = M$$



5.1 Application of mechanics of materials



5. Deflection formula



a) bending moment

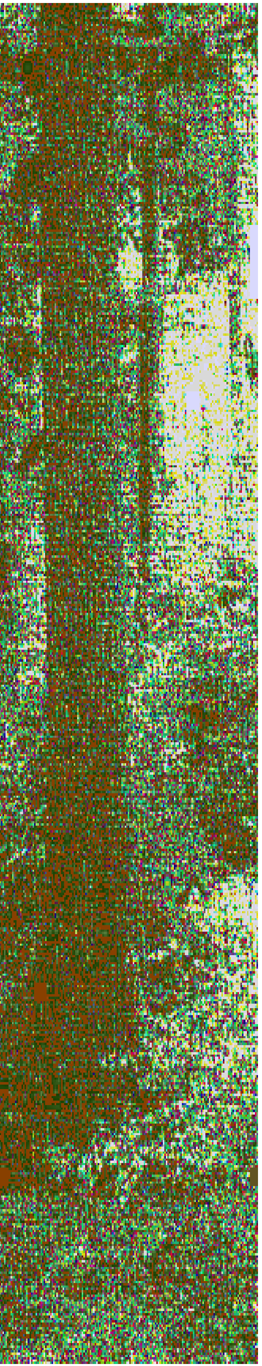
Key Terms

- 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

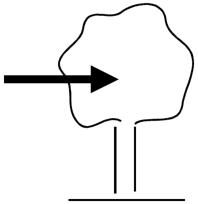
$$v = \frac{F x^2}{6 EI}(3L - x)$$

- 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)

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



5.1 Application of mechanics of materials



5. Deflection formula

a) bending moment

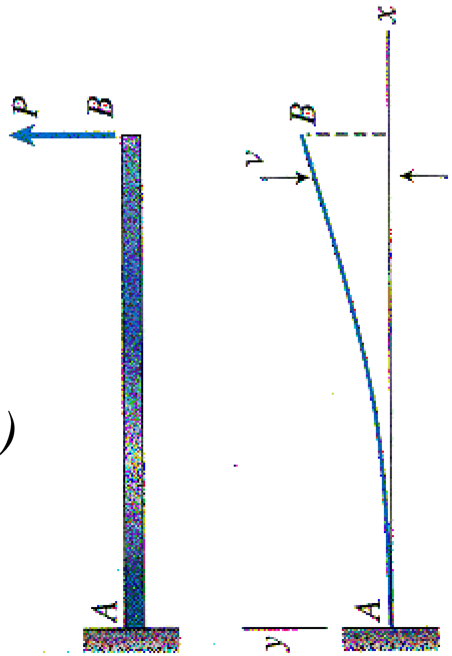
- deflection or angle of rotation = RESISTANCE TO OVERTURNING

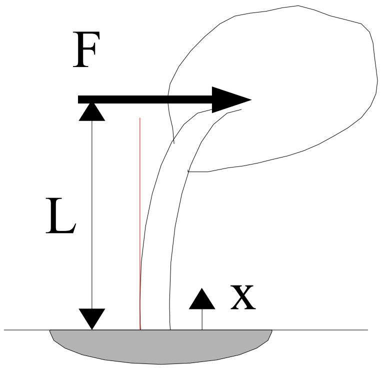
deflection of stem

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

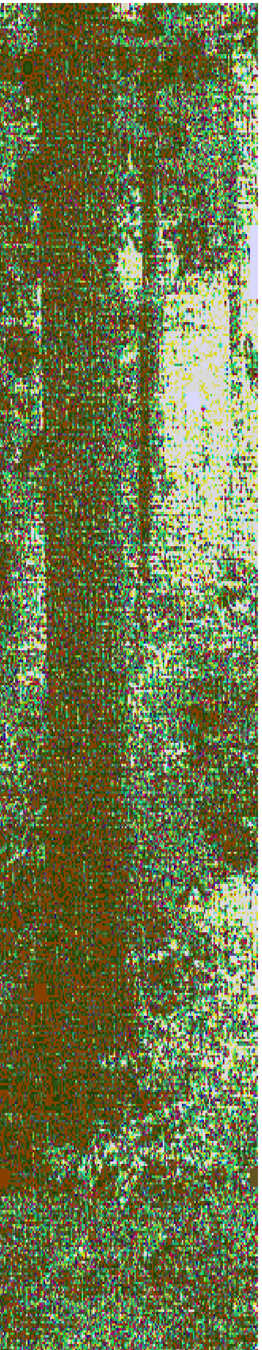
slope of deflection curve (angle)

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





5. Biomechanics of Tree



5.1 Application of mechanics of materials

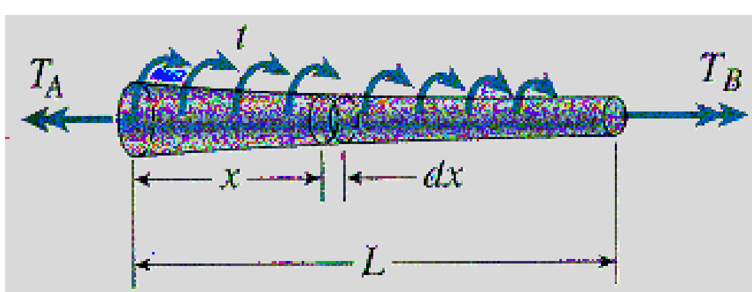
Remember ….

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%)

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

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



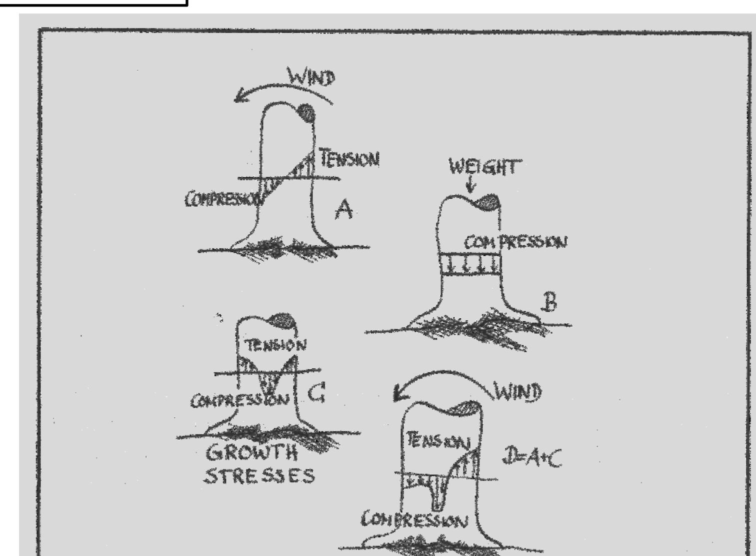
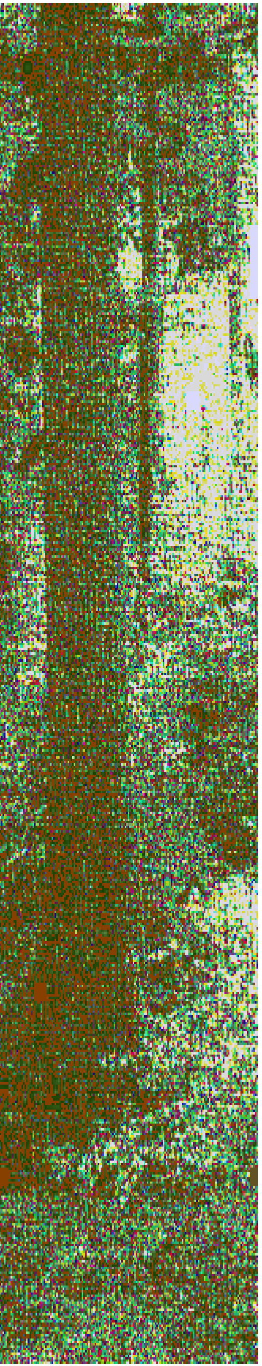


Figure 9: Main sources and effects of mechanical stresses acting in trees

5. Biomechanics of Tree



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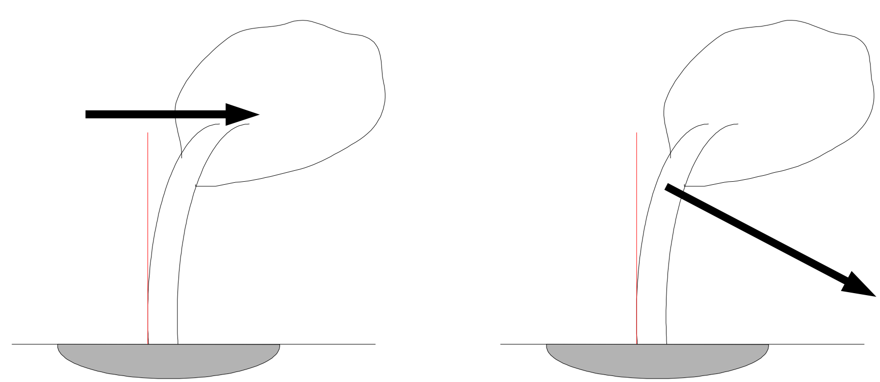
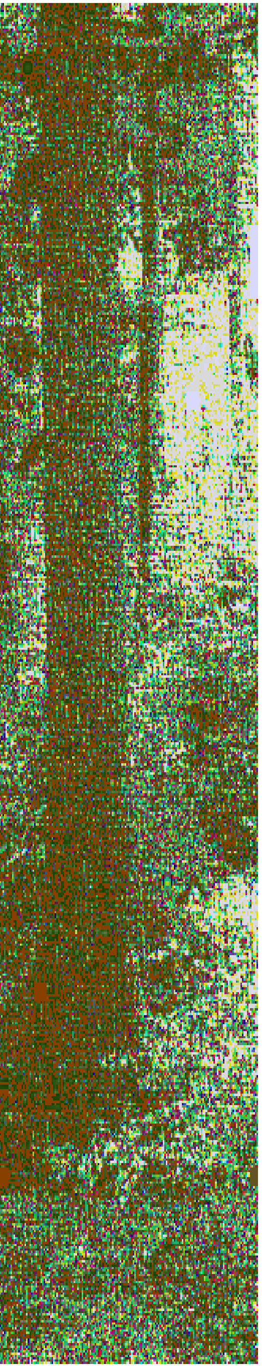
$$factor\ of\ safety = \frac{slope\ of\ deflection\ curve}{inclination\ of\ tree}\,100$$





5.2 Failure of tree

Objectives

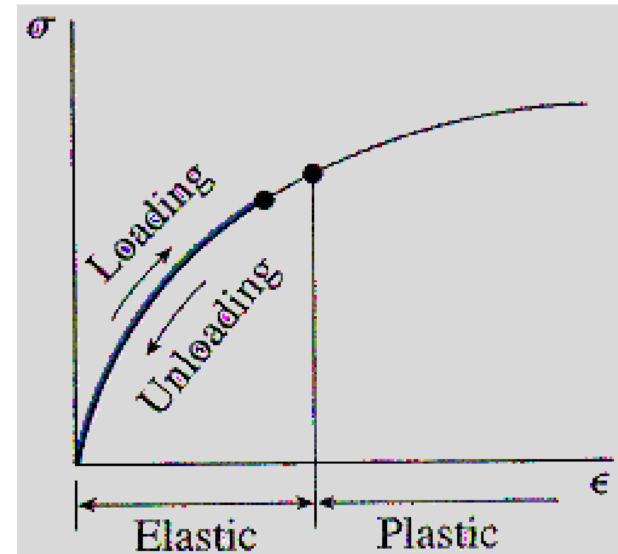
The objective is to determine the largest stresses anywhere in the structure.
No new theories are involved – only applications of previously derived formulas and concepts:

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



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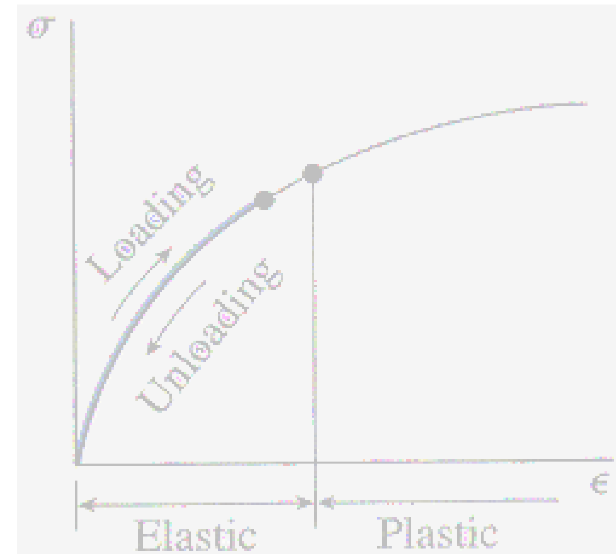
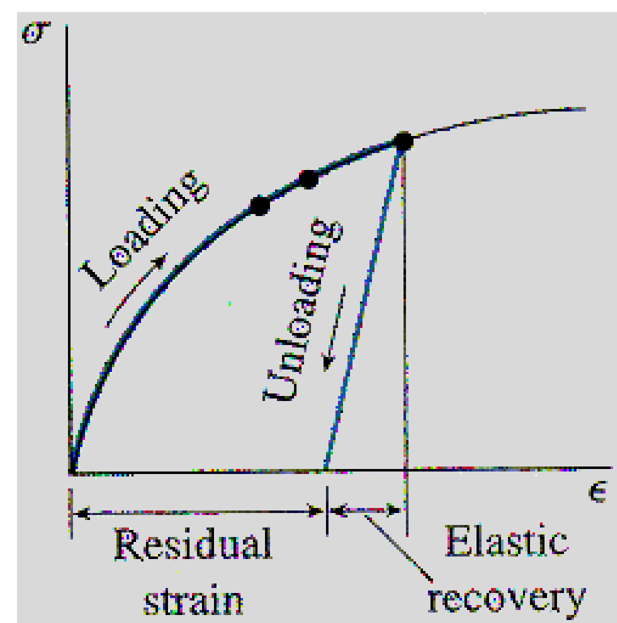


Residual Strain - the permanent strain exhibited in the material when the load is removed

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

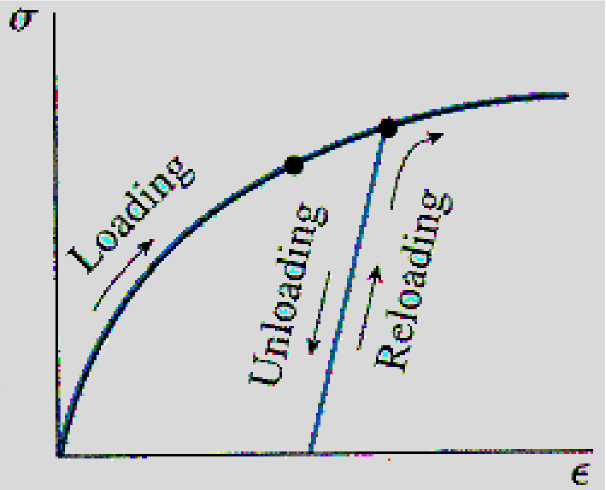
Plasticity - inelastic behavior of the material beyond the elastic limit



5.2 Failure of tree

Key Terms

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



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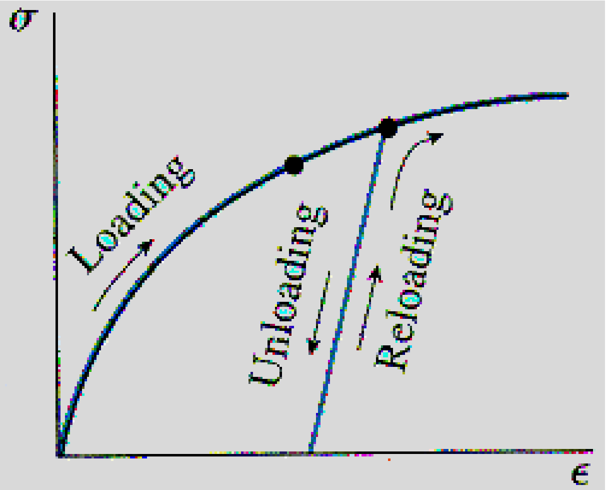


NOTE:

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)

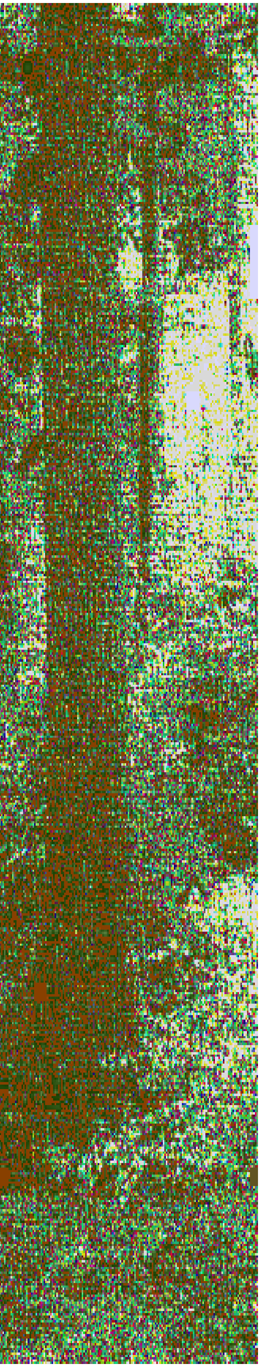
5.2 Failure of tree

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

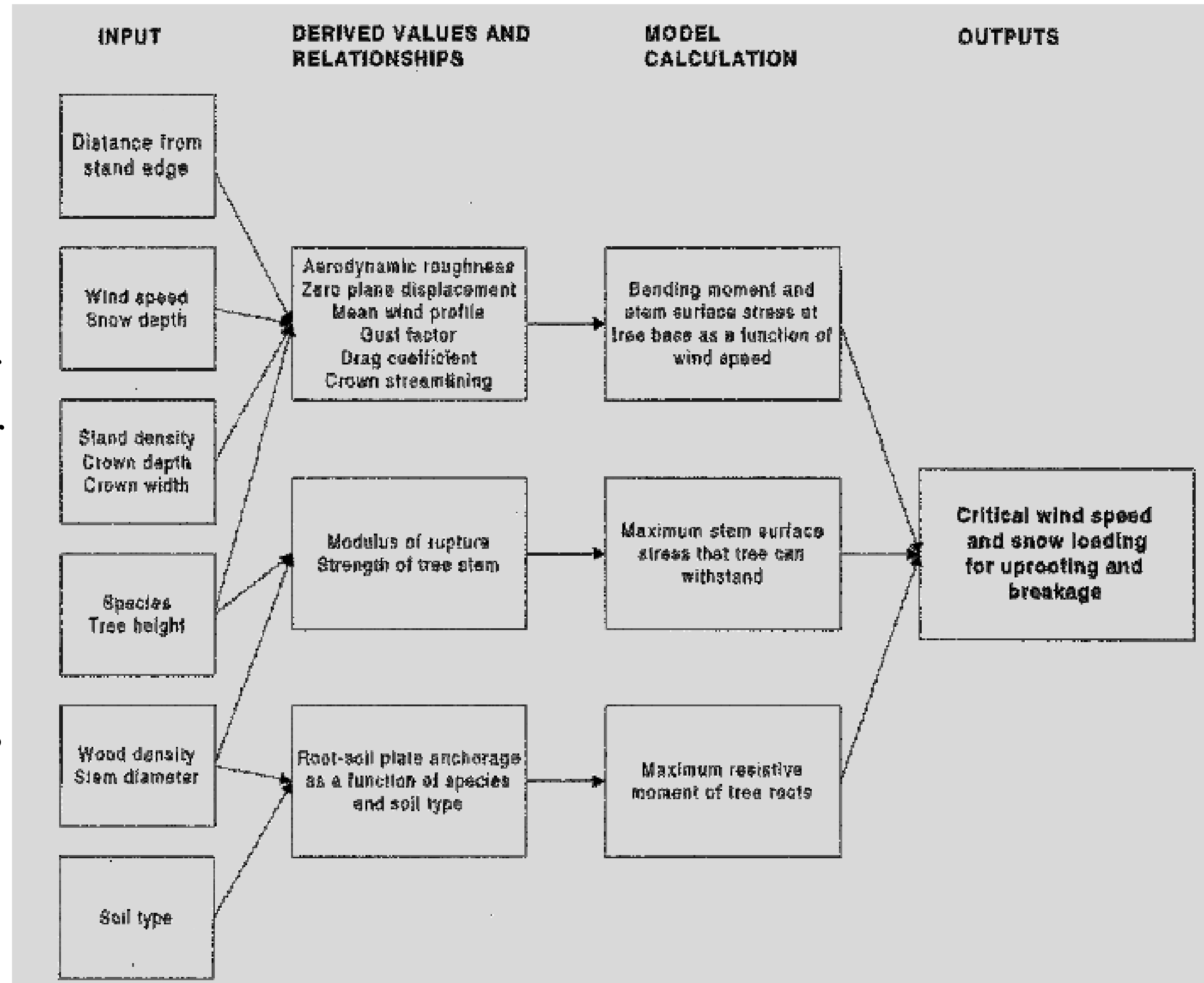
- Such an approach allows predictions of the impact of any arboricultural operations on tree stability and the design of strategies for reducing wind damage.

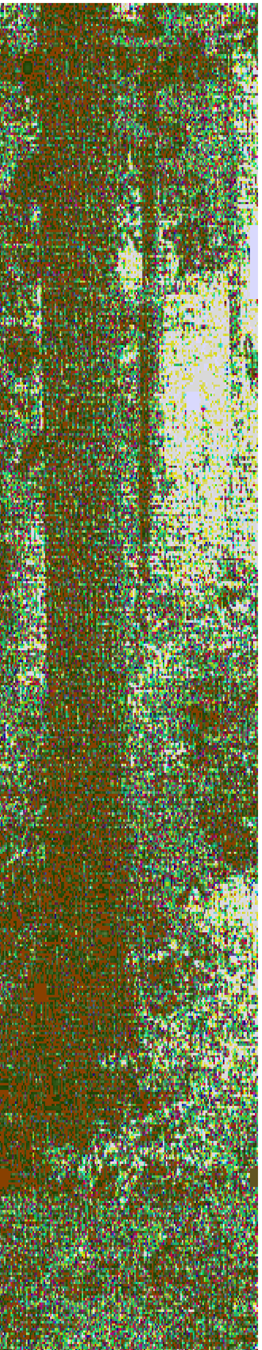


5.2 Failure of tree

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.

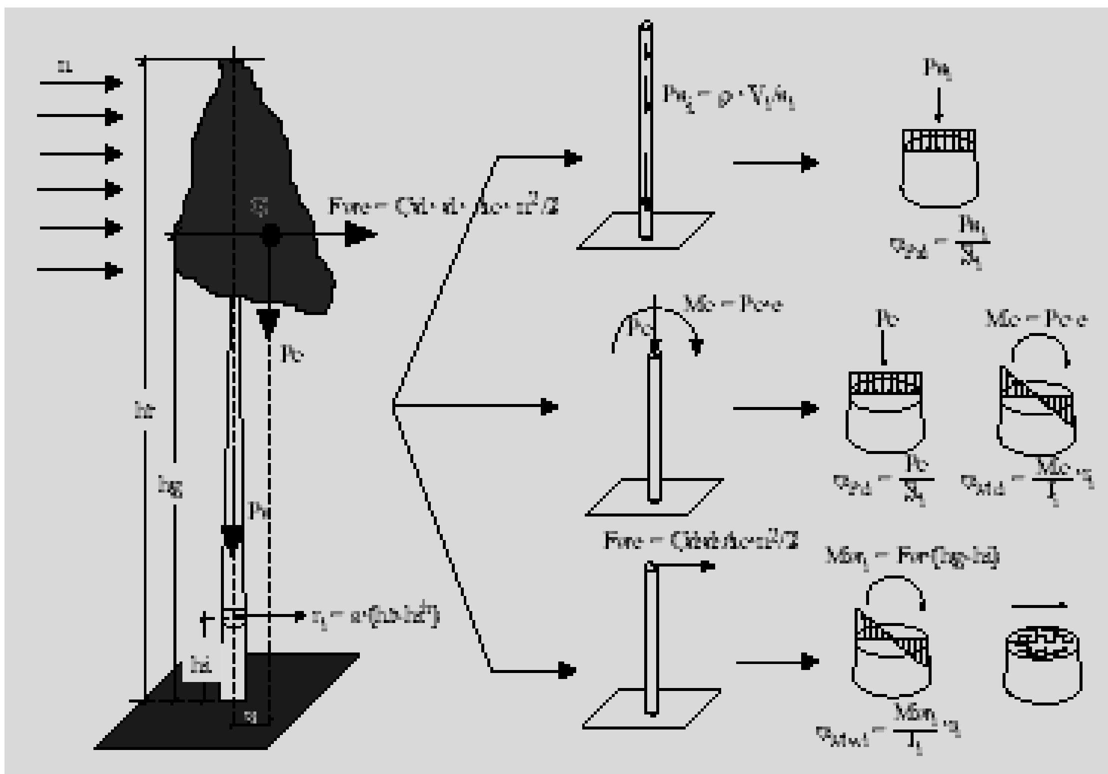




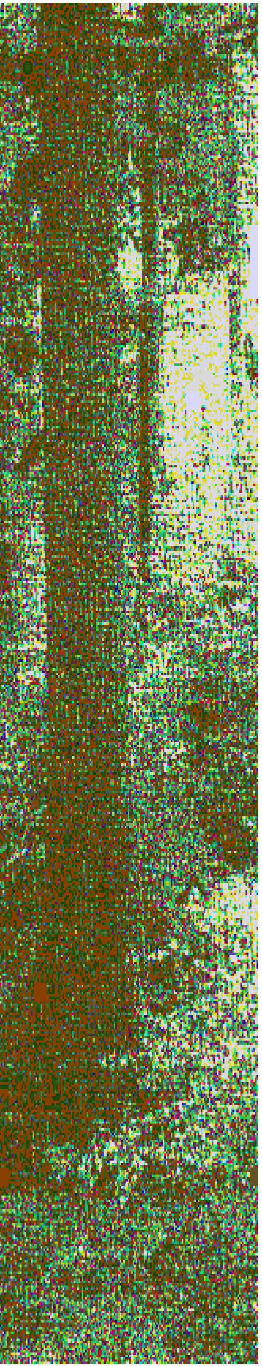
5.2 Failure of tree

Schematic representation of the mechanic model

Tree in consideration | Forces | Stresses | Sources | Loads



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



5. Biomechanics of Tree

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 stress at proportional limit in the outer fibres of lee side.

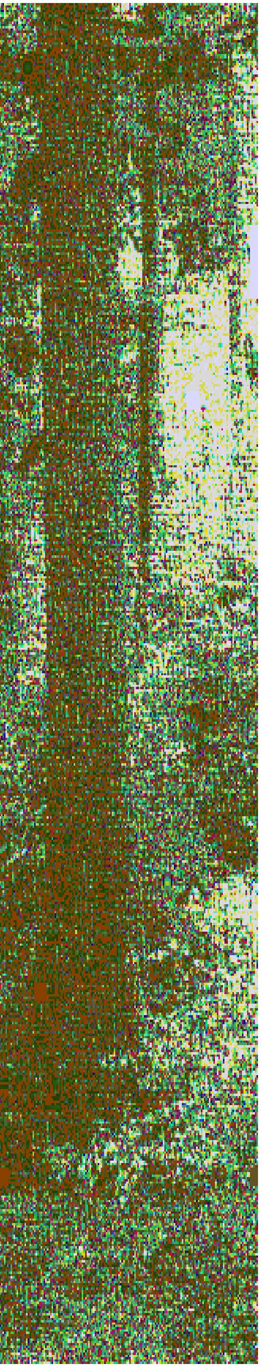
5. Biomechanics of Tree

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 stress 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.

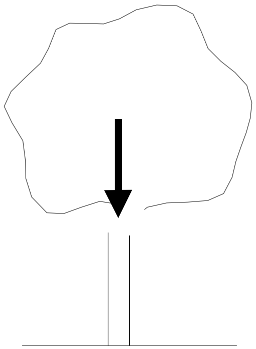


5.2 Failure of tree

Resistance to breakage

1. Tree as free-standing column

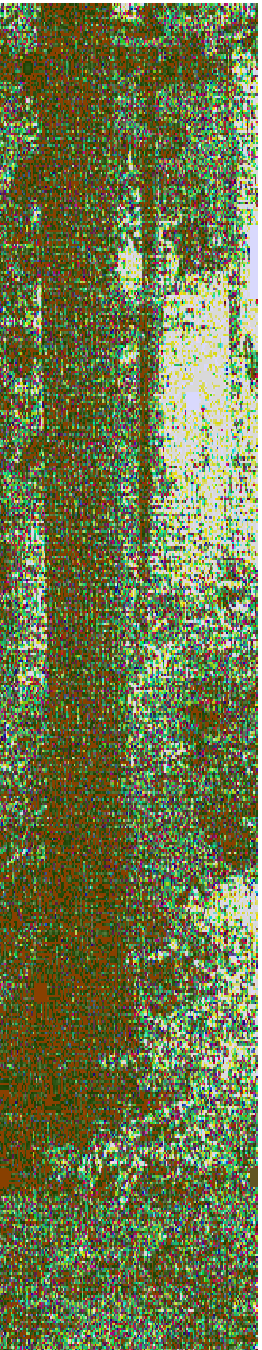
- Upright and free-standing column fixed at base
- Loaded by crown and stem mass (gravity)
- Can fail by
  a) compression or
  b) global buckling



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

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

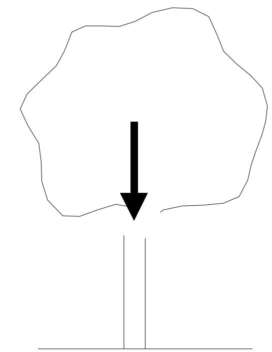
σ ≤ strength in compression



5.2 Failure of tree

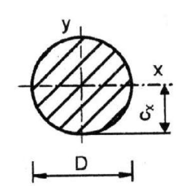
Resistance to breakage

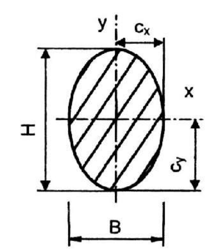
1. Tree as free-standing column



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

Load	**Area**
Function of tree hight = LENGTH (L)	Function of DIAMETER (D^2)





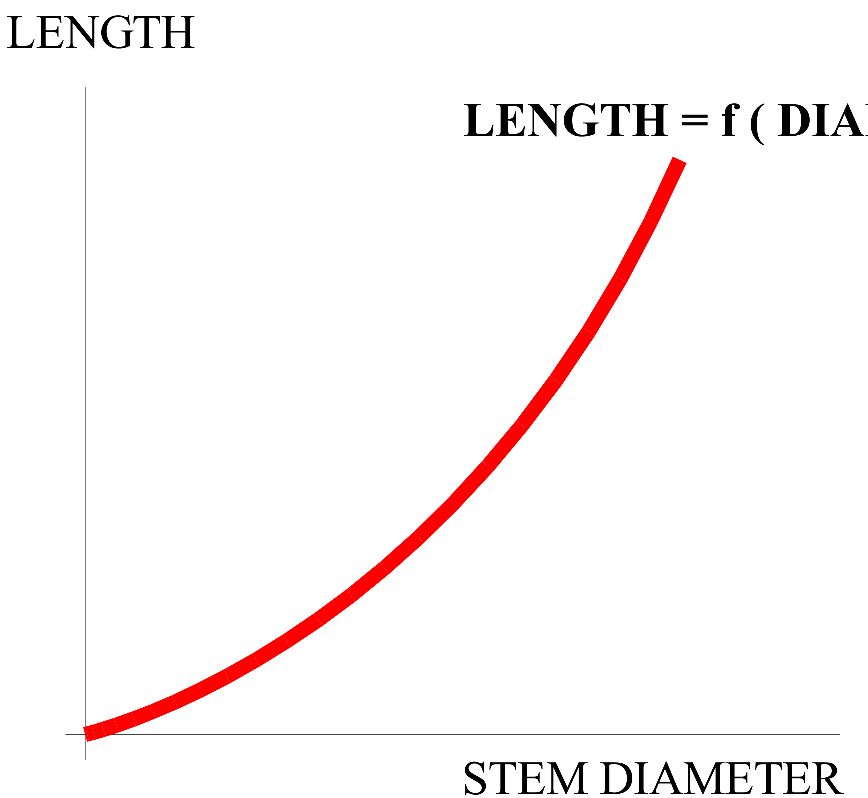
$$A = \frac{\pi}{4} D^2 \qquad A = \frac{\pi}{4} HB$$

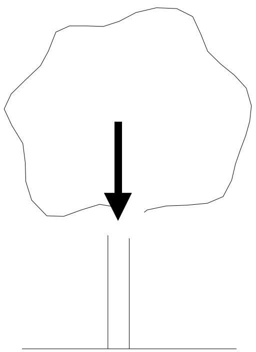
$$A = \frac{\pi}{4}\left(D^2 - d^2\right) \qquad A = \frac{\pi}{4}\left(HB - hb\right)$$

5.2 Failure of tree

Resistance to breakage

1. Tree as free-standing column



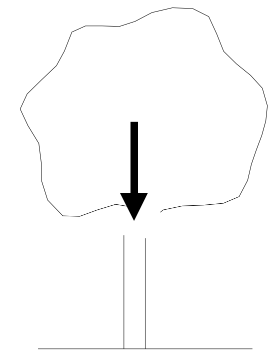


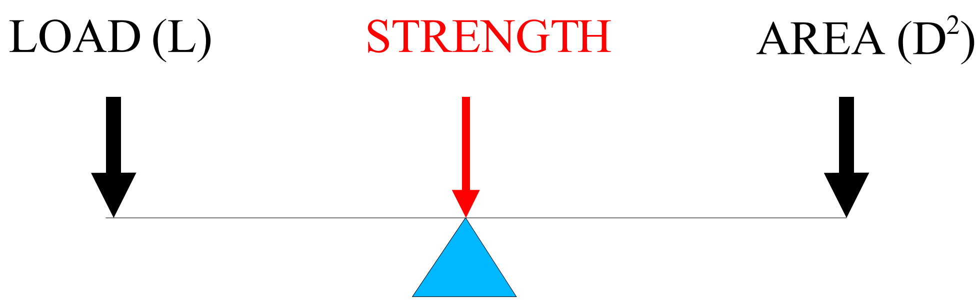
5.2 Failure of tree

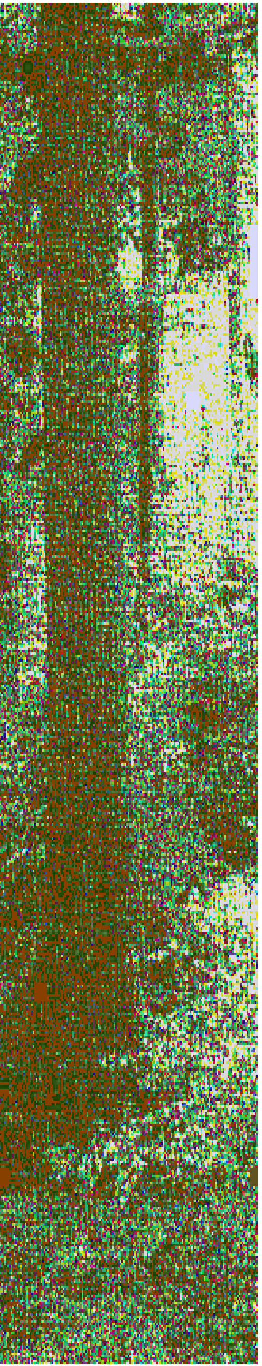
Resistance to breakage

1. Tree as free-standing column

LOAD = STRENGTH x AREA







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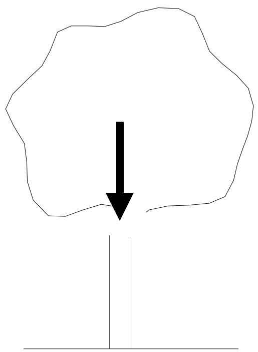

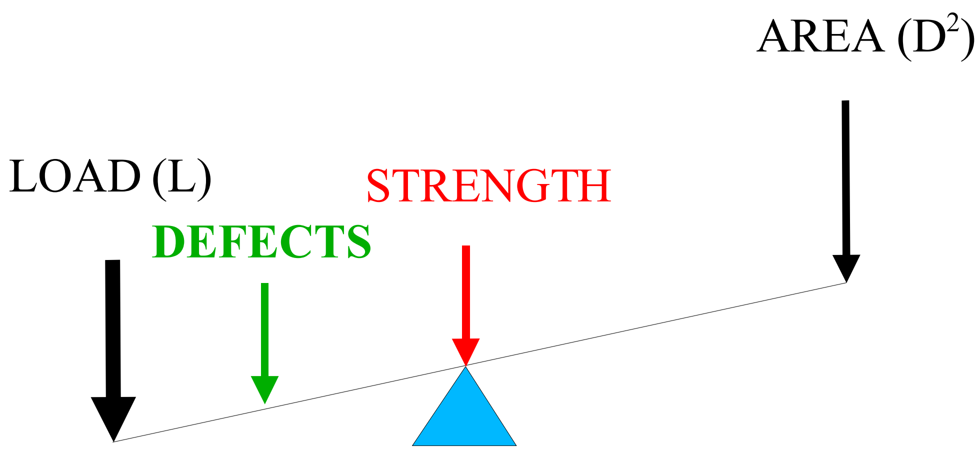

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Resistance to breakage

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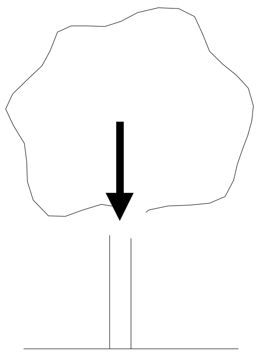
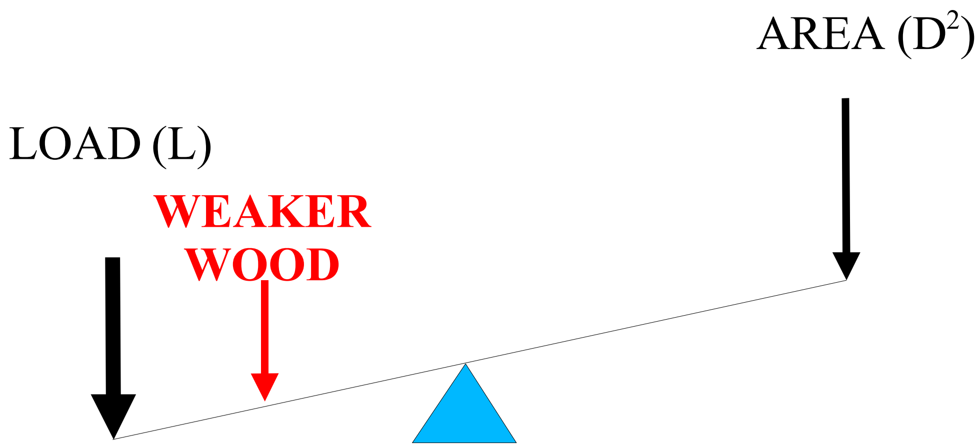




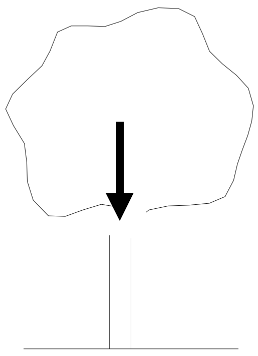
5. Biomechanics of Tree

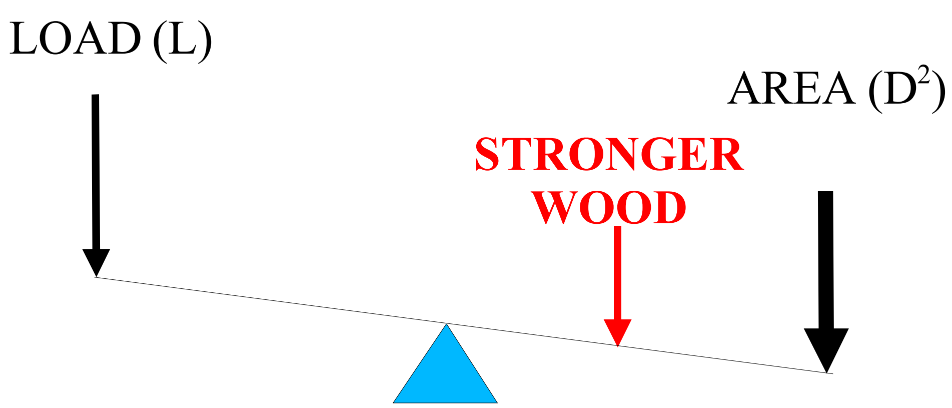
5.2 Failure of tree

Resistance to breakage

1. Tree as free-standing column

LOAD = STRENGTH x AREA

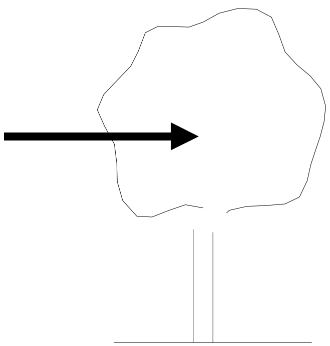




5.2 Failure of tree

Resistance to breakage

2. Tree as CANTILEVER



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

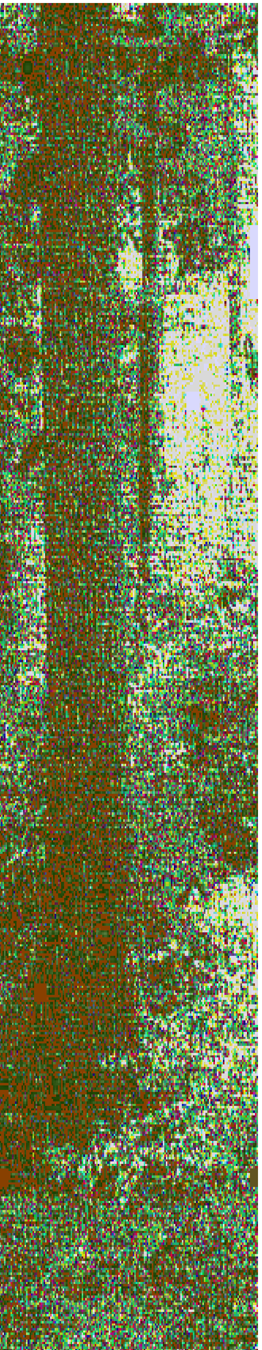
  a) bending or

  b) torsion

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

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

σ ≤ strength in compression OR shear



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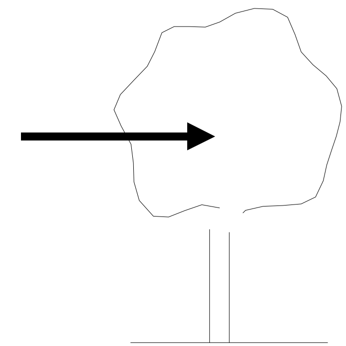
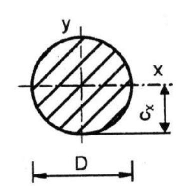
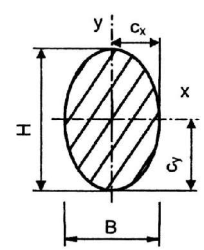
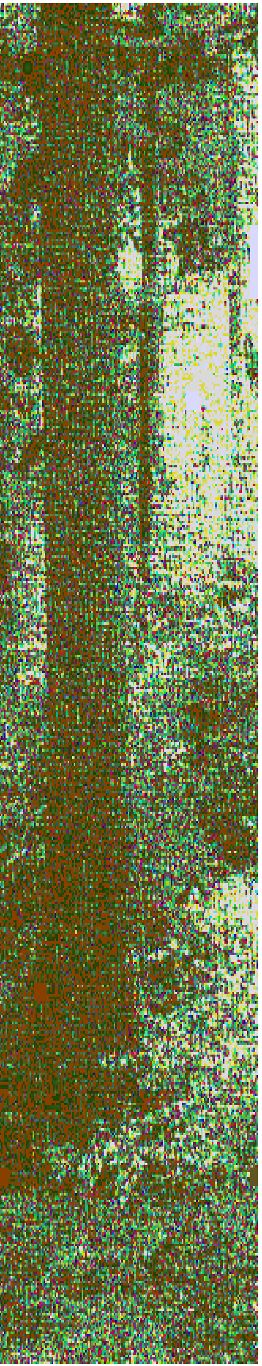


- Maximal stress ≤ strength in compression
- Strength is constant
- Resistance to breakage = balance between moment and area (section moduli)

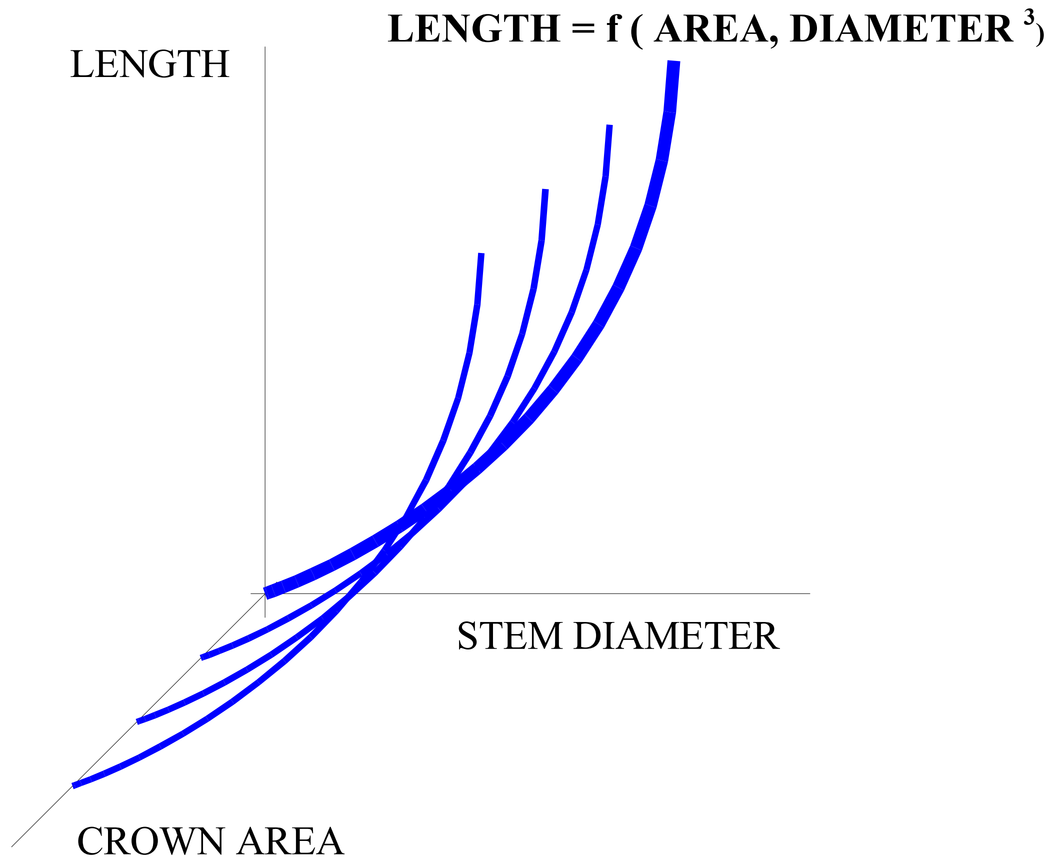
Moment	**Area**
$M = F\, h_{cg}$ $F_{wind} = \frac{1}{2} c_w \rho\, v_z^2 A$ Function of tree hight = LENGTH (L) and sail area = AREA (A)	  Function of DIAMETER (D^3) $W = \frac{\pi\, D^3}{32}$ $W = \frac{\pi}{32} \frac{D^4 - d^4}{D}$ $W_x = \frac{\pi}{32} H^2 B$ $W_x = \frac{\pi}{32} \frac{H^3 B - h^3 b}{H}$

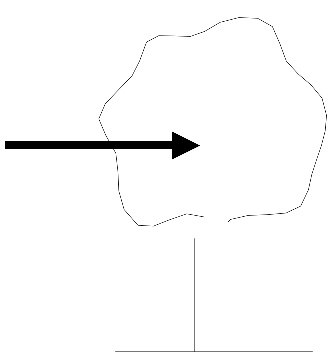


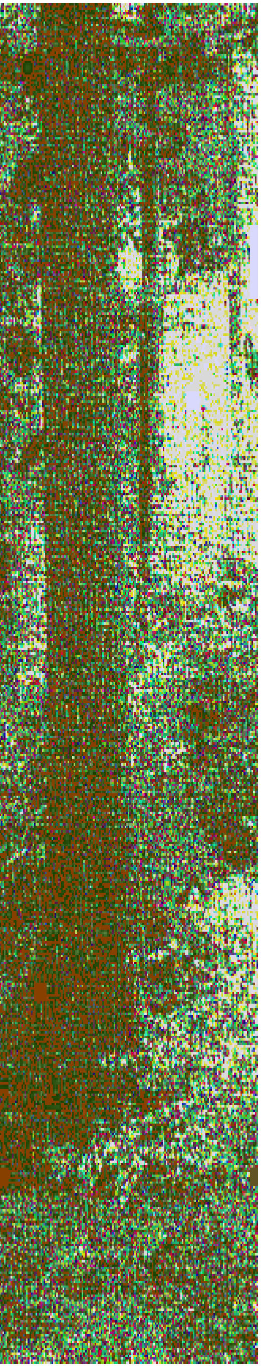
5.2 Failure of tree

Resistance to breakage

2. Tree as CANTILEVER





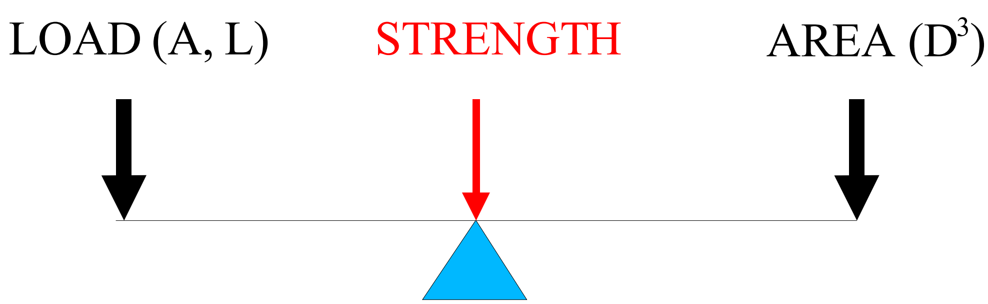


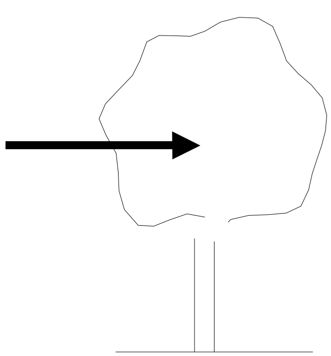
5.2 Failure of tree

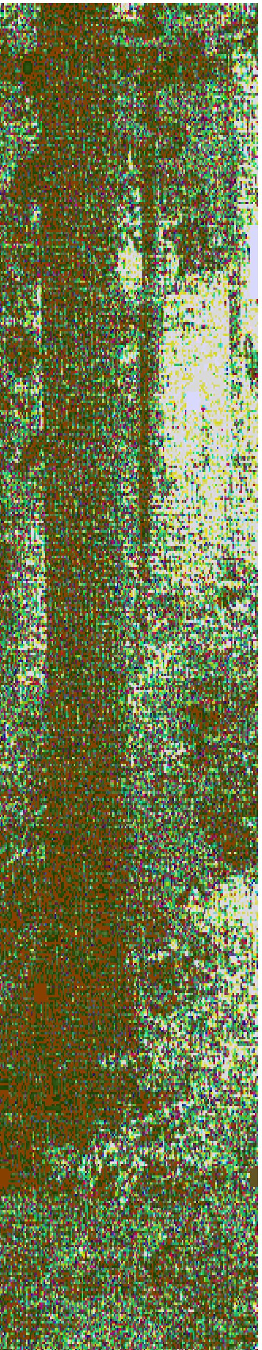
Resistance to breakage

2. Tree as CANTILEVER

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







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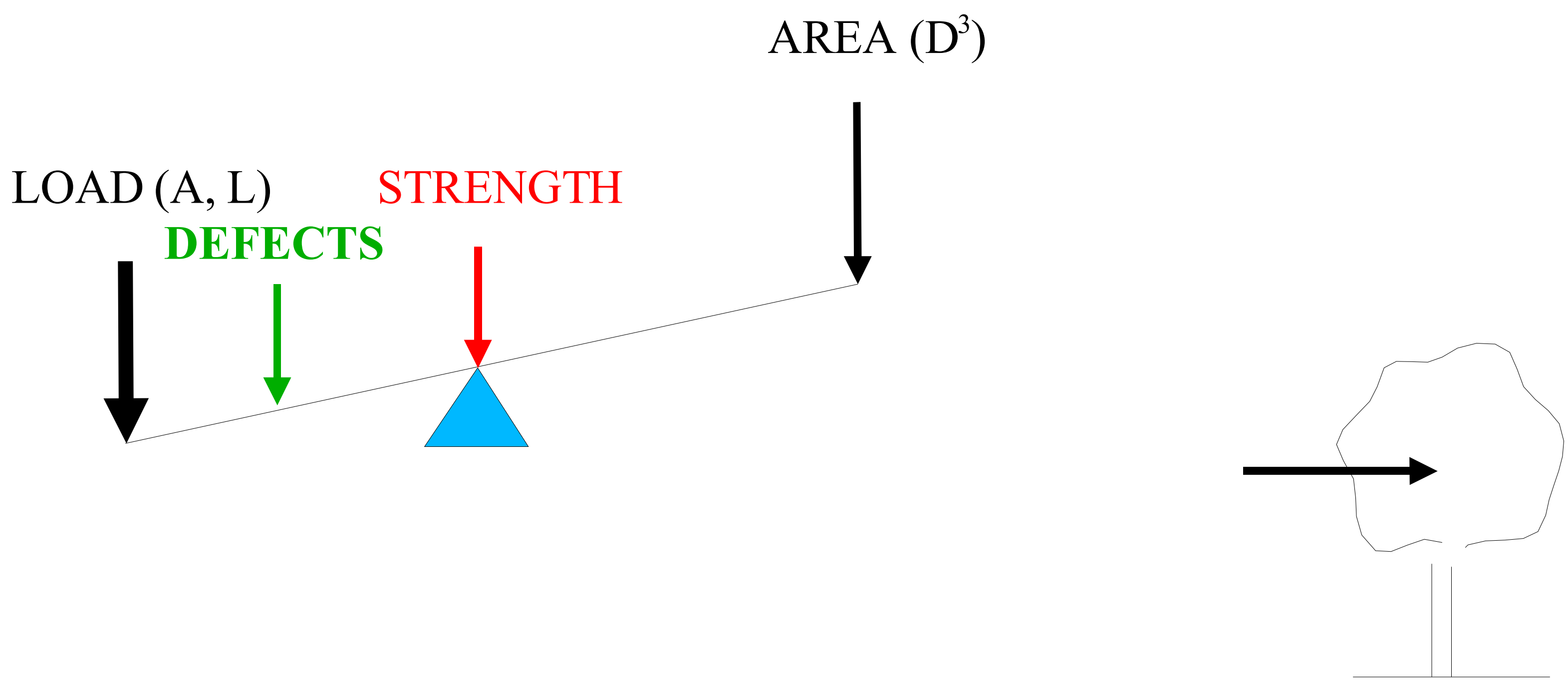

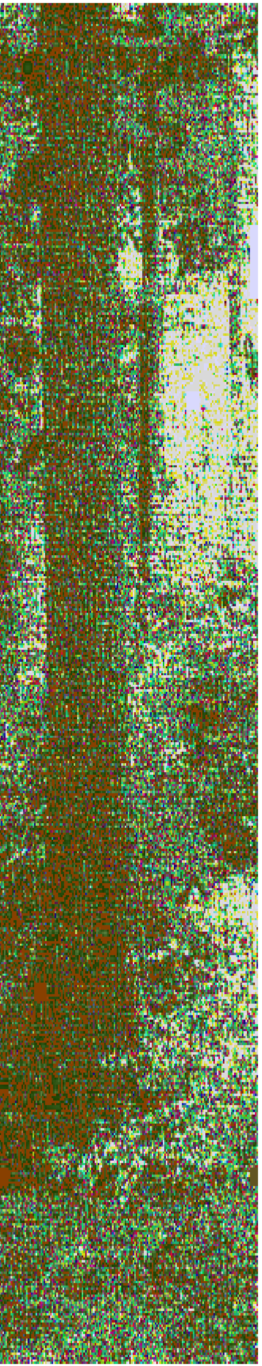

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Resistance to breakage

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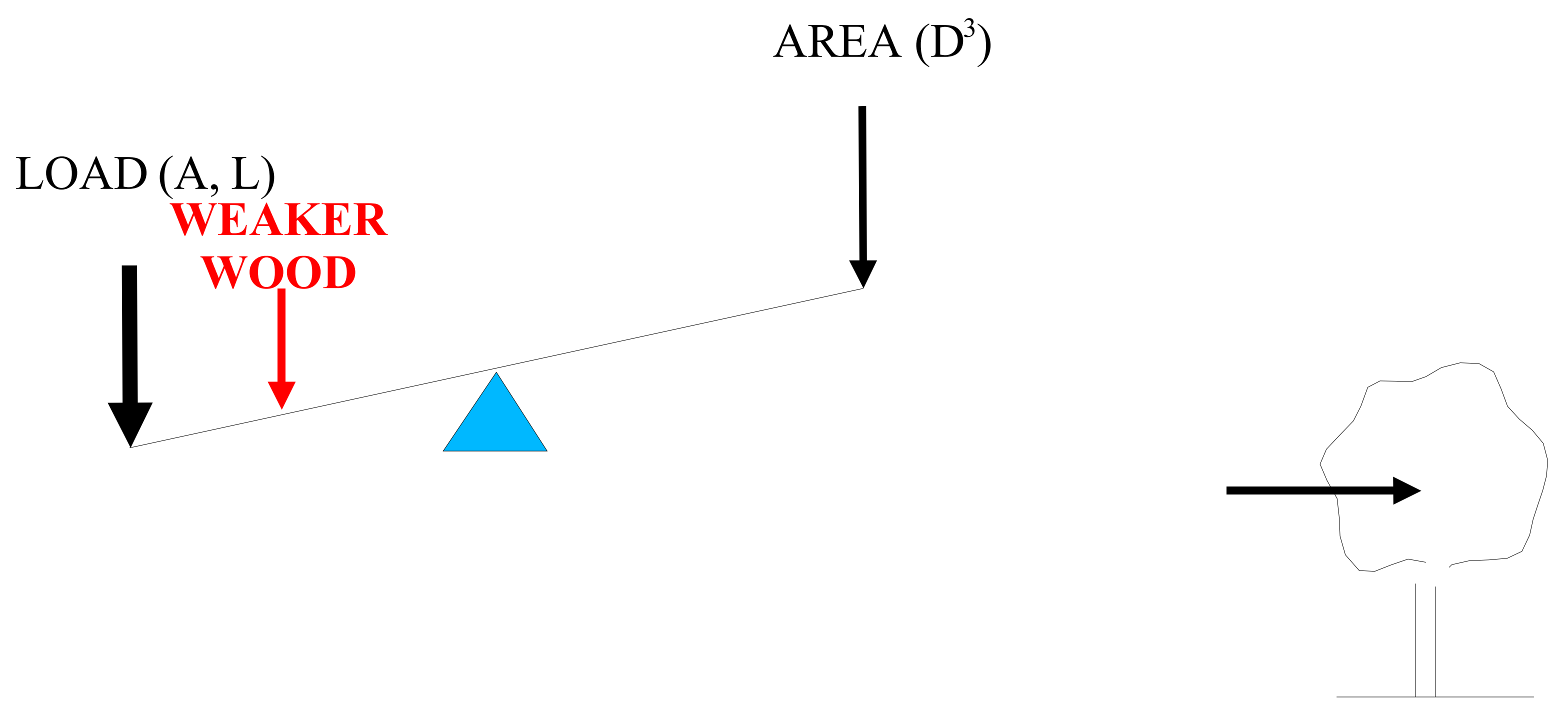

5.2 Failure of tree

Resistance to breakage

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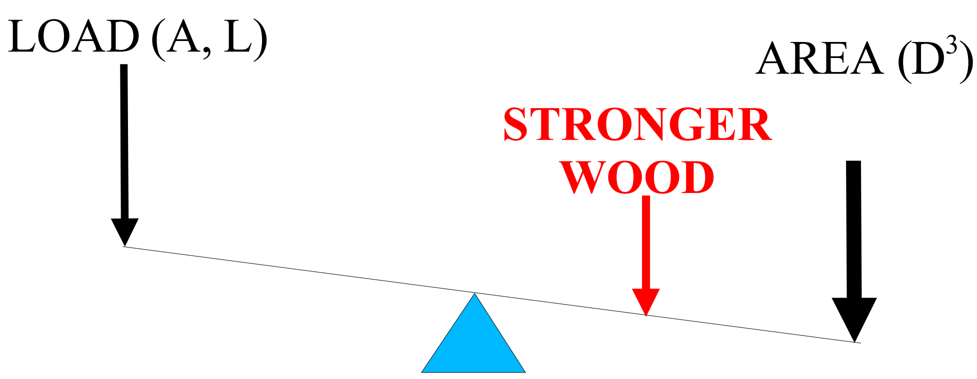
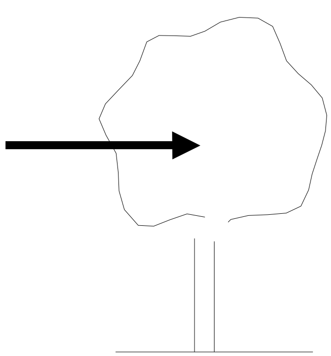
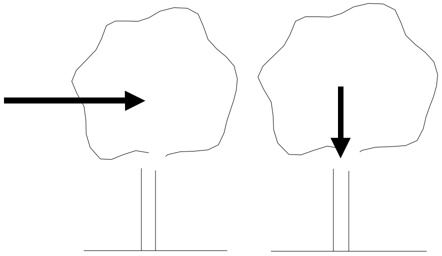


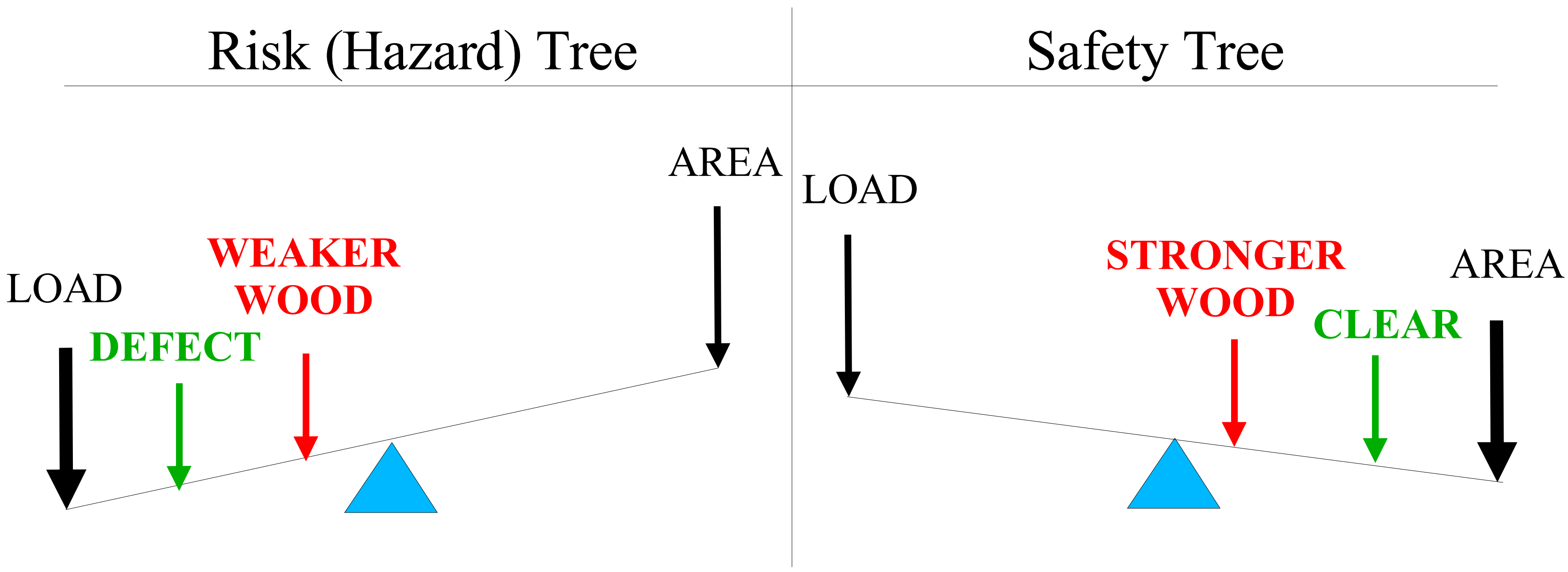


5.2 Failure of tree

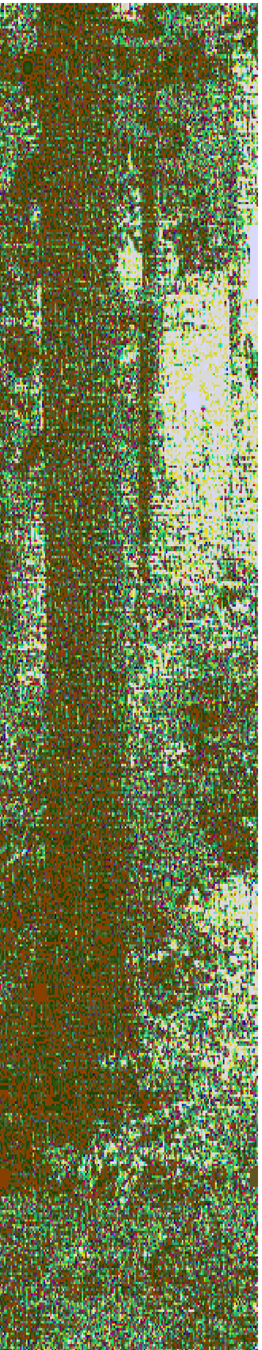
Resistance to breakage

CONCLUSION



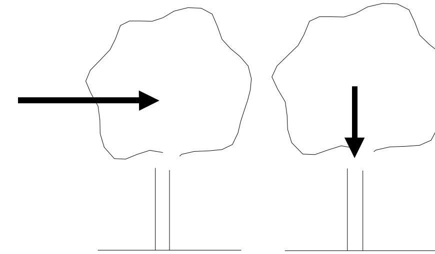


SIA – LOAD (tree hight) and AREA
SIM – WOOD STRENGTH and DEFECTS



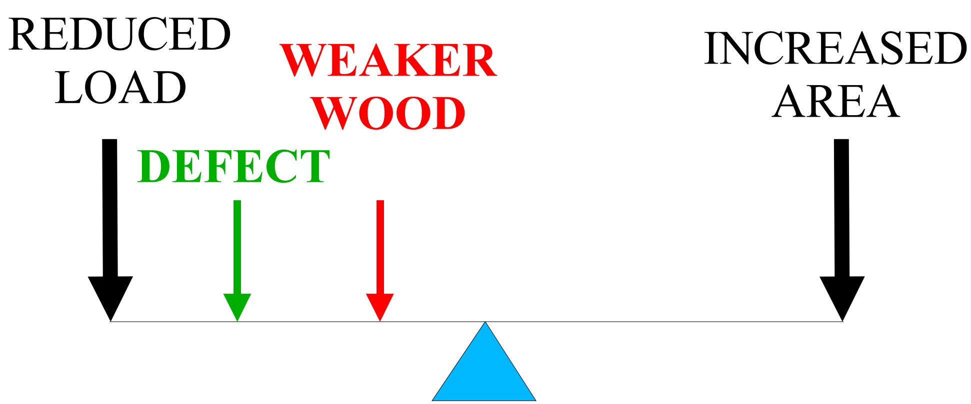
5.2 Failure of tree

Resistance to breakage

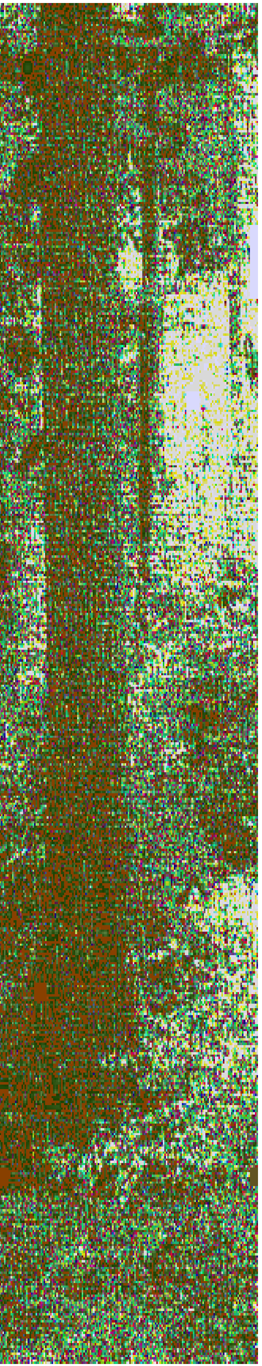


CONCLUSION

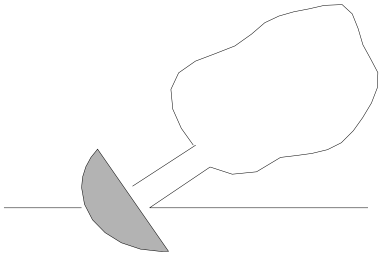
Risk (Hazard) Tree → Safety Tree



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



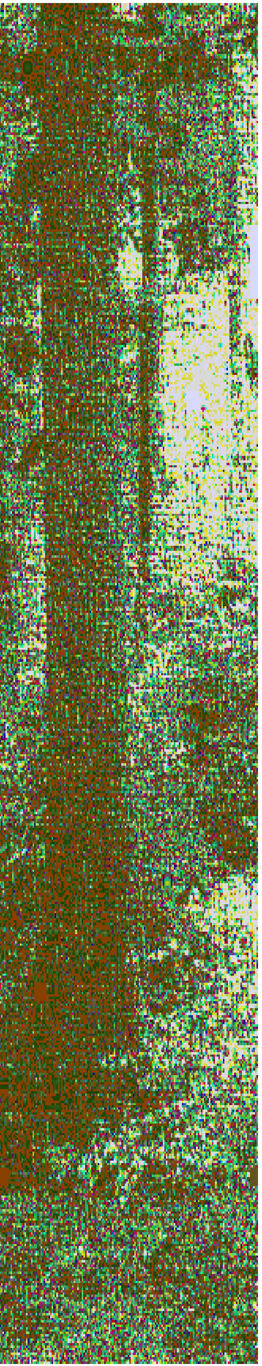
5.2 Failure of tree



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.



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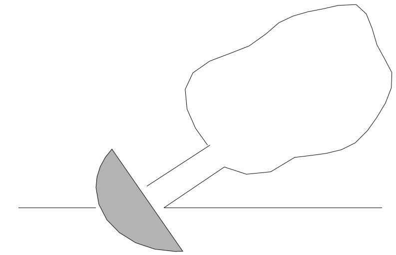
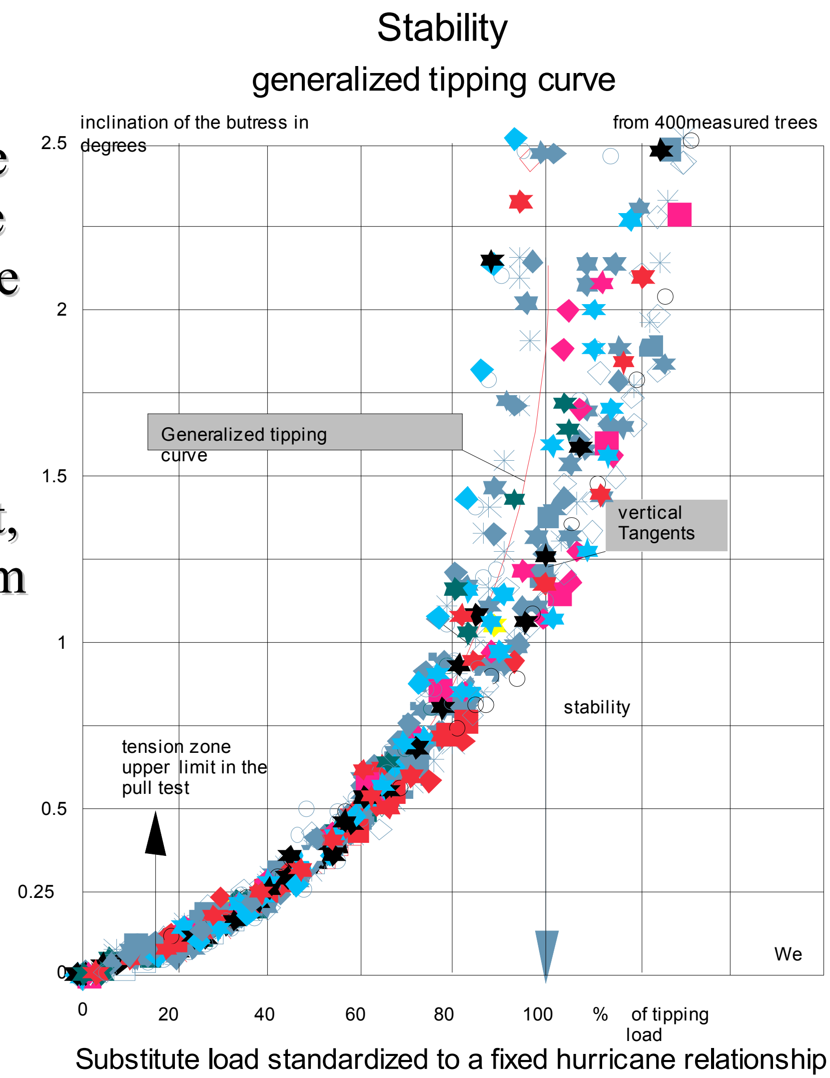


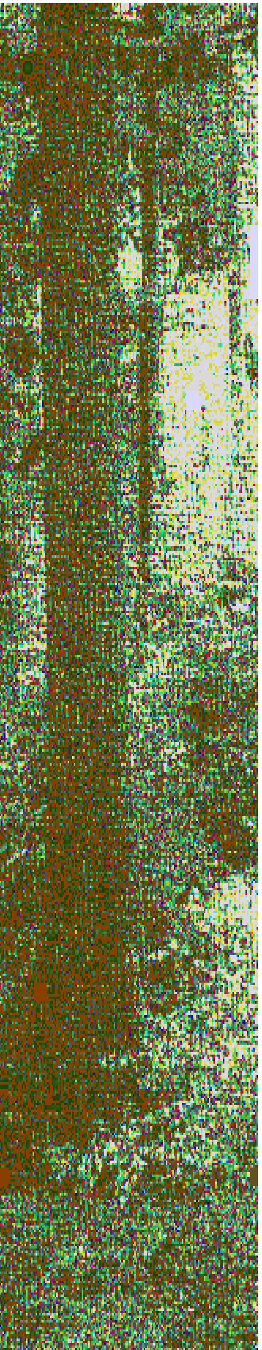
Resistance to overturning (uprooting)

1. Tree as CANTILEVER

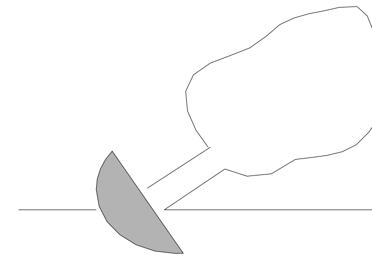
If the uprooting moment exceeds the resistive bending moment of the tree at a particular *angle of deflection*, the tree will deflect further.
The tree will give way if the uprooting moment exceeds its maximum resistive bending moment, with the relative strengths of the stem and roots determining the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



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.

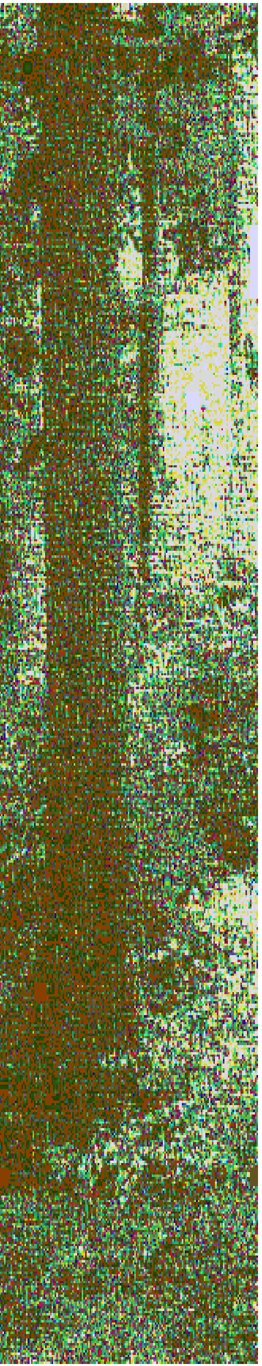
3. This means that (1) load, (2) material and (3) geometry must be known in order to solve the statics equation.

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:

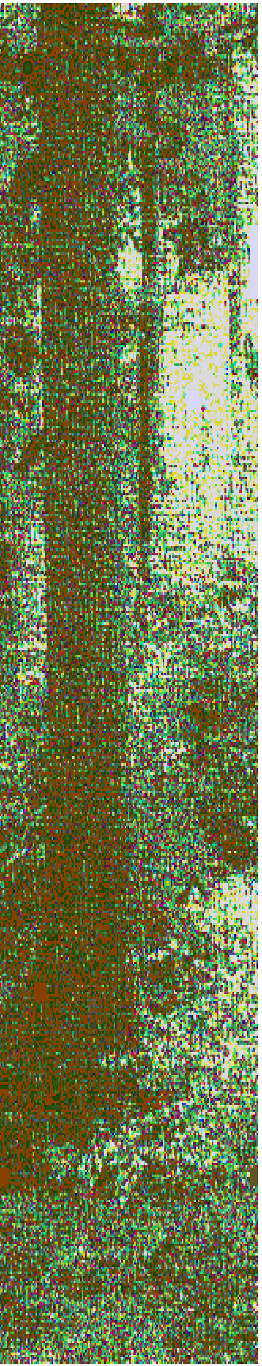
- the height, diameter, and shape of the bole
- the crown class and size of crown
- the strength and elasticity of the bole, branches, and needles
- the rooting depth and area, size and number of roots, and whether or not adjacent tree root systems interlock
- the tree defects

5.3 Factors influencing tree stability

2. Stand Level Characteristics

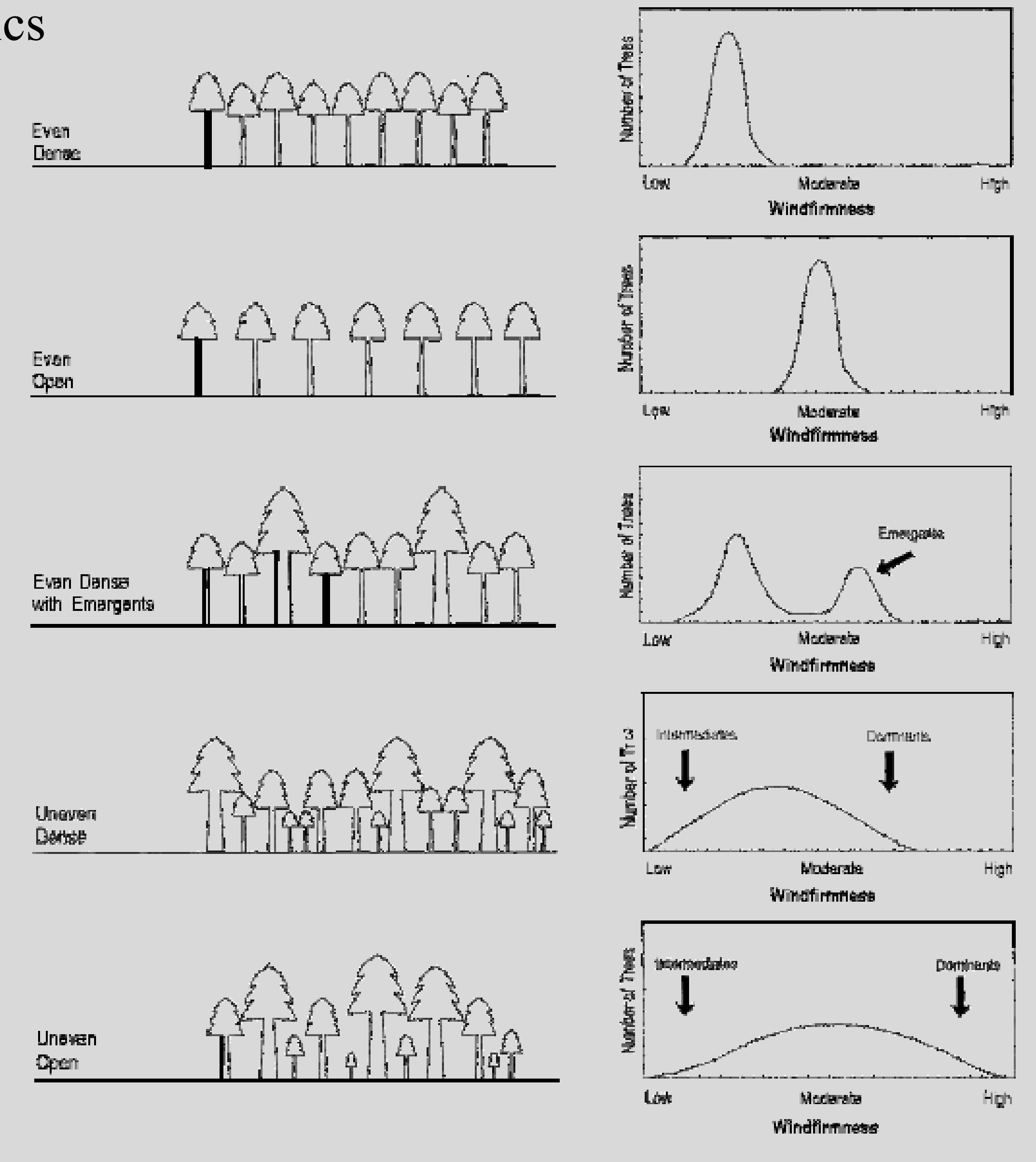
At the *stand level,* individual trees can be made more or less prone to windthrow through the effects of:

- 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



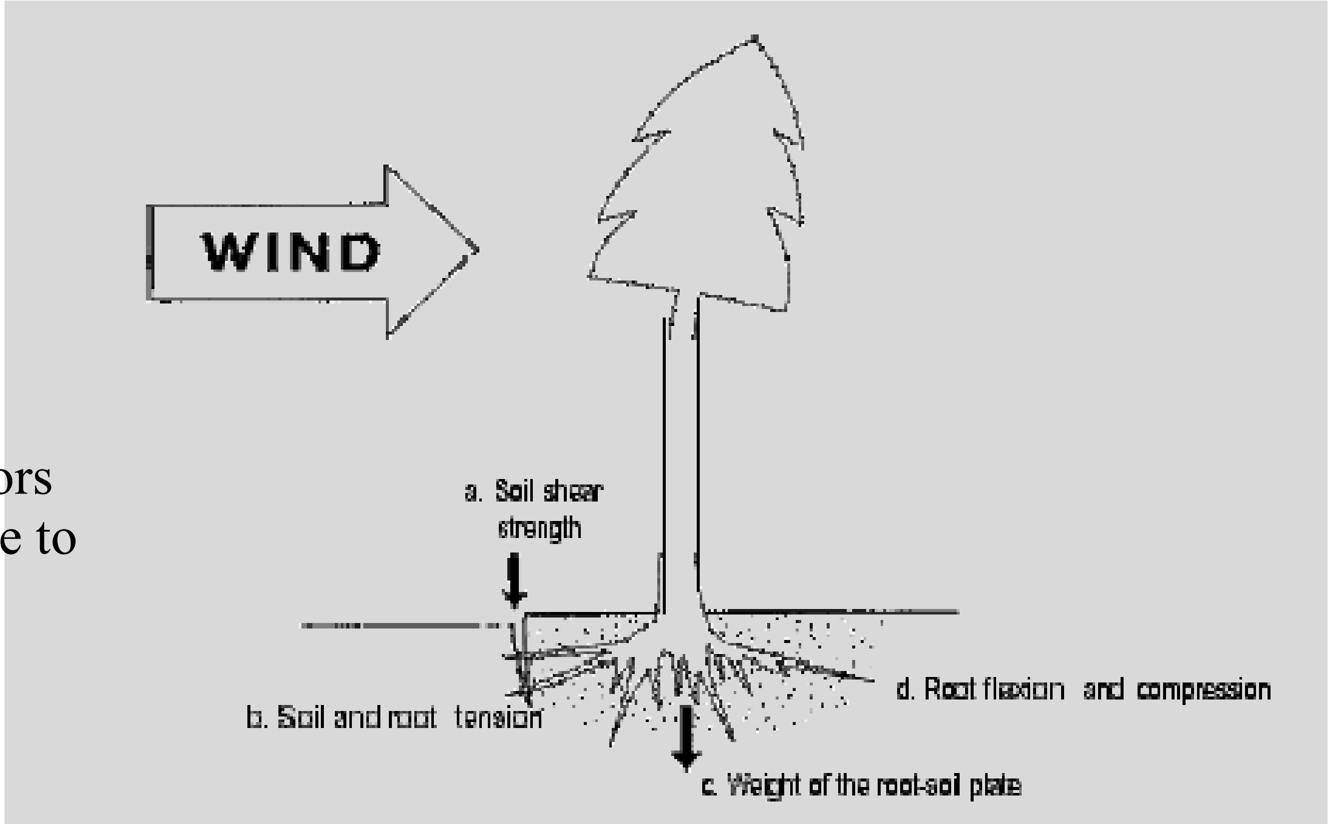
A comparison of distributions of the relative windfirmness of individual trees comprising stands with different structural characteristics.

5.3 Factors influencing tree stability

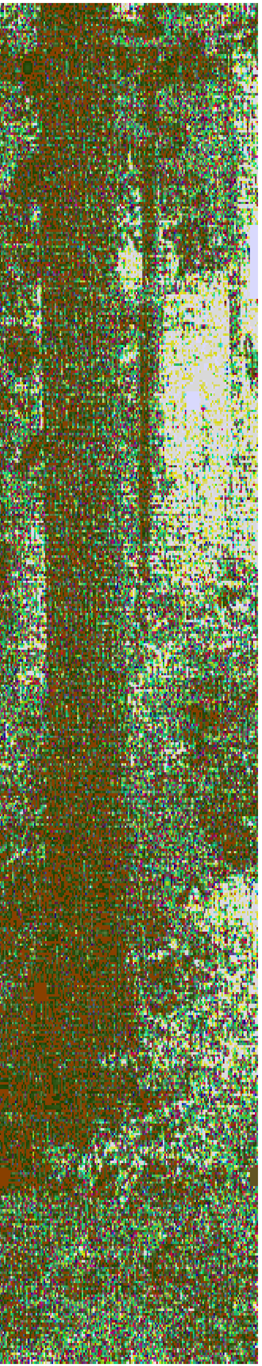
3. Soil Characteristics

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

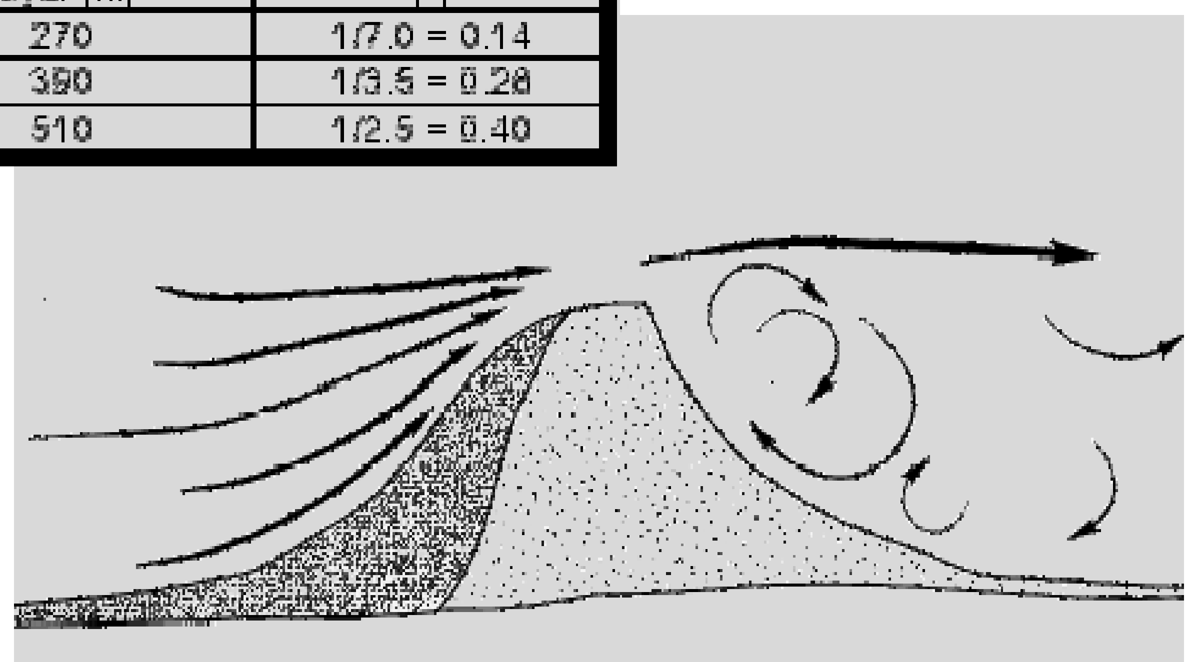
Topographic characteristics affect windthrow by modifying:

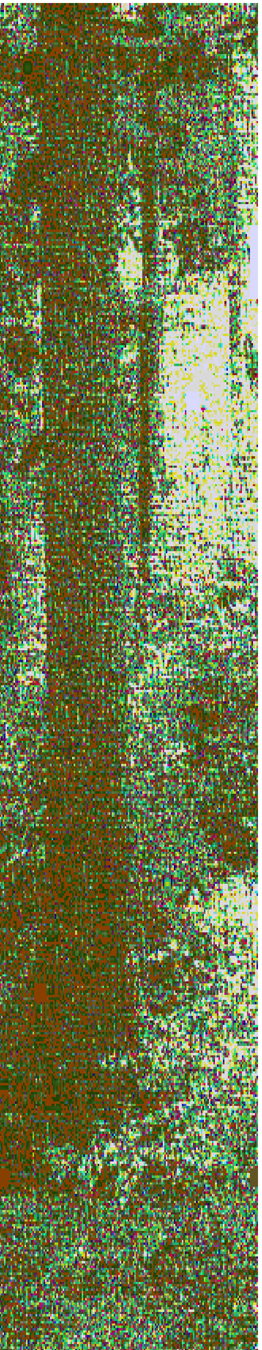
- wind exposure
- wind direction, speed and turbulence.

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.

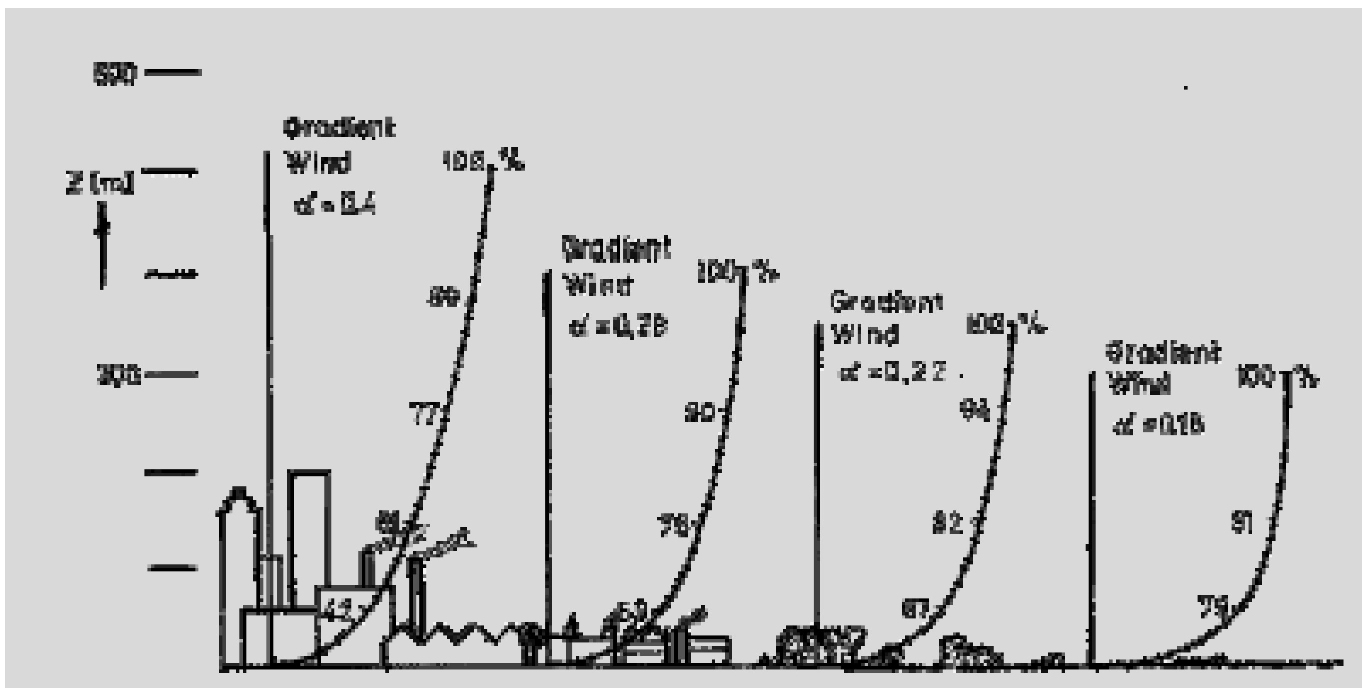




5.3 Factors influencing tree stability

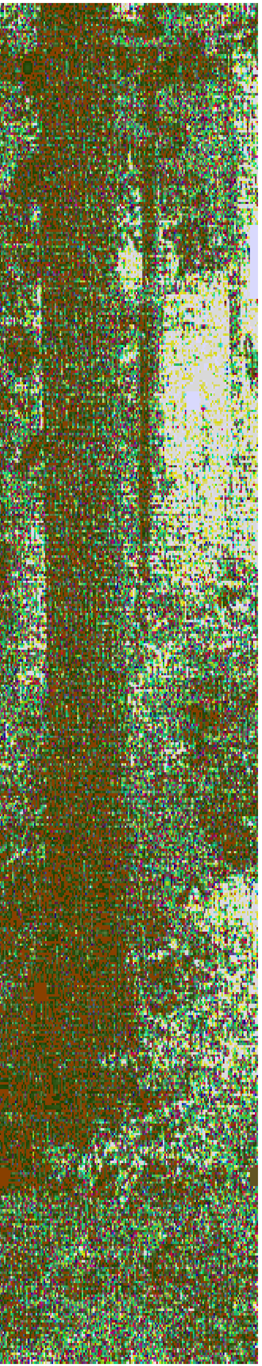
4. Topographic Characteristics

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. Biomechanics of Tree



5.3 Factors influencing tree stability

4. Topographic Characteristics

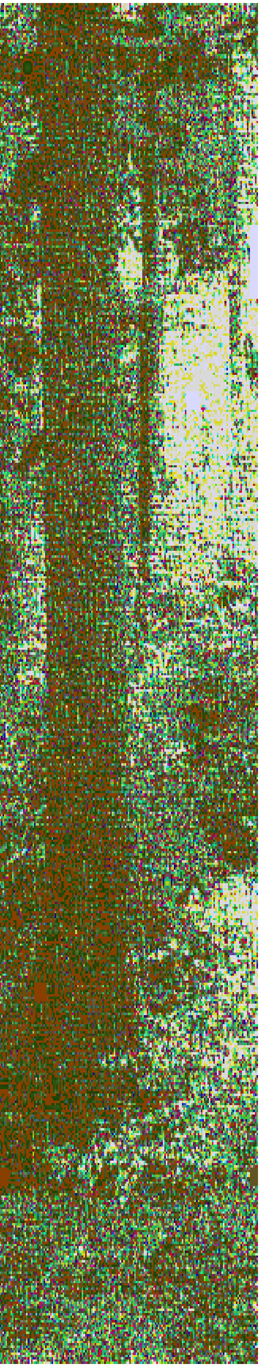
The vertical profile of a graph of wind speed in the atmospheric boundary layer depends primarily on atmospheric stability, the roughness of terrain, the surfaces surrounding the building i.e., the ground and/or other buildings, and wind speed increases with increasing height above ground. A wind velocity profile can be approximated either by a logarithmic equation or a power law expression:

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

$v(z)$ = wind speed at height z [m/s],

$v(z_0)$ = wind speed at reference height z_0 [m/s],

α= exponent (0.16 – 0.40).



5.3 Factors influencing tree stability

5. Meteorological Conditions

Meteorological conditions affect windthrow through the effects of:

- wind speed, gustiness, and storm duration
- soil moisture conditions
- snow and rain loading on the crown.

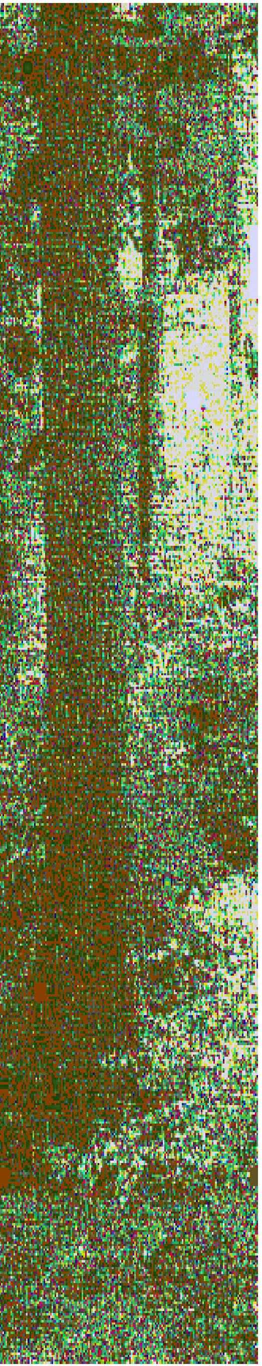
Wind velocity profile is determined by the roughness of the terrain. The value of the exponent α increases with increasing roughness of the solid boundary.
For smaller areas of rough surfaces in smoother surroundings, such as a town located in flat, open country, the velocity profile described by the equation above is valid only for a limited height above the obstacles.

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.



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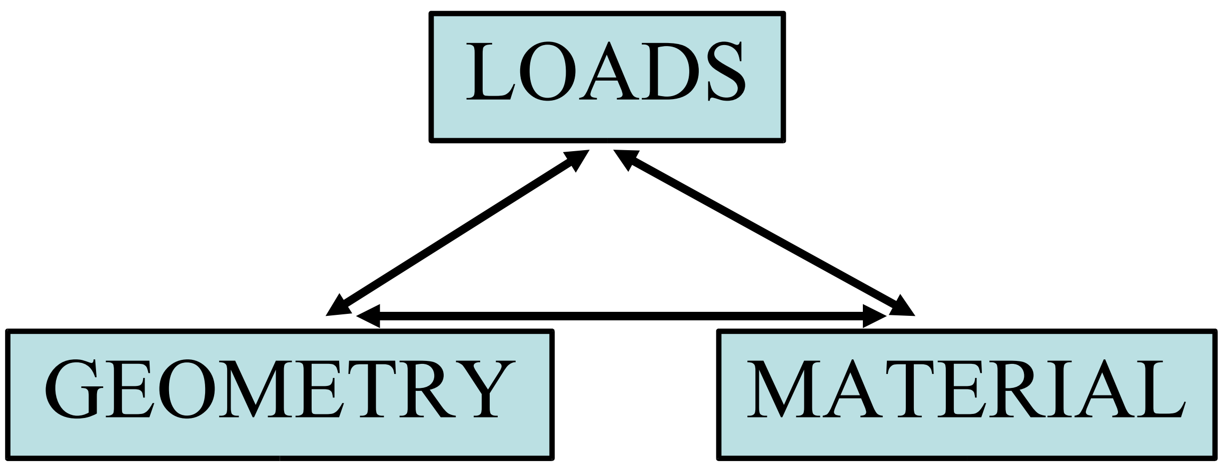

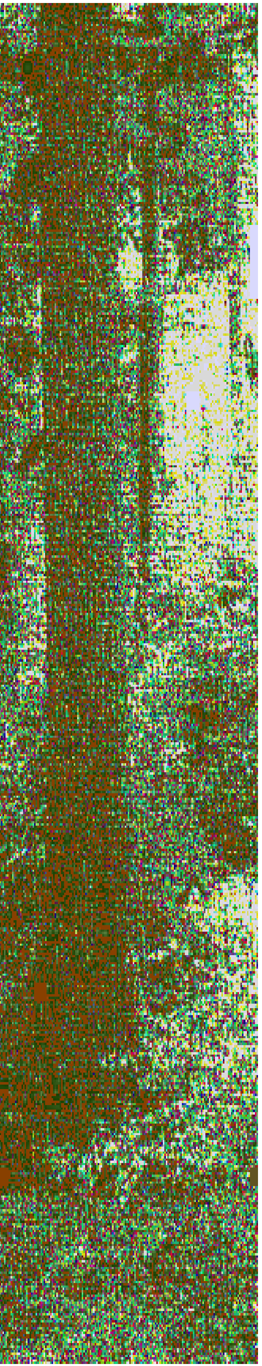

Conclusion

- 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.