TREECONSULT
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Growth Stresses and Tree Safety

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1 Introduction

Understanding growth stresses in living trees can help tree inspectors to better assess the safety of trees. The effects of longitudinal growth stresses in sycamore maple (*Acer pseudoplatanus)* and linden (*Tilia cordata*), as they may relate to predicting the safety of trees, were studied at the University of Aberdeen, Scotland and the Technische Universität München, Germany.

Growth stresses occur due to cell wall maturation and continuous increases in stem diameter. Growth stresses are not only an accidental by-product of growth, but also enhance the ability of the individual tree to cope with changing site conditions. For example, by this mechanism, leaning or partially-exposed forest-grown spruce trees that are suddenly exposed to additional sunlight can grow towards that sunlight, adjusting the crown orientation to a more favourable position for light exposure and photosynthesis. Similarly, even under the overhanging and bent leading shoots of most junipers (*Juniperus* sp.), the main stems are typically straight and upright. Therefore, it can be concluded that growth stresses must be at least partly responsible for forcing the shoots into an upright position.

In the field of structural engineering, the overall strength of a structure can be increased by pre-stressing of the construction materials. One example of this practice is in the use of concrete which has a low capacity to withstand tensile stresses, but a high capacity to bear compressive forces. When used in structures such as expanding concrete bridges, concrete requires considerable tensile pre-stressing in order to meet the operational requirements of the structure.

From a technical perspective, tree growth stresses are pre-stresses, acting to increase the ability of the stem to withstand the high wind loading experienced during storms.

1.1 Origin of growth stresses

In living trees, newly-formed cells are differentiated following cell division in the vascular cambium. According to Münch's hypothesis (Münch, 1938), growth stresses occur during cell wall maturation due to lignification, where encrusting substances are deposited between the helical cellulose and hemicellulose micro-fibrils in the S2 layer of the cell wall. Depositing material between the microfibrils changes their orientation by slightly decreasing the angle between the more or less parallel arrayed fibrils (Sahlberg et al. 1995). Greater angles between the fibrils cause a shortening of the cell and an expansion in the tangential plane. In addition to compressive tangential stresses caused by lignification, the cell walls thicken, increasing the compressive pressure on the older wood underneath.

Since the cells are connected and embedded in the stem they cannot change shape significantly, thereby causing stresses (cf. Fig. 1).

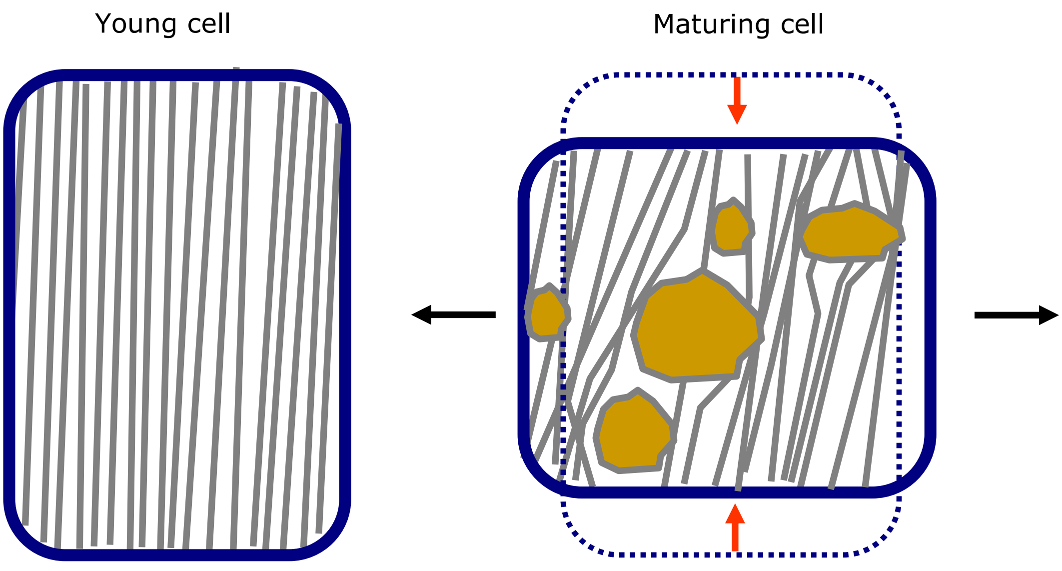


Figure 1. Encrusting substances accumulate between the cellulose and hemicellulose microfibrils of the S2 layer and press them apart. The deviation in orientation of the helical fibrils leads longitudinally to a tensile stress and a transverse compressive stress causing a belt like force in the marginal fibres of the stem.

1.2 Longitudinal stresses in living stem wood

The stem of a tree has to bear the weight of the crown causing compressive stresses in the inner part of the stem cylinder. According to Hooke's 3rd law (action is reaction) the opposite is true for the outer sheath where the fibres are under longitudinally tensile stress.

Wind gusts that cause bending of the stem create additional tension in the marginal fibres on the windward side and relax pre-stressed fibres on the leeward side of the stem. This means that before the compressive strength of the green wood can counteract the bending stress, the pre-stress has to be cancelled. (cf. Fig. 2).

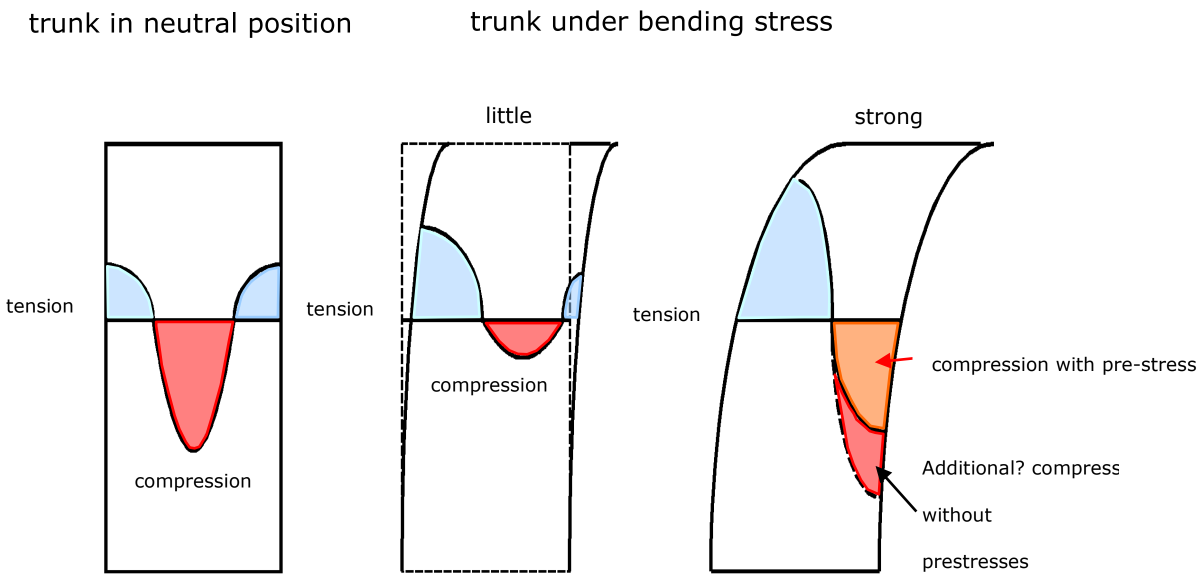


Figure 2. Displacement of tension and compression zones under bending loads.

1.3 Radial and tangential stresses in living stem wood

The cylindrical tree stem tends to bulge when bearing the load of the crown, thus leading to tensile stress between the annual rings and the radially orientated rays. With increasing distance from the pith these tensile stresses decrease in magnitude.

Since all stresses are subjected to counterstress, the opposite is true for the outer sheath of the stem where compressive stresses in the tangential and the radial plane predominate due to growth stress.

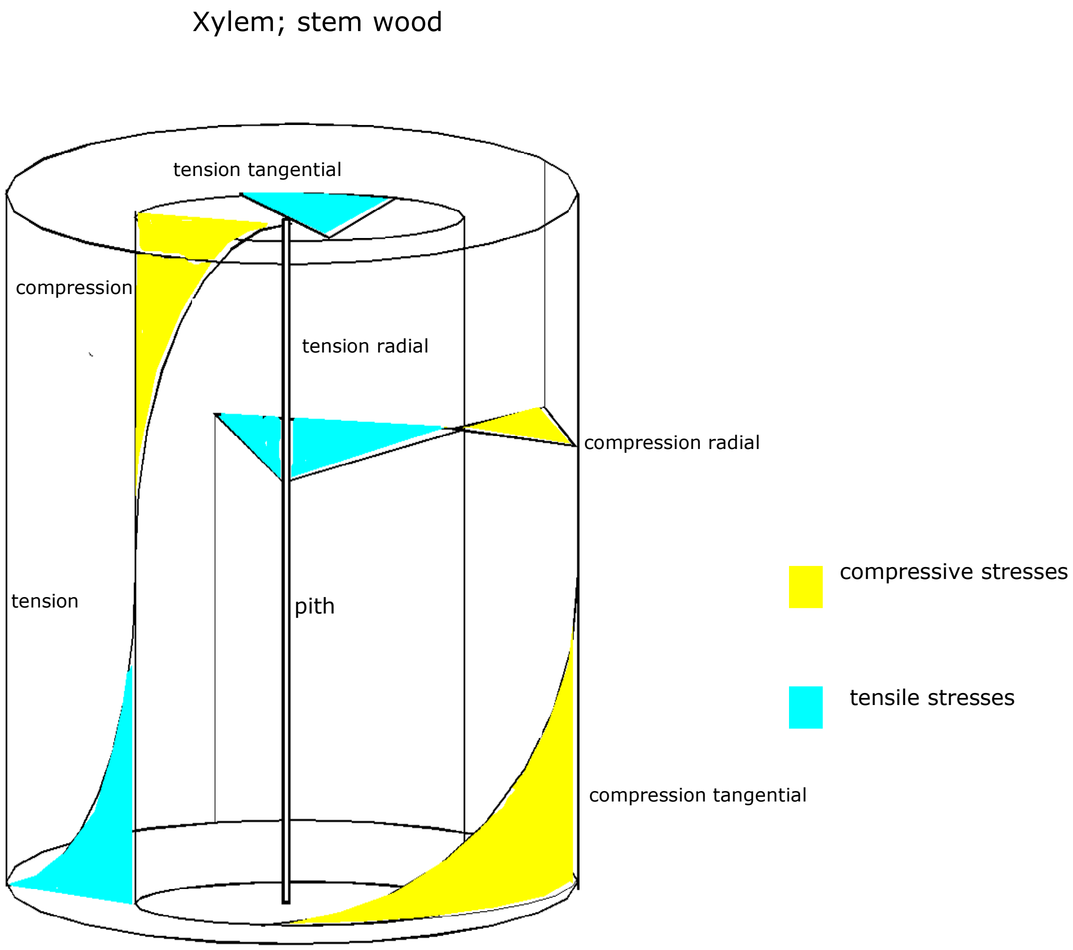


Figure 3. Stresses in trunk wood. From Kübler (1959).

According to Hooke's 3rd law, "action is reaction", all tensile and compressive stresses in the three cardinal planes are opposed to counterstresses in the same plane.

2 Pre-stress

To enhance the load bearing capacity of components used in structural engineering, the parts are mounted or installed under stress. The same principle is valid for living tree stem wood where pre-stresses acting in the cardinal planes occur during cell wall maturation and serve to increase the strength and efficiency of the stem wood.

2.1 Relevance of longitudinal pre-stress in trees

Due to the longitudinal molecular structure of cellulose and hemicellulose – the main components of wood-the compressive strength of wood is approximately half of its tensile strength. Since the compressive resistance of green wood is the weakest link in the safety analysis chain, it is important to investigate the material properties of green wood.

Pre-stress enhances the load-bearing capacity of the wood fibres on the compressive side of the stem which helps the tree to withstand storms. A more thorough understanding of the magnitude of longitudinal pre-stress will help to enhance the quality of tree safety analyses focused on resistance to stem breakage. (cf. Fig. 2).

In the timber industry, pre-stress in wood causes significant losses. Stems under high pre-stress can split in saw mills when high stresses are released during cutting.

2.2 Advanced tree risk assessment with pulling tests.

Advanced tree risk assessment requires the assessor to understand the interplay of wind forces, material properties of green wood and the influence of the load bearing geometry (i.e., stem diameter, extent of decay). Neglecting any one of these factors will lead to inaccurate results in tree risk and safety analyses.

During a tree pulling test, the breaking resistance of a tree stem is measured in different planes using a strain gauge called an elastometer. These high-precision devices measure wood fibre deformation with an accuracy of 10^{-3} mm (cf. Fig 6). In conjunction with the fibre deformation measurements, the substitute wind load (typically applied via a steel cable and winch combination) is measured with a load cell, or dynamometer.

Following the physical testing of the tree, a wind load analysis must be performed. This analysis typically considers a number of safety related factors such as: air pressure (altitude, temperature), aerodynamic drag factor, crown surface, tree height, neighbourhood factor and the protection provided by buildings, structures or other trees. By incorporating these factors, the stresses and bending moments acting upon the lower part of the stem can be estimated. These wind load forces are incorporated into a broader protocol wherein the field data from the elastometers are combined with the known wood strength data of the subject tree species. Once the wind load analysis is combined with these other data, the breaking resistance in the measured plane is given as a percentage value. When the safety values are above 150% it is generally acceptable to retain the subject tree.

One of the current limitations in the evaluation of pulling tests is that the material properties of stress-free samples were used in the development of the Stuttgart Strength Tables. These tables are the standard resource in which the green wood strength properties of a number of tree species are outlined. Consequently, all safety value calculations using this data set tend to underestimate the breaking resistance of tree stems. In the study presented here, the pulling test method was only used to record the longitudinal Modulus of Elasticity (MOE) in standing trees.

2.2.1 Statics integrating method

Based on the data derived from over 2,000 pull-tested trees, the SIA-method (Wessolly, 1998) provides a field protocol for rapid preliminary tree safety assessments to be undertaken by consulting arborists. As with the methodology described above, this new type of tree safety analysis considers the three basic parameters of statics: wind load analysis, material properties and stem geometry.

In the SIA method four different sheets, from A to D, help the practitioner assess the safety of trees on site. On the “A” sheet the required sound under bark diameter of a stem is determined. These calculations comprise material properties of green but stress free wood of the referring species and the wind load occurring during a storm of gale force. The crown shape, site conditions (wind exposure) and flexibility of the crown (drag factor) are incorporated into the calculations.

The required stem diameter is used in diagram “B” to determine the breaking safety of the subject stem at breast height. The “C” diagram allows for the incorporation of information about the extent of stem hollowness. The “D” diagrams enable the practitioner to assess how crown reduction influences the safety analysis.

If the quantity of longitudinal pre-stress is known, that value can be added directly as an extra safety margin on the result derived from the “B” diagram.

The SIA method is designed to give a tree risk assessment practitioner a quick overview of the basic static situation.

The limitations of the SIA method are:

- the standard crown shapes often do not match with those in the field;
- it only can be applied for isolated, free standing trees and it is not suitable for tree groups where the individuals grow close together in clusters;
- the material data are only available for a limited number of species commonly found in central Europe, and;
- growth stresses are neglected because the material tests were performed with stress-free specimen samples.

For example, a horse chestnut (*Aesculus hippocastanum*) 25 m tall with an 88 cm under-bark stem diameter would have a “basic safety” of 100% at a wind-speed of 117 km/h (or the lowest range of Hurricane Category 1 on the Saffir-Simpson Scale). Theoretically, this tree would fail should wind speeds reach 118 km/h, as shown by the absence of a “safety margin”. (cf. Fig. 6). Pre-stress in the stem enhances the breaking resistance and would provide an additional “safety margin” for the tree used in the example above. Knowing the extent of pre-stress could directly influence SIA calculations (cf. Fig 4).

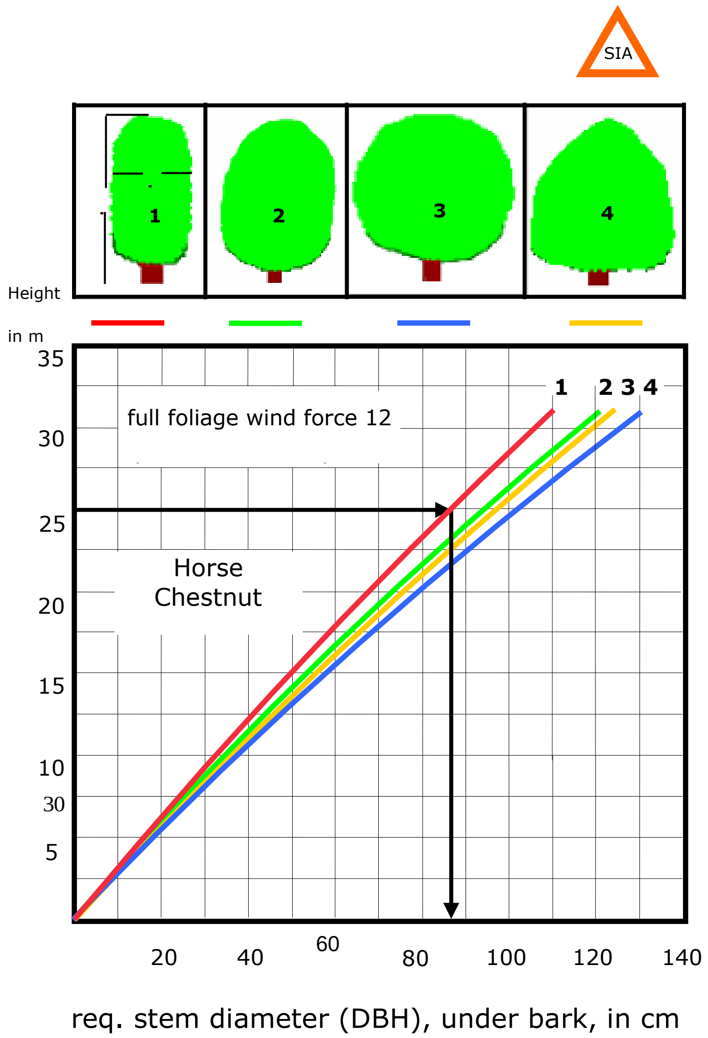


Figure 4. SIA Method, A-Diagram (Wessolly)

3 Methods

3.1 Study parameters

The compressive strength of green wood is a key parameter in the study of pre-stresses on wood fibres; modulus of elasticity (MOE) is another. The MOE measurements were recorded in standing trees with all pre-stresses still *in situ*, using the pulling test method. The compressive strength was obtained from studies using material testing machines. Additionally, specific weight, wood density and wood moisture were recorded.

3.2 Subject trees

In Hanauer Straße in München, Germany, 37 *Tilia cordata* had to be removed for subway construction works. The trees were planted in uniform sites along the street. Their age at the time of removal was 28-30 years. All trees had lived under similar conditions in uniform-sized planting beds and were similar in size.

Additionally, 10 *Acer pseudoplatanus* at Craibstone Estate and Kirkhill Forest, (both near the city of Aberdeen, Scotland) were used for these experiments. The trees at Craibstone Estate were located in a woodland at the edge of a windthrow area, whereas those at Kirkhill Forest were located in the forest interior.

3.3 Methodology

Three different techniques were used to measure longitudinal pre-stresses in the subject trees:

1. sawing method
2. drilling method
3. drilling method with DRLM[1]

(cf. Fig. 5, a, b, c)

The first two methods were used in München, where electricity was available on-site. The CIRAD forêt growth strain gauge (DRLM) method was used in the Scotland forest trials, due to its portability.

Regardless of the methodology used, all trees had first to be de-limbed to avoid wind influence during measurements. All stems were marked with a different colour at three different levels: 600, 800 and 1000 [mm] above ground level. When the trees were subsequently felled, wood samples were taken from these three levels.

[1] déformation résiduelle longitudinales de maturation, CIRAD forêt growth strain gauge , Fournier, 1994

a b c

Single hole method:

Modified platform for a high-rpm milling machine used in Munich.

Sawing method:

Two horizontal cuts at a distance of 210 mm lead to fibre contraction that was measured with a high resolution Elastometer.

Two vertical cuts helped to avoid influences from radial compression on the longitudinal stress recordings.

The CIRAD forêt grow
gauge (DLRM) with a
of 10^{-3} mm was used
stress measurements
deen area.

Figure 5. Measuring methods

3.3.1 Measuring the modulus of elasticity (MOE)

Pulling tests were performed on standing de-limbed trees to determine modulus of elasticity (MOE). Branch stubs were left on the tree to avoid unintentional stress release.

A cable was attached to the crown and connected via a winch to a neighbouring anchor tree (cf. Fig 6a, c; 8b). A measured load was applied, and elastometer measurements were performed at 60 cm, 80 cm and 100 cm heights. After the data were collected the trees were removed and stem discs from 60, 80 and 100 cm saved in plastic bags to avoid moisture loss. Subsequently, samples from the discs were cut parallel to the grain and compressed to failure in a material testing device (cf. Fig. 9). The material tested was beyond the point of fibre saturation (> 35% moisture content throughout).

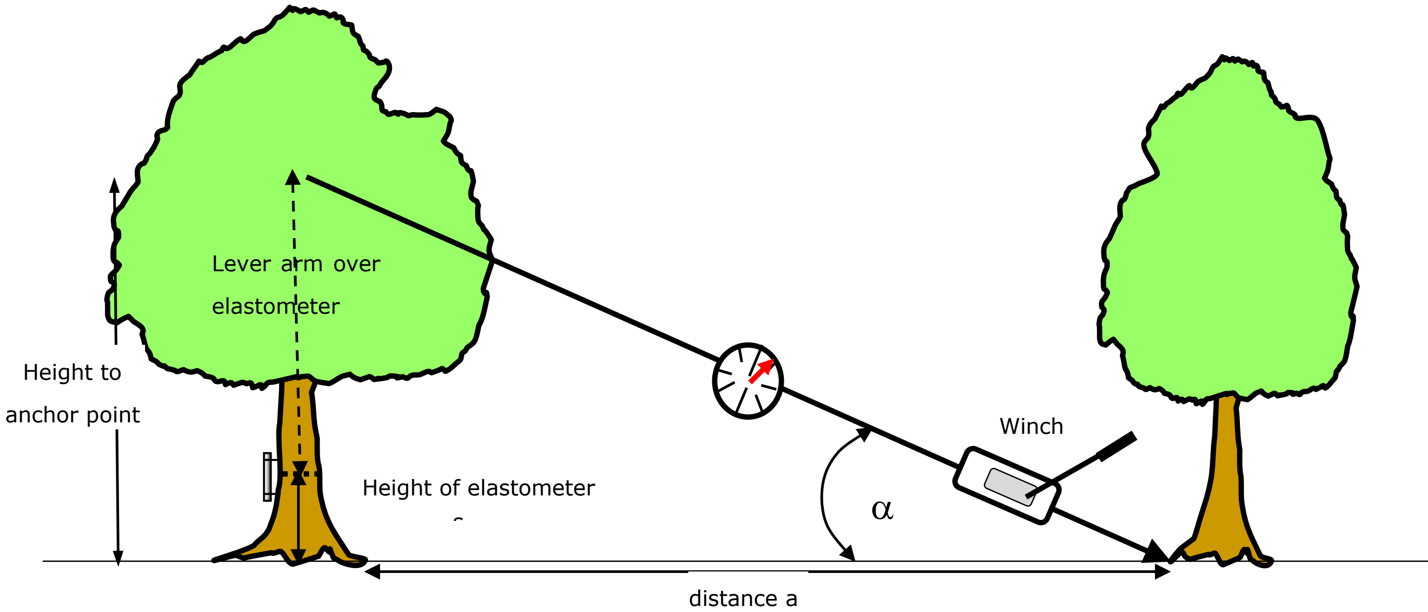


Figure 6. Set up for a pulling test to record the modulus of elasticity (MOE). The MOE was obtained from pulling tests in standing trees measured at stem heights of 600, 800 and 1000 [mm] .

according to:

$$\mathbf{E} = \sigma / \varepsilon \quad (1.0)$$

with:

σ from pulling tests results
$\varepsilon = l/\Delta l$ with l from measured value (elastometer) and Δl for reference length L = 200 mm

with:

$$\varepsilon = \Delta l / l \qquad (1.1)$$

with:

$$\mathbf{M_b = F^* \ (H - S)^* \cos \alpha} \qquad (1.2)$$

with the moment of inertia M_I of the stem

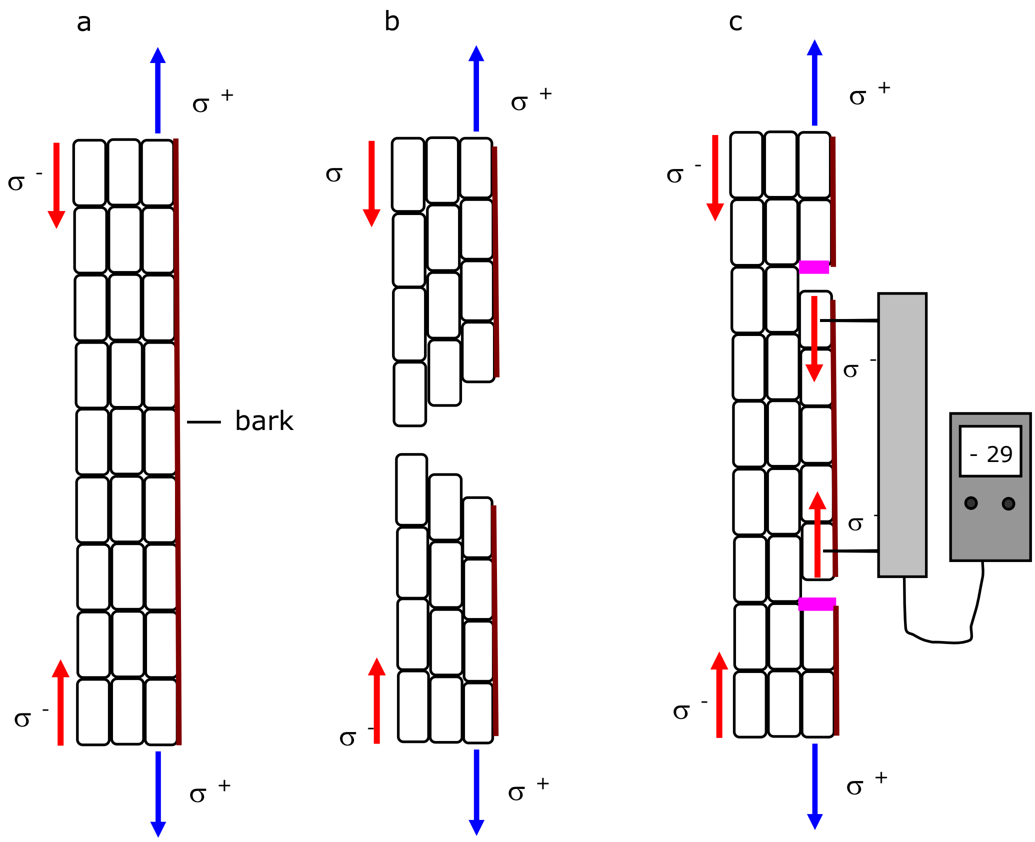
$$\mathbf{M_I = d_1^2 * d_2 * \pi / 32} \qquad \text{(elliptic formula 1.3)}$$

σ	stress in N/mm^2
F	force in N (dynamometer)
H	height of cable attachment
S	height of elastometer, measuring plane
α	angle of steel cable
d_1	trunk diameter, 1 m above ground
d_2	trunk diameter perpendicular to d_1, 1 m above ground

$$\boldsymbol{\sigma} = \mathbf{M_b}_{\text{ (bending moment)}} \ / \ \mathbf{M}_{\text{ (inertia)}} \qquad (1.4)$$

3.3.2 Sawing method

Using the sawing method, two cuts were made at a distance of 5 mm above and below the probes of the high-precision elastometers. Cutting above and below the device caused a contraction of the fibres underneath the device, which was recorded (cf. Fig 5b). To avoid the influence of tangential or radial stress on the results, two vertical cuts were also made parallel to the elastometer.



a. stress in the standing tree

Compressive stress in the centre of stem.

Tensile stress at the outer sheath.

b. After drilling a hole

Pre-stressed fibres in the outer sheath are stress released and shorten. Their change in geometry and form is limited due to shear stresses between the growth rings.

c. Saw cuts above and below device

Pre-stressed fibres in the outer sheath are stress released and the section between the probes shortens. The contraction of fibres is recorded with high precision tools.

Figure 7. Longitudinal stress in the marginal fibres

3.4 Single hole method

For the single hole method, a 20 mm diameter hole was drilled into the stem. 12.5 mm above and below the edge of the hole, probes were pressed into the sapwood fibres to record the changes in fibre length during the drilling test (cf. Fig. 7b) The single hole method was applied with two different devices: In Munich a high speed electric milling machine with a modified platform and a modified elastometer was used for the thin barked *Tilia* specimen trees. In the rougher terrain of the Aberdeen forest locations the CIRAD forêt growth strain gauge (DLRM) was advantageous due to its smaller dimensions and the possibility to use it in conjunction with a hand drill.

3.4.1 Wood testing in a material-testing device

Approximately 1,500 samples were collected from the 37 linden trees in München and 300 samples were obtained from the sycamore maples in Scotland. For the testing machines, crossbeams and load cells with a capacity of 10 tonnes were used. The high density of measuring points at a rate of 10 Hz and at maximum test speed of 11 mm/ sec. allowed for a precise determination of the point where linear deformation changed into creeping represented by an exponential curve.

All samples were well above the fibre saturation range that differs in a small band between 32% - 35% (Niemz, 1993). Beyond the 35% moisture content the mechanical properties of wood show only a very small variation.

The size of samples varied between 20x20x30 [mm] and 20x20x60 [mm].

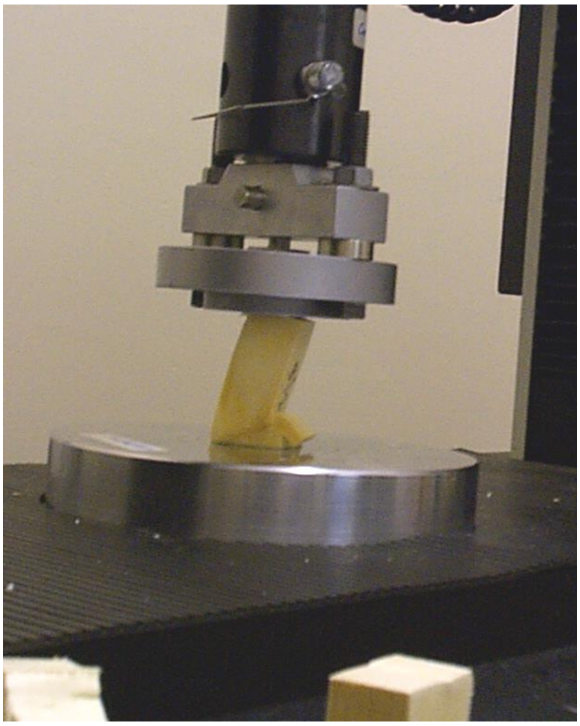


Figure 8. Wood testing machine (here: INSTRON)

3.4.2 Determining pre-stress

The pre-stress was calculated using the data obtained from the elastometer readings according to:

$$\sigma = E * \Delta l * \phi \quad (1.5)$$

where:

σ = pre-stress

E = E-modulus

Δl = relative length variation

ϕ = calibration factor (GRIL 1998, for *Tilia* 11.0, for *Acer* 11.1 [1/m])

4 Results

With correlation and regression analysis, the main factors influencing the modulus of elasticity such as trunk inclination, density and compressive strength were tested. It was found that only density and pre-stress had a significant influence on the MOE.

Tab. 1 Mean values of MOE for *Tilia cordata* in 1000 mm trunk height. Location: Hanauer Strasse, Munich

Mean value in N/mm²	Standard deviation
Total mean value	
491,02	St. deviation
4949.7	935.2
	In % from MV = 19,06

Table 1 presents the mean values of E-moduli in N/mm² for 37 *Tilia cordata,* derived from pulling tests. The mean value was 4949.7 N/mm² (±935.2 N/mm²).

Tab. 2 Mean values of MOE at 1000 mm trunk Location: Aberdeen, species: *Acer pseudoplatanus*

Location	MV E-Moduli in N/mm²	comments E-moduli in N/mm²	St.Dev.	comments St.Dev.
Craibstone Estate	7595.80		1157.64	
Kirkhill Forest	6428.38	5491.48 without 3 K	2252.37	St.Dev. :970.70 without 3 K
MV both locations	7012.1	6522.23 without 3 K		

The MOE values varied significantly between the locations and the samples, even when the outlier data (after sample 3 K) were removed from the analysis. The Craibstone Estate sycamore maples were significantly stiffer than those in Kirkhill Forest, which might be a consequence of their location on an exposed site at the edge of the windthrow area.

4.1 Compressive strength tests

The strength research used in engineering based tree safety assessment focuses on the point of primary failure described as limit of elasticity (Wessolly, 1998) where the linear deformation under stress proceeds to a permanent deformation of fibres. In this work, the strength of green wood was needed for comparison with the magnitude of the measured pre-stress.

Tab. 3 **Compressive strength of *Tilia cordata*, from Hanauer Strasse, Munich. Mean values for compressive strength of *Tilia cordata* were 19.7 N/mm², 2.5 N/mm² (12.7% of mean).**

Maximum compressive stresses in the trunk layer 0-20 mm					
Sample #	*Stress*	Sample #	*Stress*	Sample #	*Stress*
	N/mm²		*N/mm²*		*N/mm²*
101	*22,67*	1401	*18,20*	2701	*17,62*
201	*24,21*	1501	*21,07*	2801	*17,65*
301	*19,84*	1601	*19,29*	2901	*17,32*
401	*20,31*	1701	*20,30*	3001	*21,04*
501	*20,53*	1801	*19,15*	3101	*15,34*
601	*21,17*	1901	*22,31*	3201	*17,71*
701	*16,44*	2001	*20,54*	3401	*15,01*
801	*21,30*	2101	*21,63*	3501	*22,87*
901	*21,87*	2201	*24,73*	3601	*20,17*
1001	*18,78*	2301	*21,75*	3701	*16,14*
1101	*17,98*	2401	*19,97*	Mean Value	*19,66*
1201	*18,47*	2501	*19,56*	=	19,7 N/mm²
1301	*17,32*	2601	*25,16*		mean compression
					in 0 - 20 mm
				St. Dev.	2,50
				corresponds to a	
				deviation of	12,70%

Tab. 4 **Compressive strength of *Acer pseudoplatanus*, from Kirkhill-forest, Aberdeen**

	compressive strength between 0-20 mm in N/mm² Craibstone								
Sample	1 Craibstone	Sample	2 Craibstone	Sample	3 Craibstone	Sample	4 Craibstone	Sample	5 Craibstone
	N/mm²		N/mm²		N/mm²		N/mm²		N/mm²
1C10011	23,88	2C10011	25,77	3C10011	26,96	4C8011	24,3	5C10011	26,47
1C10021	23,5	2C10021	26,23	3C10021	24,79	4C8021	26,09	5C10021	31,63
1C10031	24,04	2C10031	24,58	3C10031	26,34	4C8031	27,53	5C10031	17,74
1C10041	24,83	2C10041	27,09	3C10041	26,71	4C8041	24,54	5C10041	30,24
MV	**24,06**		**25,92**		**26,2**		**25,62**		**26,52**
St. dev.	0,56		1,05		0,97		1,50		6,25
% of MV	2,33		4,04		3,72		5,87		23,55
MV $_{total}$	**25,66**	St. dev. $_{to}$	0,96	% of MV	3,72				

Tab. 5 **Compressive strength of *Acer pseudoplatanus*, from Craibstone Estate, Aberdeen**

	Compressive strength between 0-20 mm in N/mm^2, Kirkhill								
Sample	1 Kirkhill	Sample	2 Kirkhill	Sample	3 Kirkhill	Sample	4 Kirkhill	Sample	5 Kirkhill
#	N/mm^2	#	N/mm^2	#	N/mm^2	#	N/mm^2	#	N/mm^2
1K10011	23,6	2k6011	26,38	3k10011	40,77	4K10011	27,58	5k10011	9,395
		2K6021	23,54			4K10021	23,78	5k10021	23,19
		2K6031	26,44	3k10031	38,36	4K10031	28,87	5k10031	23,15
		2K6041	23,24	3k10041	35,48	4K10041	24,34	5k10041	26,38
MV	**23,60**		**24,90**		**38,20**		**26,14**		**20,53**
St. dev.			1,75		2,65		2,47		7,58
% of MV			7,02		6,93		9,46		36,90
Mean $_{total}$	**26,67**	St. dev. $_{total}$	6,77	% of mean	25,40				
Mean $M_{OD.}$	23,79	St. dev. $_{MOD.}$	2,41	% of mean	10,13				

For *Acer pseudoplatanus* at Kirkhill the mean compressive strength was 26.7 N/mm^2 ± 6.8 N/mm^2, for Craibstone the value was 25.7 N/mm^2 ± 0.96 N/mm^2.

4.2 Results of pre-stress recording

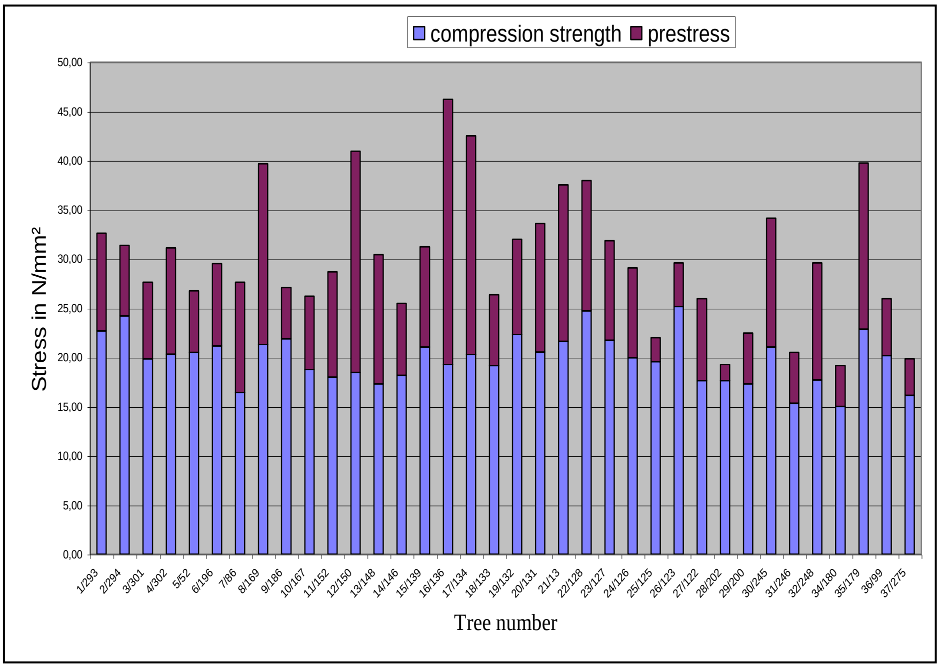


Figure 9. Additive effects of pre-stress on safety against fracture in Tilia cordata

The mean value for the pre-stress found in *Tilia cordata* at Hanauer Straße in München was 8.3 N/mm² with mean values for the single hole method of 8.32 N/mm² and 8.27 N/mm² for the sawing method.

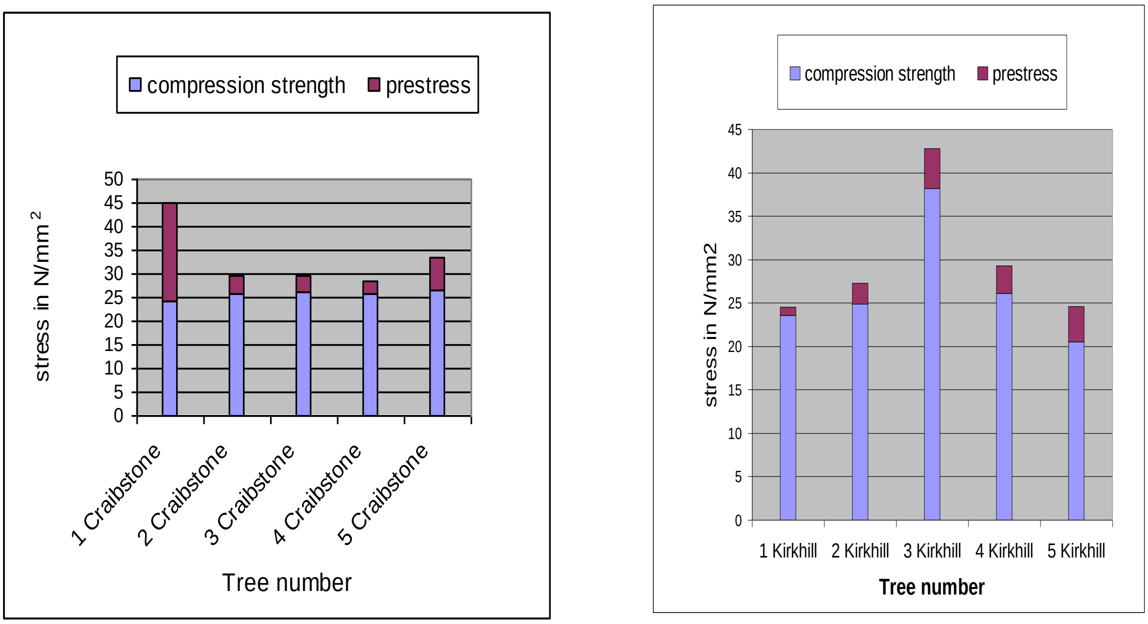


Figure 10. Additive effects of pre-stress on safety against fracture in Acer pseudoplatanus.

The mean value for the pre-stress (Sigma) found in *Acer pseudoplatanus* at Kirkhill Forest and Craibstone Estate was 3.58 N/ mm^2. In Kirkhill forest the mean pre-stress value was 3.03 N/mm^2 and at Craibstone Estate the mean pre-stress was 4.12 N/ mm^2.

In summary, it can be stated that in *Acer pseudoplatanus* the mean pre-stress from both Aberdeen locations was approximately 57% lower than those obtained from *Tilia cordata* in Munich.

Pre-stress can be regarded as an additional statical safety reserve in the tree, but it is not evenly localised as suggested by the architectural model (Fig. 3). Different measuring heights and directions, such as those performed with *Acer pseudoplatanus* indicated great differences in Δl obtained for determining the pre-stress. In principle, however, major stresses were localised in the range of 0 -10 mm penetration depth in the trunk. The general trend showed increasing Δl in the first 10 mm penetration depth followed by plateauing with increasing drilling or sawing depth. Since pre-stress also depends on material-specific constants like density or E-modulus, it can be very different locally due to the heterogeneity of the wood.

5 Summary

Growth stresses occur in all three anatomical planes within a tree trunk and are in a technical sense pre-stresses. They develop during cell maturation as the S2 layer thickens causing a swelling in the radial and tangential plane and contraction in the longitudinal plane. In the outer sheath of the stem longitudinal contraction causes tensile pre-stress (Kübler, 1959) and the swelling of cell walls causes compressive stresses in the radial and tangential plane. In the central trunk the opposite forces are active keeping a tree in its state of equilibrium.

The Statics Integrating Method – SIM (WESSOLLY, 1998) is currently used by consulting arborists (www.sag-baumstatik.de) in different European countries. According to this method the assessment of tree safety is based on the interrelation of wind loading, material properties of green wood and the shape of the load bearing stem.

The SIM calculations are based on material properties of green, but stress free wood obtained from laboratory tests.

Pre-stresses as a result of trunk growth enhance the compressive strength and can be regarded as an additional safety reserve of trunks and branches against fracture. The aim of this research was to quantify the longitudinal pre-stress which influences the compressive strength of a trunk under bending load.

The specimen trees used in this work are 37 Tilia cordata from Hanauer Straße at Munich, Germany and 10 Acer pseudoplatanus from Craibstone Estate and

Kirkhill Forest near Aberdeen, Scotland. Unintentional wind influence on the measuring results was avoided by removing the tree crowns, leaving short stumps.

In order to determine the quantity of longitudinal pre-stresses, two methods were used: the single hole method and the sawing method (ARCHER, 1983, FOURNIER, 1994). Both methods released the longitudinal stresses causing alterations in the length of the fibres. The sawing method with cuts above and below the strain gauge (elastometer) causes a fibre contraction and negative readings. By contrast the measured values using the single hole method were positive due to an extension of the fibres between the drill hole edge and the elastometer probes. The length alterations delivered by both methods are recorded and used to calculate the quantity of prestress according to Hooke´s law:

$$\sigma = E * \varepsilon \quad (1.0)$$

with

σ = stress

E = Modulus of Elasticity (E-Modulus)

ε = strain ($\Delta l/l$)

The E-Modulus as one factor in the equation above was obtained from pulling tests measuring the strain in the marginal fibres of the trunks with a modified strain gauge called an elastometer (measuring accuracy 1/1000mm) under a defined load (dynamometer, measuring accuracy 0,1kN).

The mean E-Modulus for Tilia cordata was found to be 4949 N/mm² and that for Acer pseudoplatanus 6522 N/mm².

The cutting geometry of each method is influenced by the anisotropy of wood. Therefore it is important to incorporate a factor of correction (GRIL, 1998, 2001) into all pre-stress calculations.

$$\sigma = \Delta l * \phi * E \quad (1.6)$$

σ stress in N/m²

Δl length alteration related to base length in 10^{-6} m

E modulus of elasticity in N/m² from pulling tests

(c.f chapter 3.3.1)

ϕ factor of correction in 1/m.

Directly after finishing the measurements of the E-moduli and the pre-stress values, all sample trees were felled and disks of 100 mm thickness were cut from various heights up the stem. To avoid moisture loss, the specimens were immediately sealed up on site in airtight plastic bags and deep frozen at a temperature of -20° Celsius.

The wood specimens were cut parallel to the grain to specimens of 2/2/3 and 2/2/6 (Acer pseudoplatanus) [cm] size. The specimens obtained from disks of 1 m and 0,8 m trunk height were used for compressive tests carried out with Instron machines at the Institut für Holzforschung, Munich and at the University of Aberdeen. The remaining disks from 0,6 m trunk height were used for density and moisture tests.

All specimens used for compressive stress tests had moisture contents well above the fibre saturation point.

For Tilia cordata the mean compressive strength was 9,7 N/mm² and for Acer pseudoplatanus,25,6 N/mm².

The mean pre-stress value for Tilia cordata obtained from both methods was 8,3 N\mm² showing a steep increase of measured strains in the first 10 mm cutting depth.

The mean pre-stress value for Acer pseudoplatanus (single hole method only) was 3,58 N/mm² showing a higher scattering of data but also confirming the trend of steep increase of strains in the first 10 mm drilling depth.

For both Tilia cordata and Acer pseudoplatanus, the strain measurement trends show that between 10 and 20 mm cutting depth the values still increased steeply but beyond the 20 mm depth level to the final cutting depth the values plateaued or even decreased. From the data obtained it can be concluded that the highest pre-stresses occur in the marginal fibres near the vascular cambium.

Statistical analysis of the data showed that the influence of density and pre-stress on the modulus of elasticity were significant but not linearly related. The evaluation of the e-modulus data derived from leaning trunks compared to those from straight, upright trunks gave no evidence for a significant influence on the elastic properties.

One way and two way analysis of variance allowed the conclusion within set limits that pre-stress (measured as strain) and modulus of elasticity were independent from each other which allowed for a better differentiation of cutting depth values and further pre-stress calculations (cf. formula 1.6).

Tilia cordata and *Acer pseudoplatanus* are common street trees in many European countries. They are exposed to stem and root damage which leads to decay and reduced breaking safety. Tree inspectors and tree consultants using the SIM should consider the additional safety reserves from pre-stress when assessing the safety of *Tilia cordata* and *Acer pseudoplatanus* (cf. Fig. 10 and 11).

The results of this study allow the conclusion that longitudinal pre-stresses increase the breaking safety by 50% on average for *Tilia cordata* and only 20% for *Acer pseudoplatanus*.

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