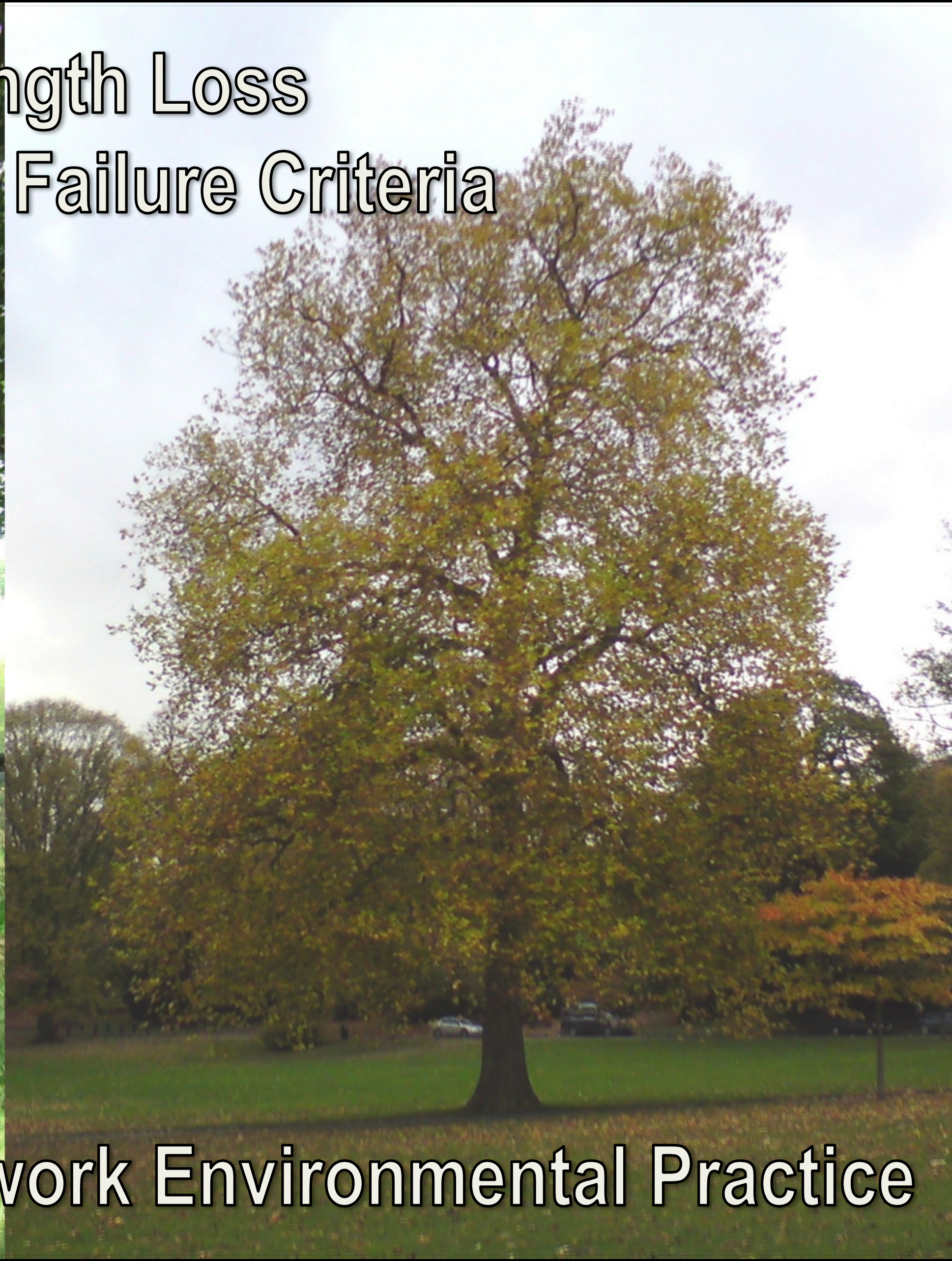
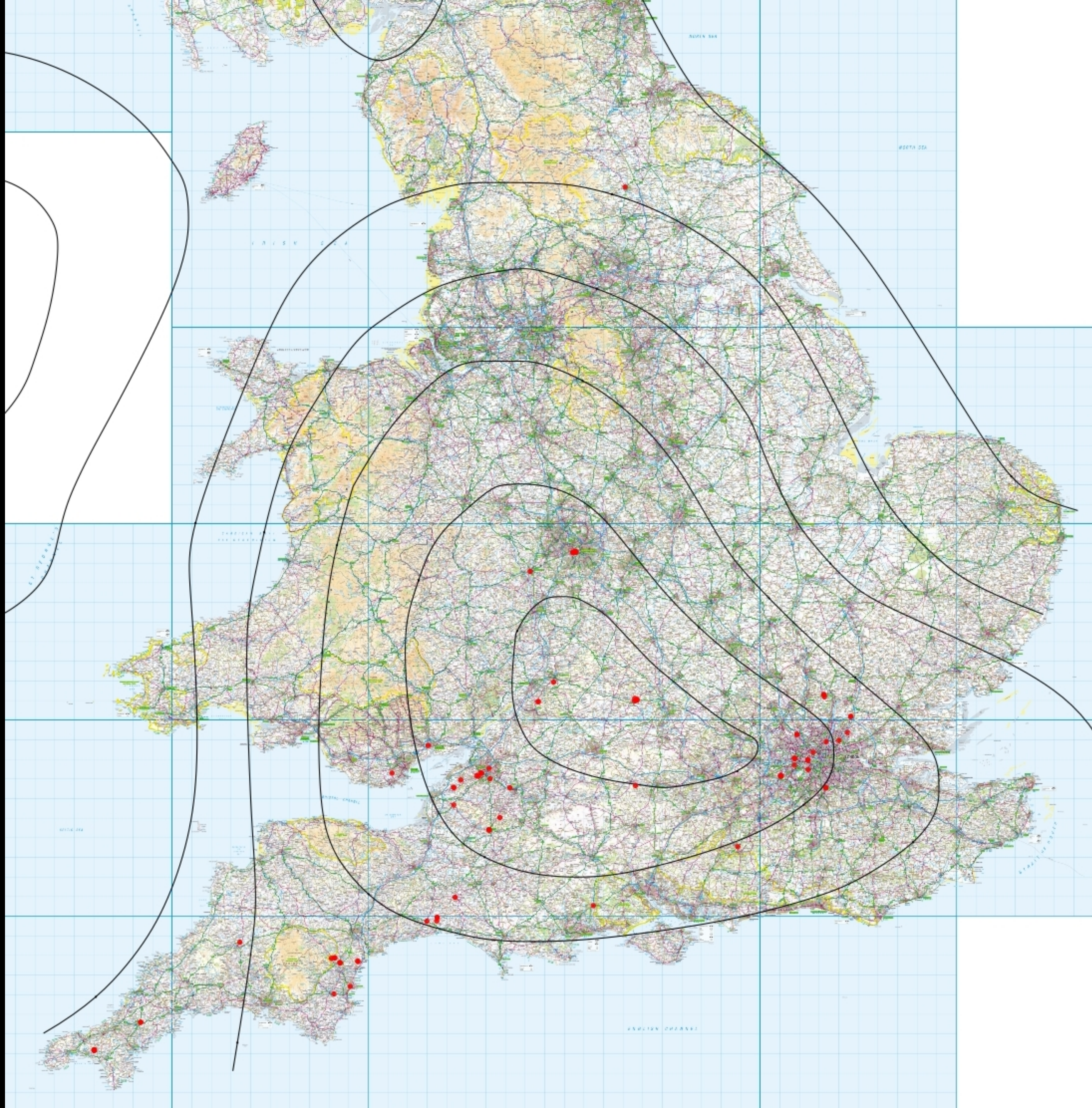
Safety Factors Versus Strength Loss
Choosing Appropriate Tree Failure Criteria



Paul Muir - Treework Environmental Practice


Treework Environmental Practice Seminar 1 - 2003

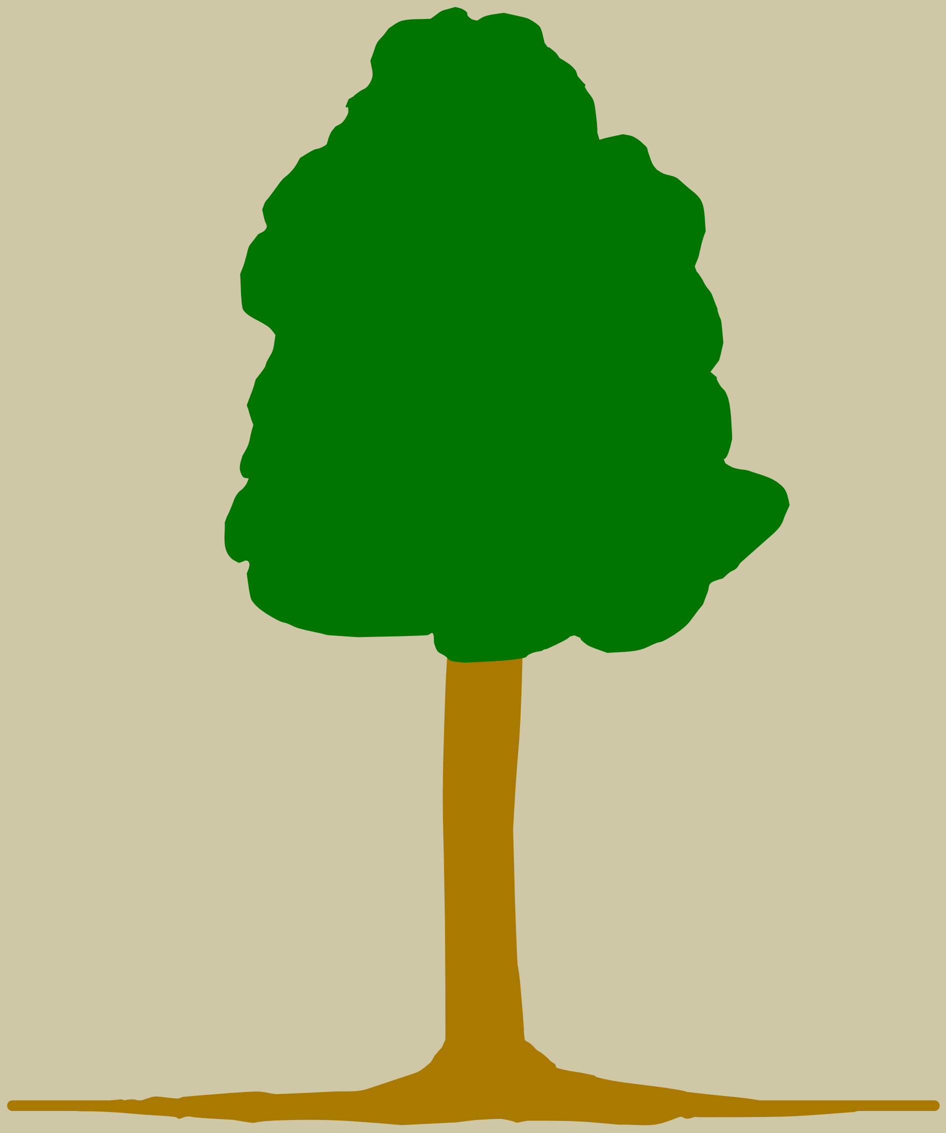

SAG Baumstatik Group



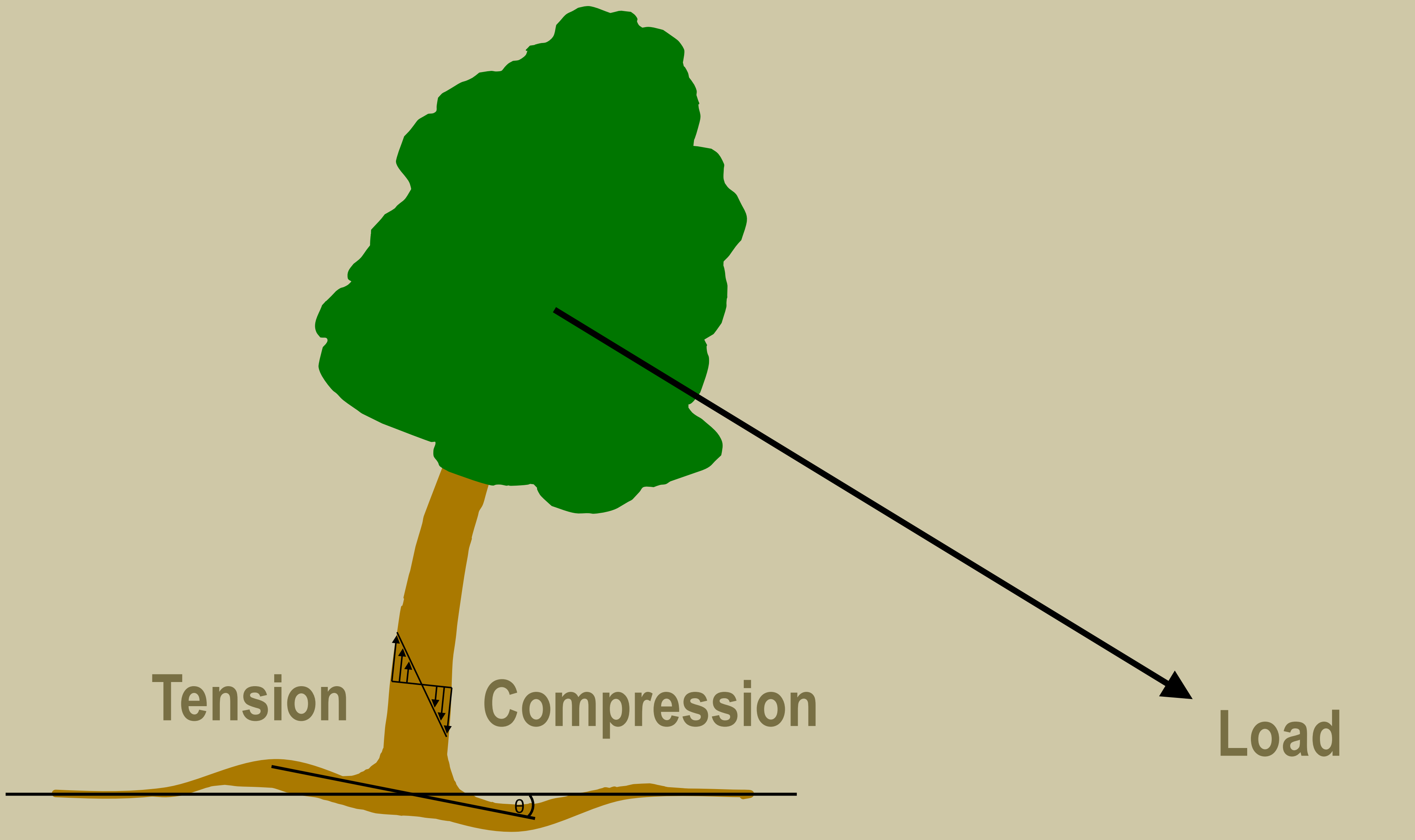
Safety Factors versus Strength Loss

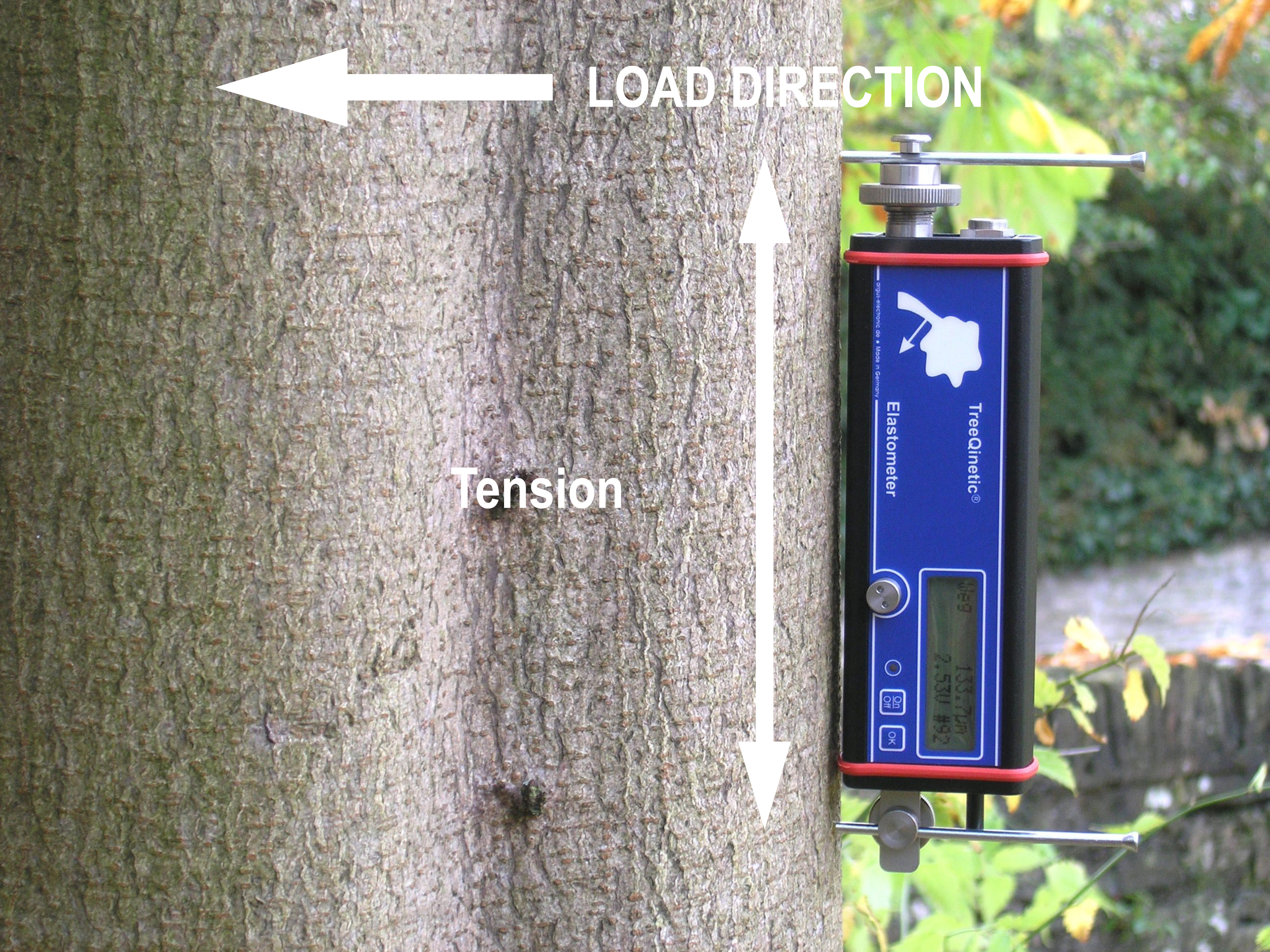
- The Static Load Test
- The Triangle of Statics
- Safety Factors
- Section Modulus
- Case Studies

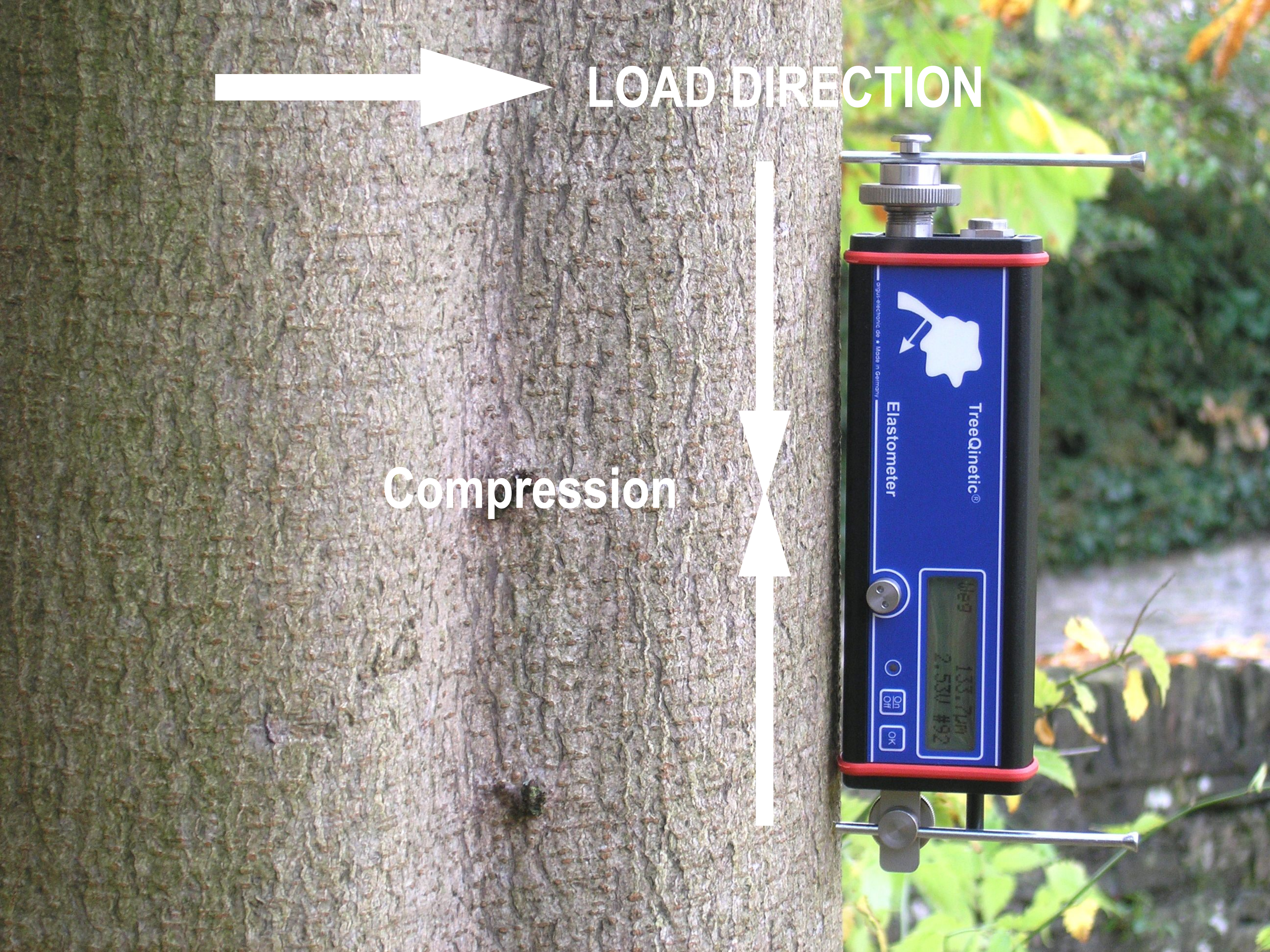
Static Load Test

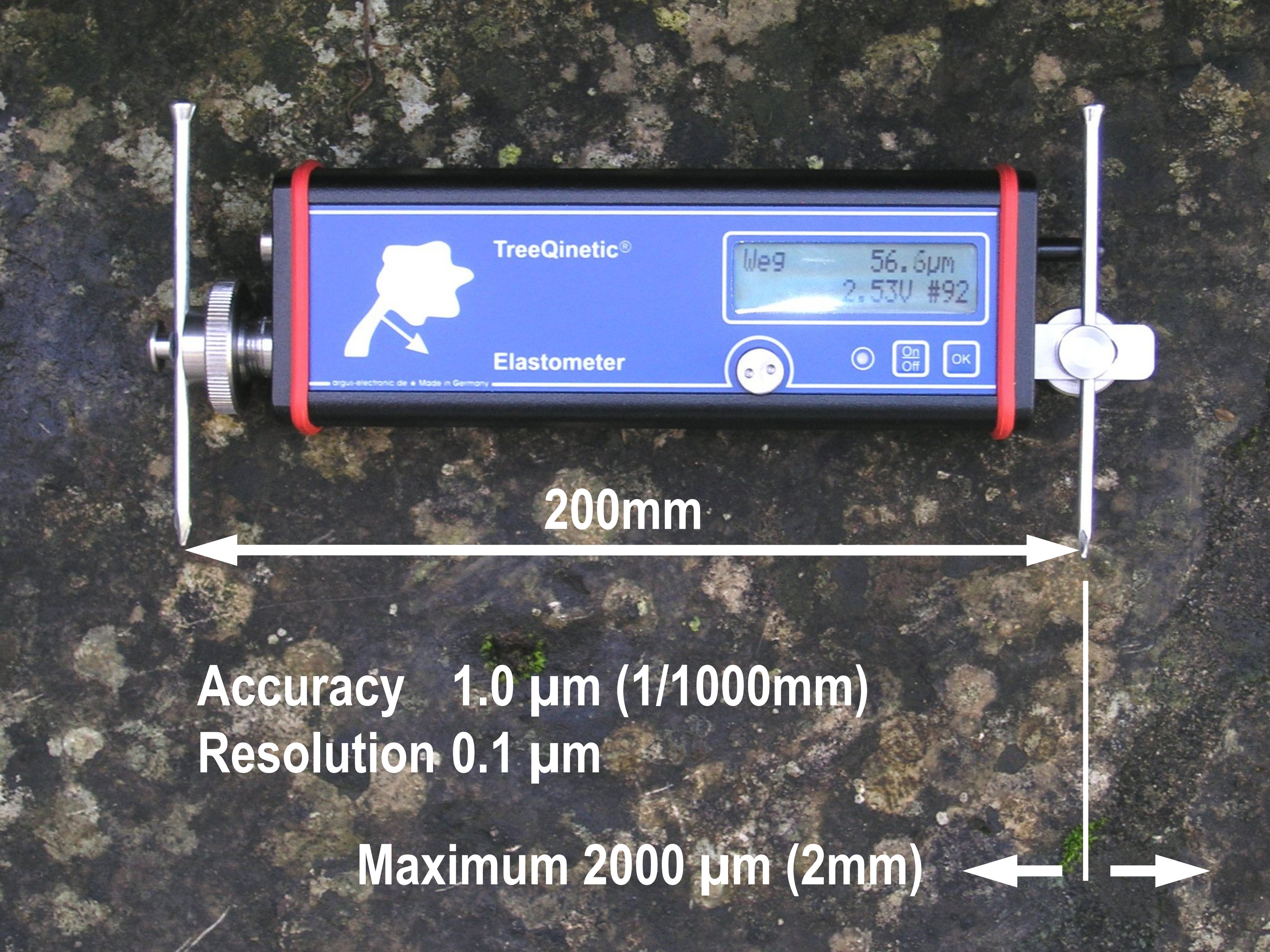


Static Load Test

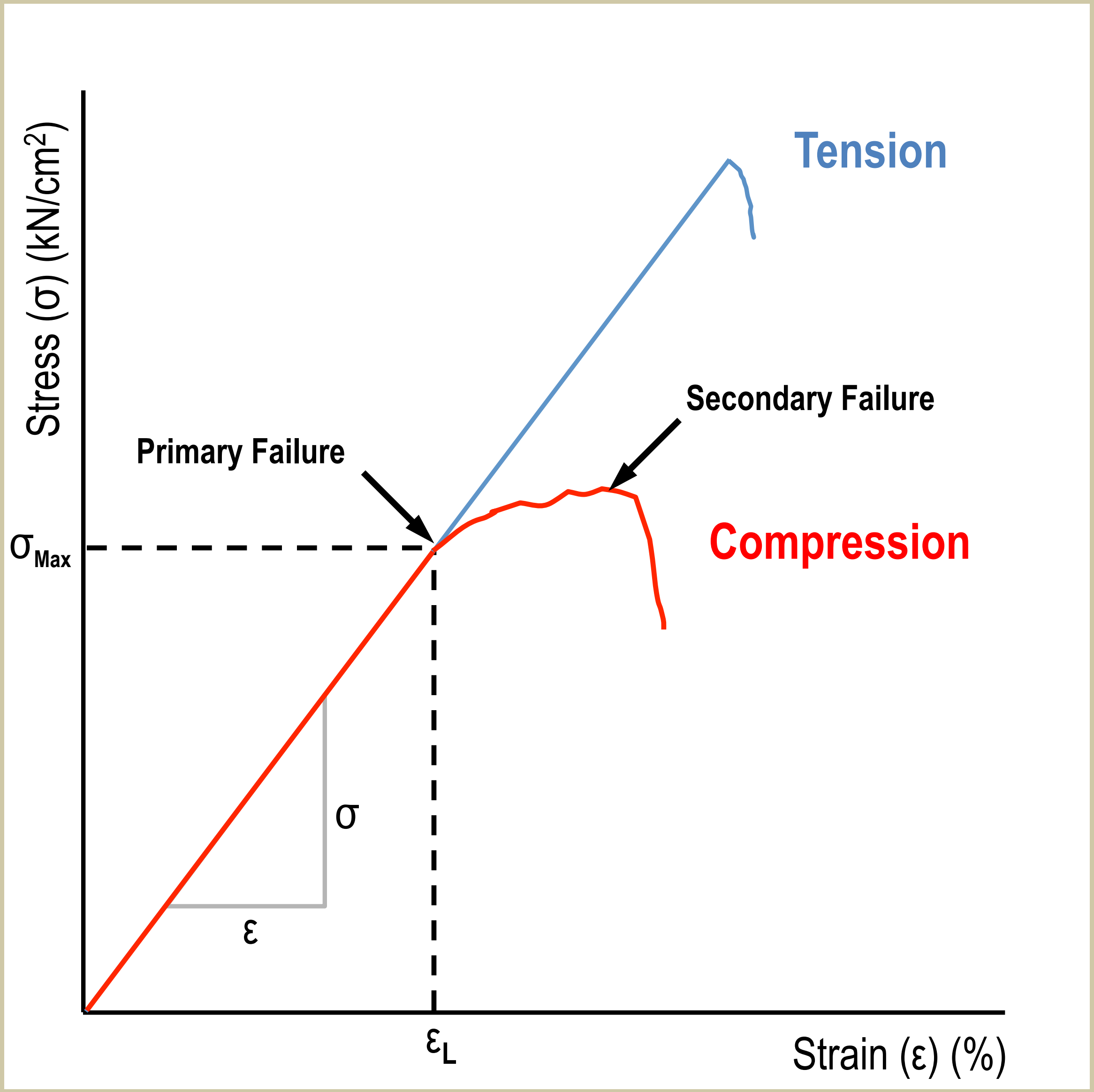



LOAD DIRECTION
Tension
TreeQinetic®
Elastometer


LOAD DIRECTION
Compression
TreeQinetic®
Elastometer
OK


TreeQinetic®
Weg 56.6µm
2.53V #92
Elastometer
On
Off
OK
200mm
Accuracy 1.0 µm (1/1000mm)
Resolution 0.1 µm
Maximum 2000 µm (2mm)

Stress-Strain Curve

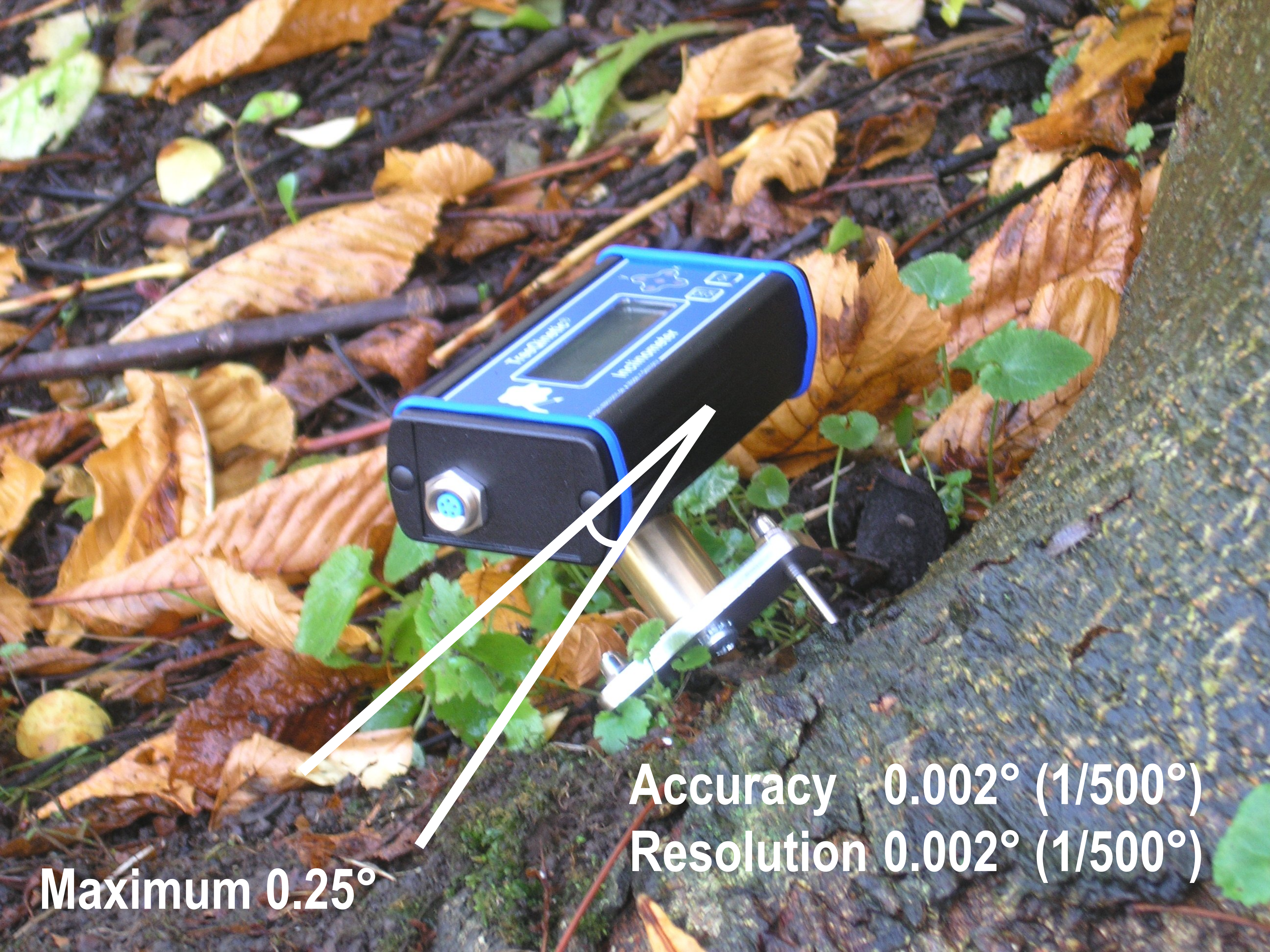


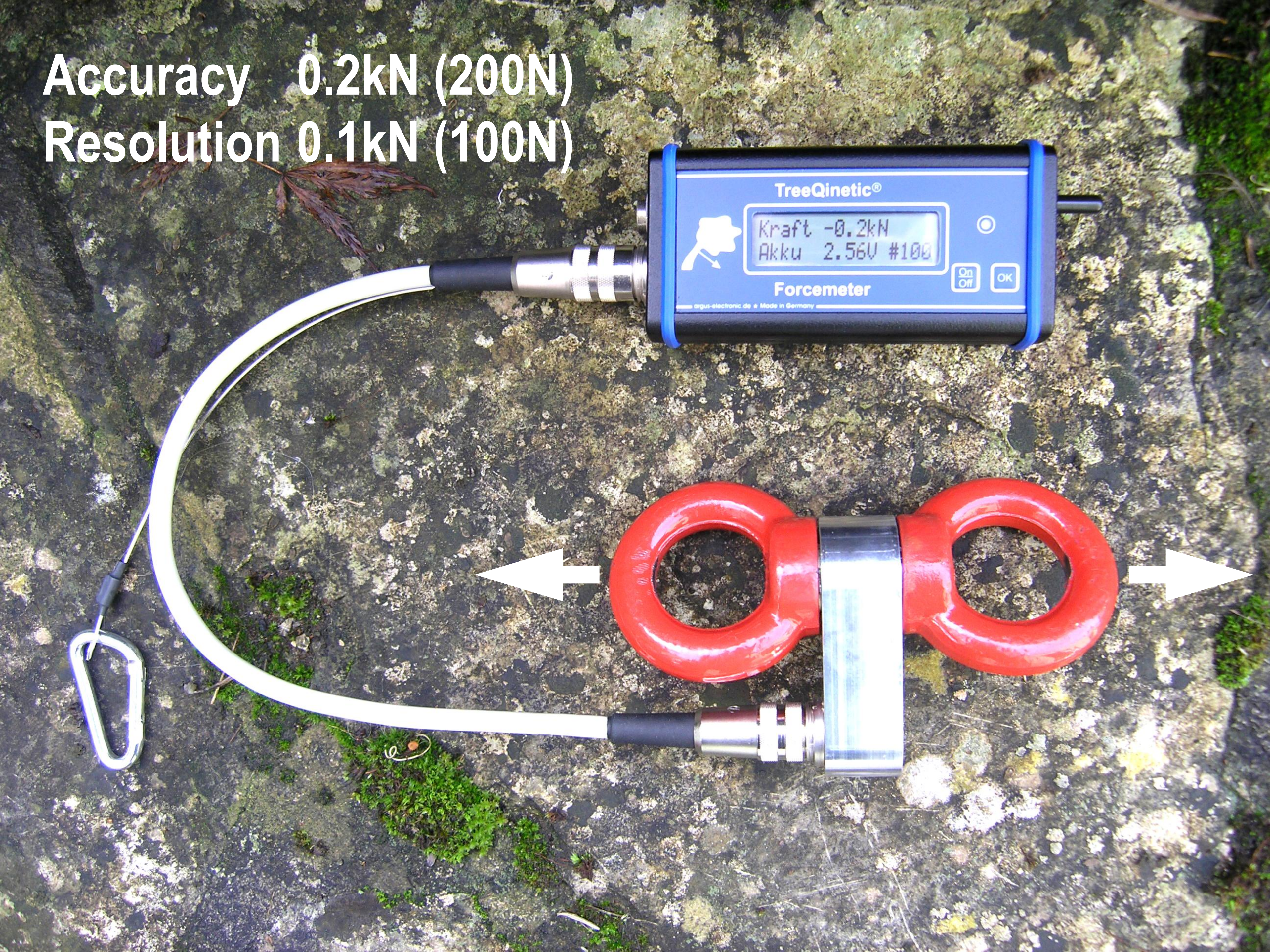
σ_{Max} = Yield Strength

ε_L = Elastic Limit

Young's Modulus

E = Stress / Strain


Accuracy 0.002° (1/500°)
Resolution 0.002° (1/500°)
Maximum 0.25°

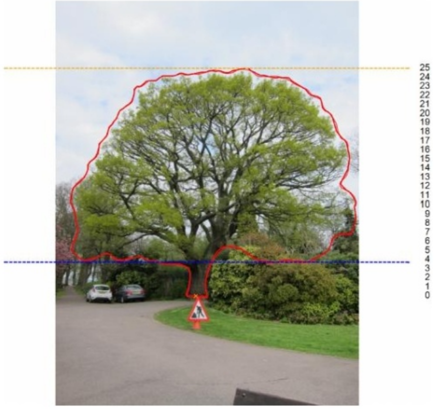

Accuracy 0.2kN (200N)
Resolution 0.1kN (100N)
TreeQinetic®
Kraft -0.2kN
Akku 2.56V #100
On Off
OK
Forcemeter

Wind Load Analysis analogous to DIN 1055-4

Project			Site	Tree Number	T1
Project Name	Brandon Hill				
Project Number	C087				
Test Date	17/04/2015		Altitude a. sea level	62	m

Tree Data				Applied Material Properties		
Tree Species	Quercus robor			as for	Quercus robur	
Stem circumference		535	cm	Source	Stuttgart	
Stem Diameter	||	155	cm	Compressive Strength	28	MPa
in 1m height	_|_	155	cm	Modulus of Elasticity	6900	MPa
Bark Thickness		4	cm	Limit of Elasticity	0.41	%
Tree Height		**25**	**m**	Green Density	1.03	g/cm³

Crown Outline



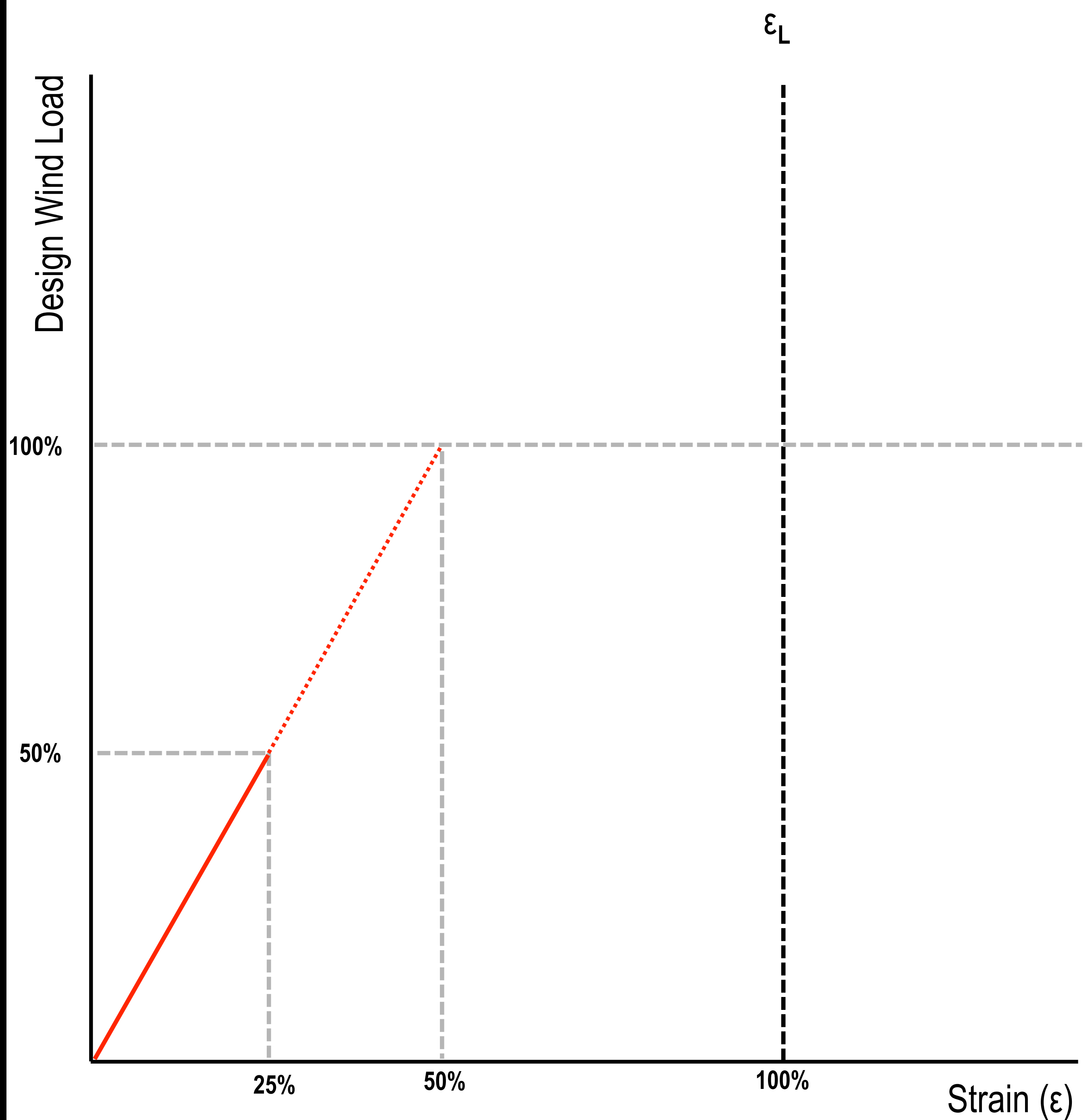
Load Direction	NNE/20°	
Surface Area Analysis		
Crown Base	3.7	m
Effective Height	16.5	m
Total Surface Area	541	m²
Crown Eccentricity	2.3	m
Applied Structural Parameters		
Drag Factor	0.25	
Natural Frequency	0.75	Hz
Damping Decrement	0.6	
Form Factor for Dead Weight	0.8	
Applied Site Parameters		
Windzone	GB 21	
Speed of Applied Design Wind Speed	22	m/s
Air Density	1.28	kg/m³
Roughness Catagory	Landscape	
Exponent for Wind Profile	0.16	
Proximity Factor for Effects in Near Ground Wind Flow	1.08	
Factor for Crown Exposure	1.00	

Results

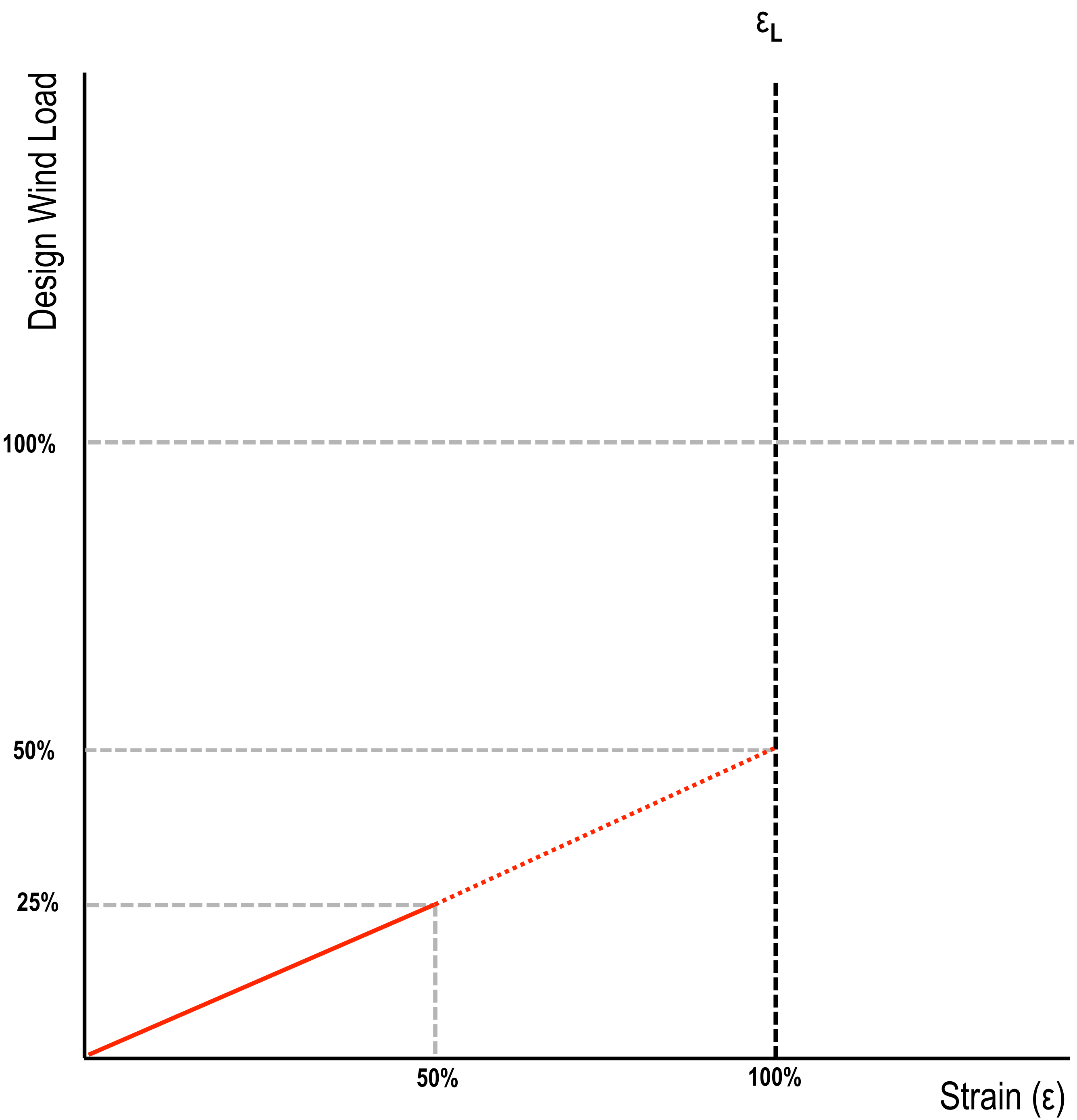
Wind Load Analysis			**Tree Static Analysis**		
Mean Wind Pressure	52.4	kN	Dead Weight Tree	35	t
Gust Reaction Factor	1.96		Critical Degree of Hollowness	94	%
Load Centre	14.1	m	Critical Residual Wall Thickness	4	cm
Torsion Moment	235	kNm	Assuming an Uncompromised Residual Wall		
Design Wind Load	**1443**	**kNm**	**Basic Safety Factor**	**6**	

General

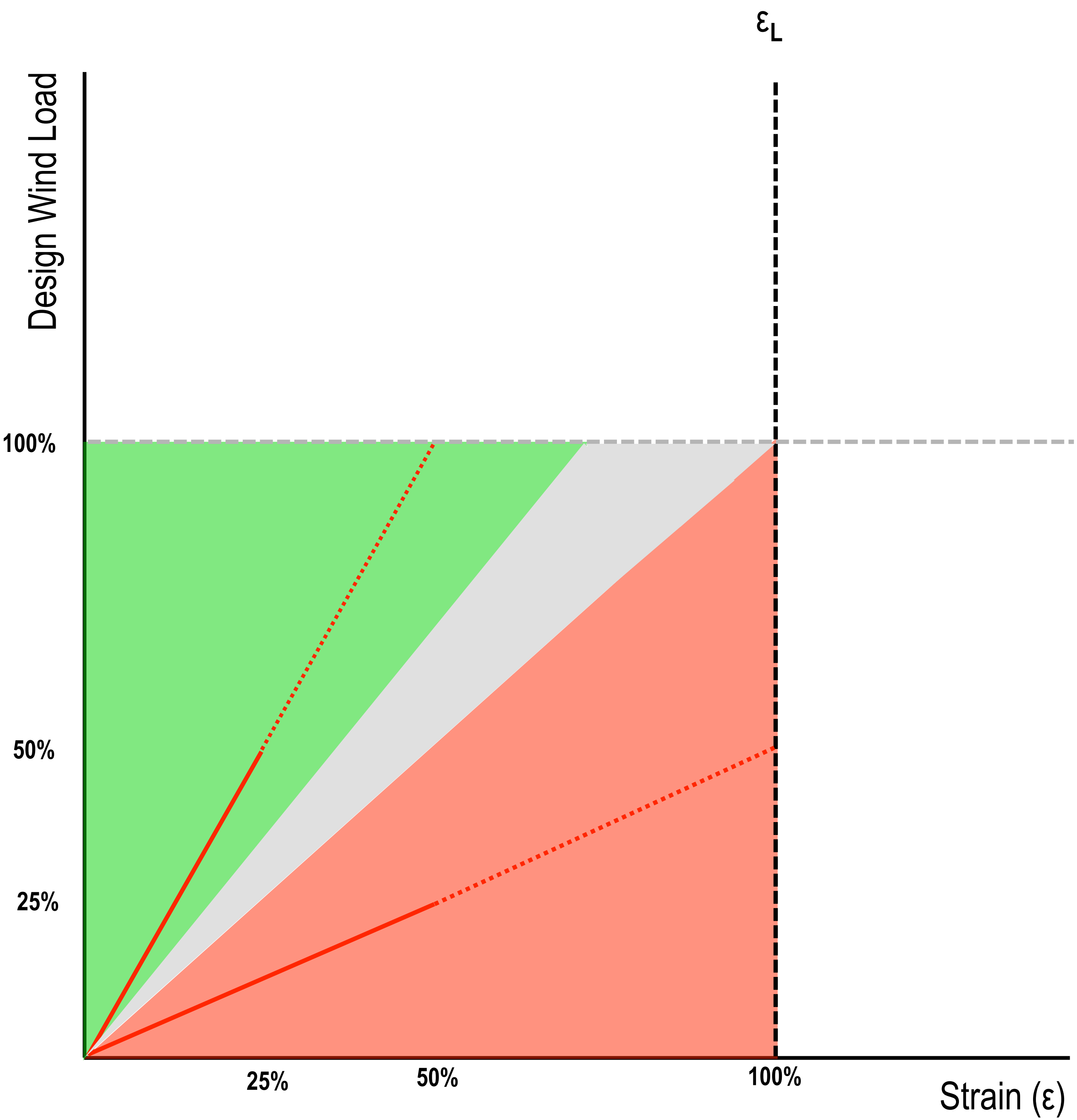
Comments



ε_L
Design Wind Load
100%
50%
25%
50%
100%
Strain (ε)



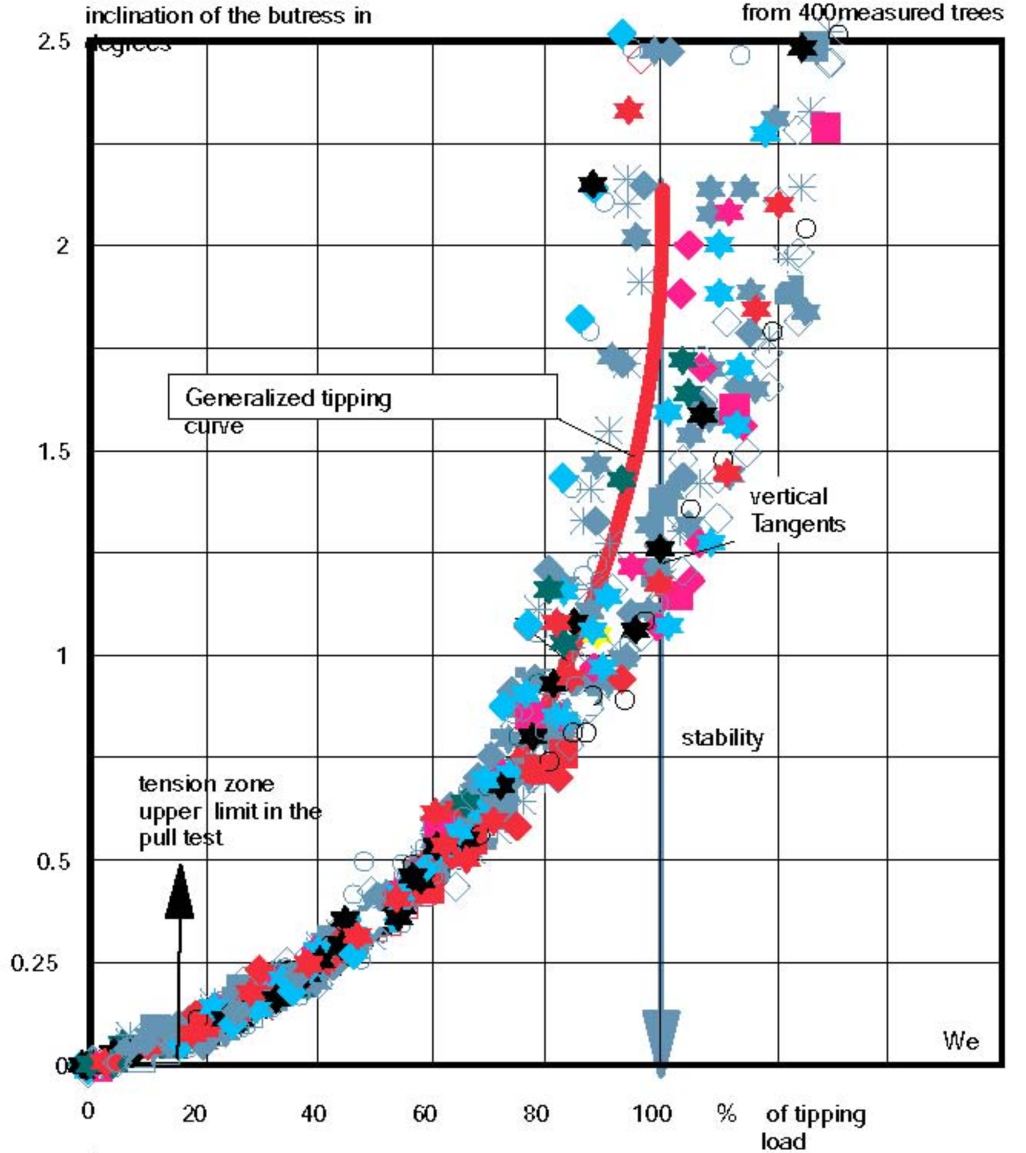
ε$_L$
Design Wind Load
100%
50%
25%
50%
100%
Strain (ε)



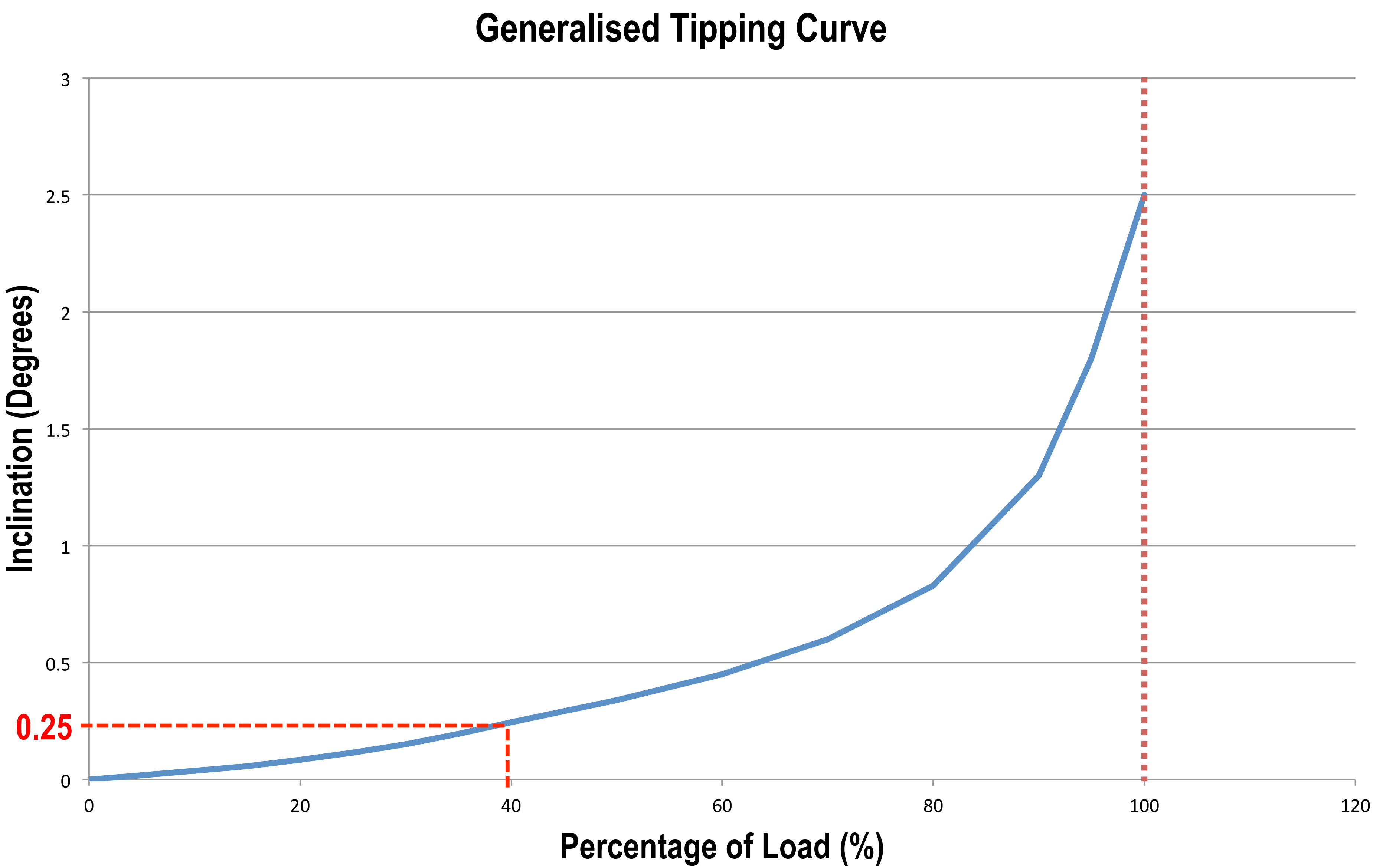
ε L
Design Wind Load
100%
50%
25%
25%
50%
100%
Strain (ε)

Stability

generalized tipping curve



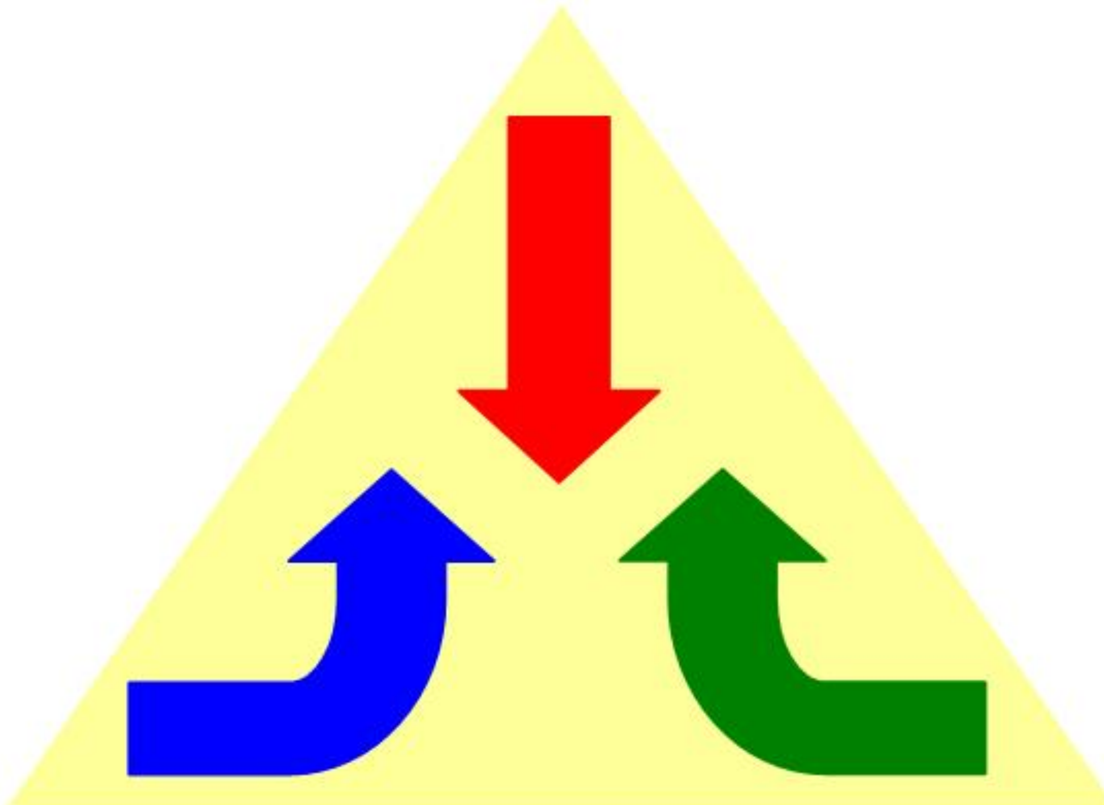
Substitute load standardized to a fixed hurricane relationship


Generalised Tipping Curve
Inclination (Degrees)
3
2.5
2
1.5
1
0.5
0.25
0
0
20
40
60
80
100
120
Percentage of Load (%)


WHAT ON EARTH AM I DOING IN HERE ON THIS BEAUTIFUL DAY?! THIS IS THE ONLY LIFE I'VE GOT!!
AAAAAAAAAA

LOAD

Maximum load a structure is expected to be exposed to.



FORM

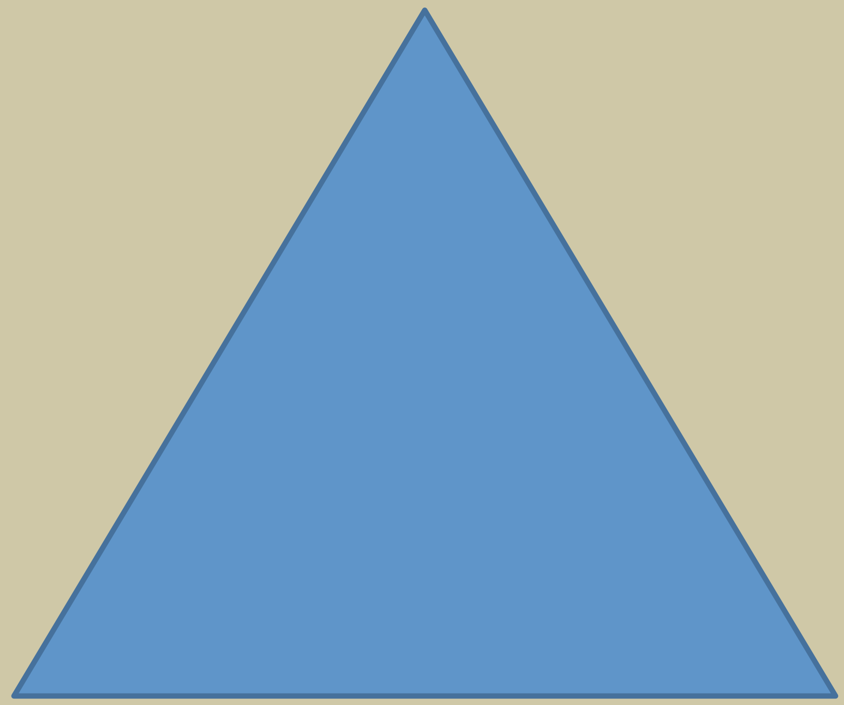
Geometry - the shape and size of a structure

MATERIAL

The physical properties of the material of the structure

Quantified Tree Risk Assessment (Ellison, 2005)

TARGET



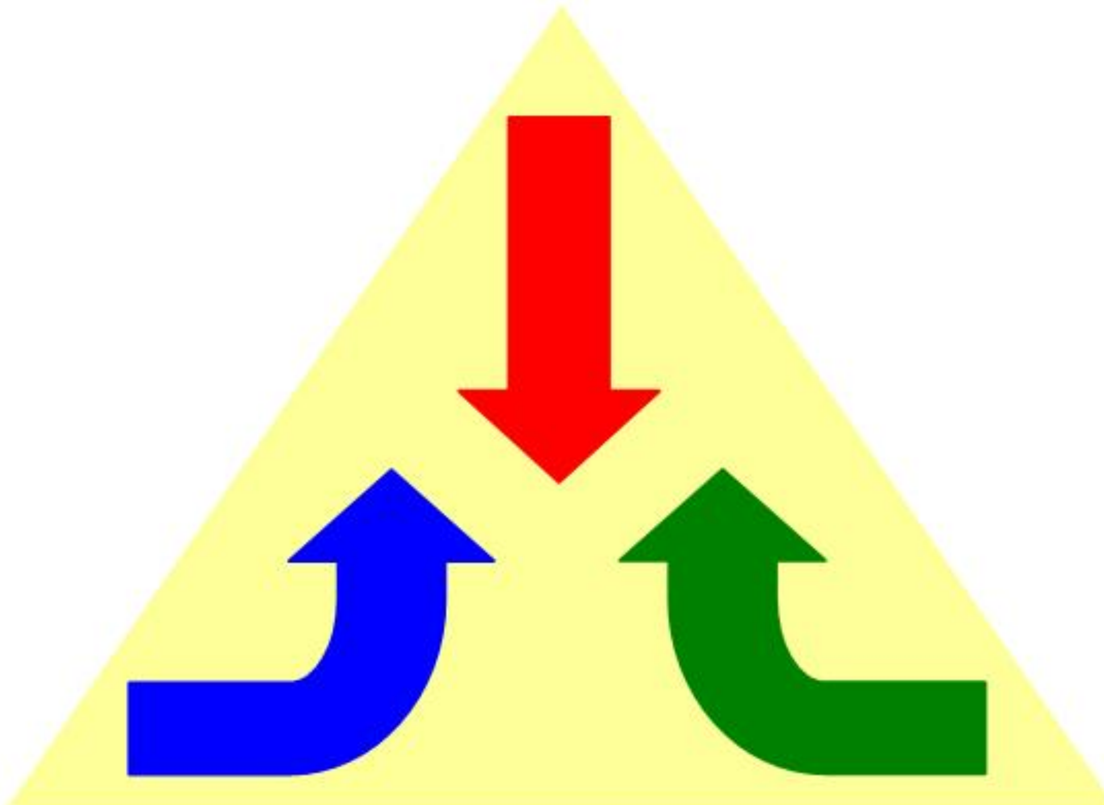
CONSEQUENCE

LIKELIHOOD

Quantified Tree Risk Assessment (Ellison, 2005)

LOAD

Maximum load a structure is expected to be exposed to.



FORM

Geometry - the shape and size of a structure

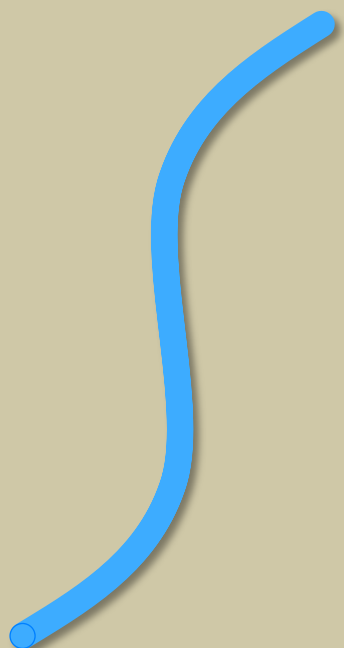
MATERIAL

The physical properties of the material of the structure

Safety Factor

Polypropelene Rope

Ø 22mm



Steel Cable

Ø 16mm

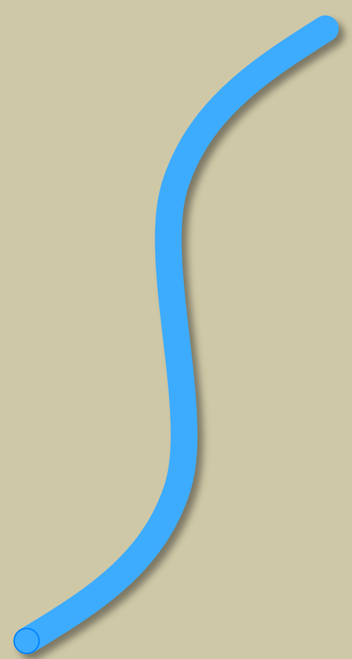
Dyneema Rope

Ø 14mm

Safety Factor

Polypropelene Rope

Ø 22mm - MBS 50kN



Steel Cable

Ø 16mm - MBS 150kN

Dyneema Rope

Ø 14mm - MBS 200kN

Safety Factor

Polypropelene Rope

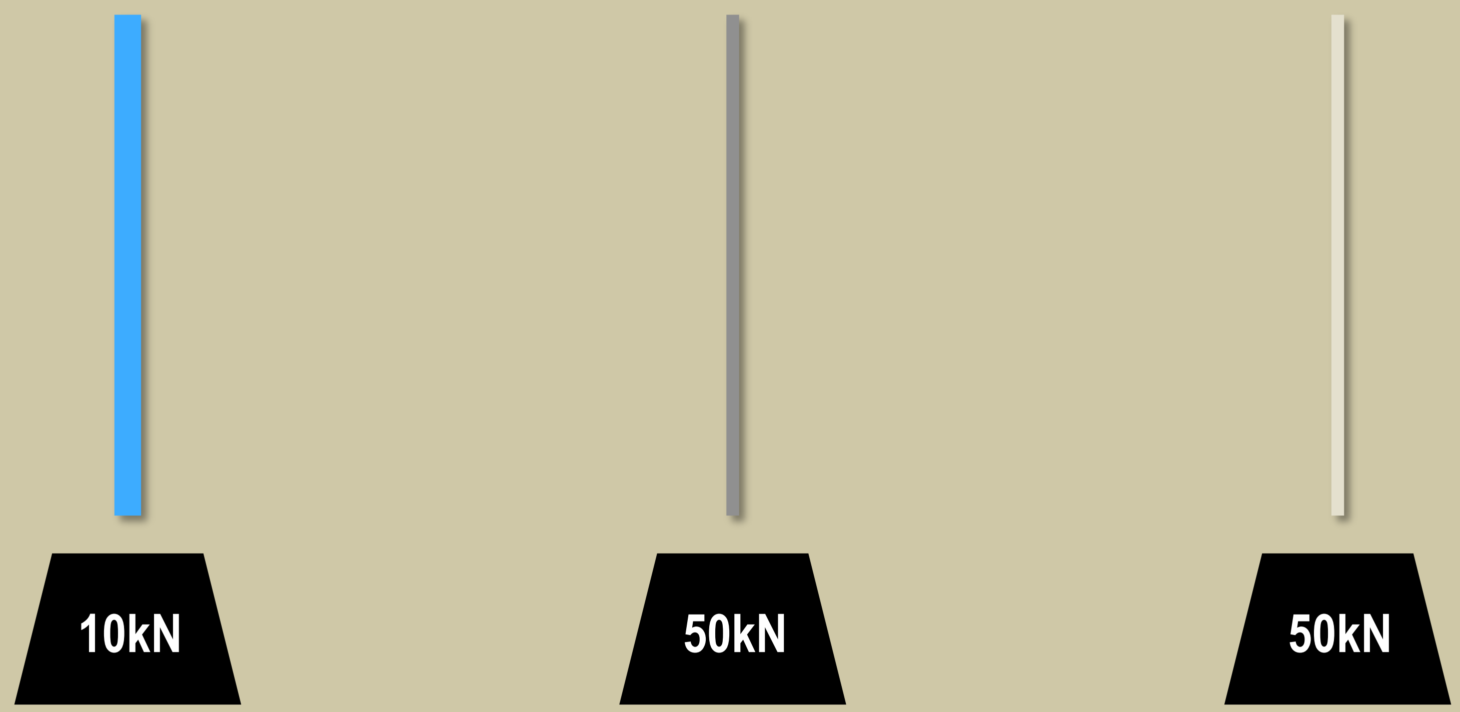
Ø 22mm - MBS 50kN

Steel Cable

Ø 16mm - MBS 150kN

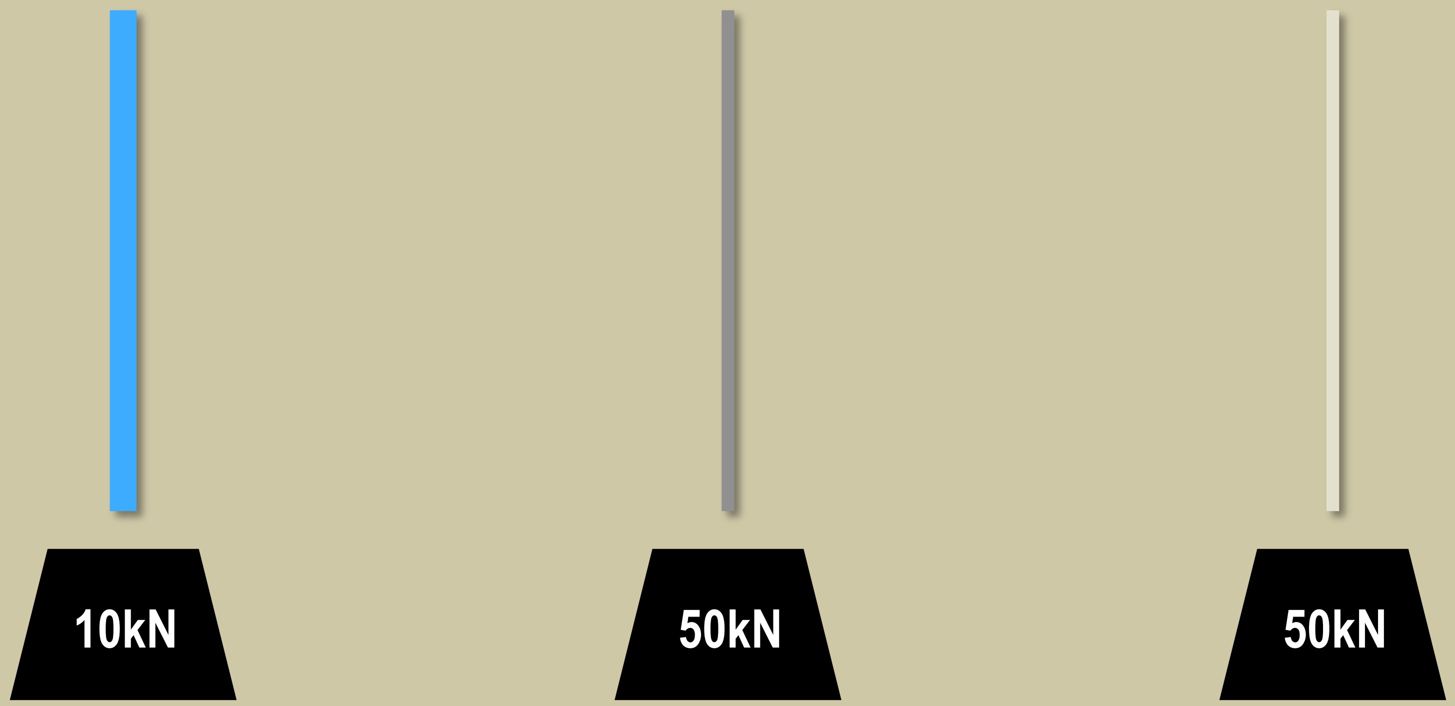
Dyneema Rope

Ø 14mm - MBS 200kN



Safety Factor

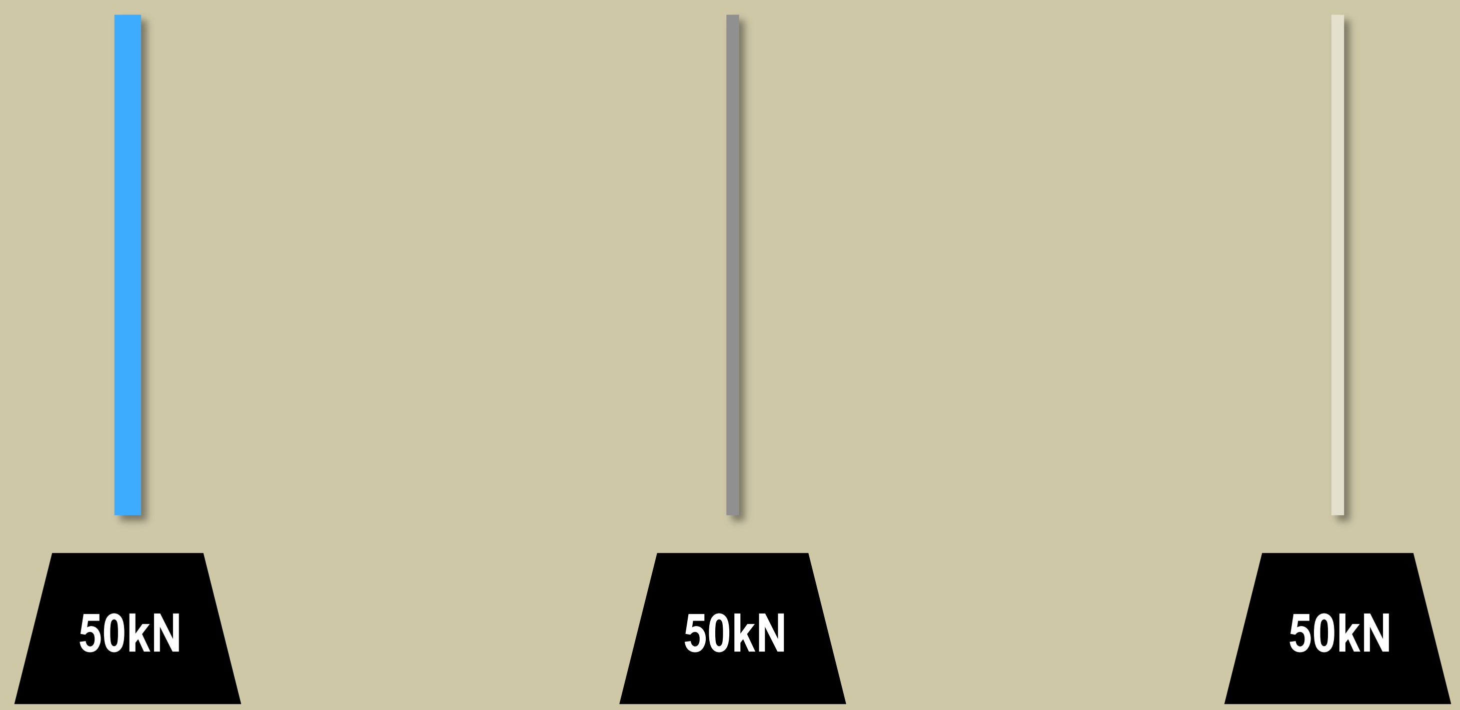
Polypropelene Rope	Steel Cable	Dyneema Rope
Ø 22mm - MBS 50kN	Ø 16mm - MBS 150kN	Ø 14mm - MBS 200kN



SF = 5	SF = 3	SF = 4

Safety Factor

Polypropelene Rope	Steel Cable	Dyneema Rope
Ø 22mm - MBS **50kN**	Ø 16mm - MBS **150kN**	Ø 14mm - MBS **200kN**



SF = 1	SF = 3	SF = 4

Safety Factor

Polypropelene Rope

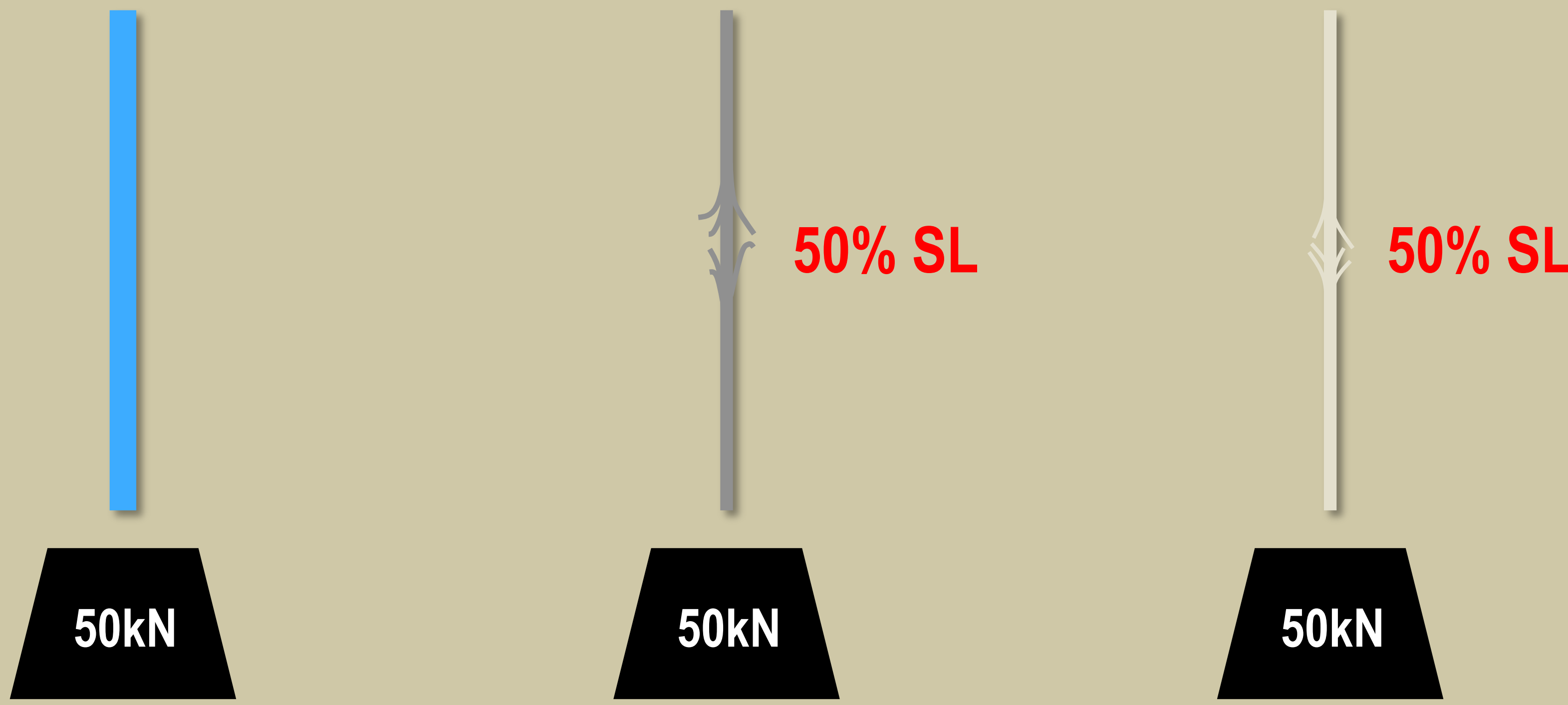
Ø 22mm - MBS 50kN

Steel Cable

Ø 16mm - MBS 150kN

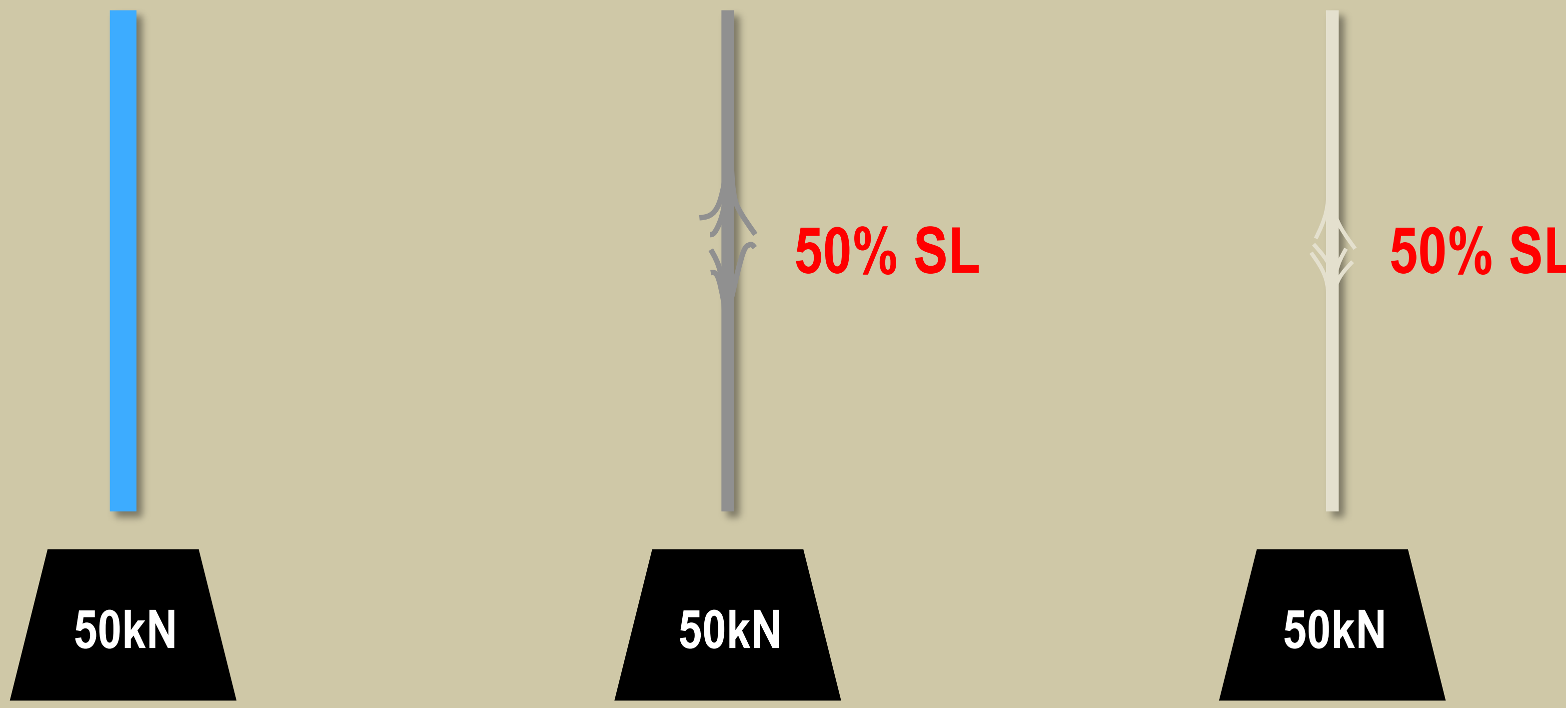
Dyneema Rope

Ø 14mm - MBS 200kN

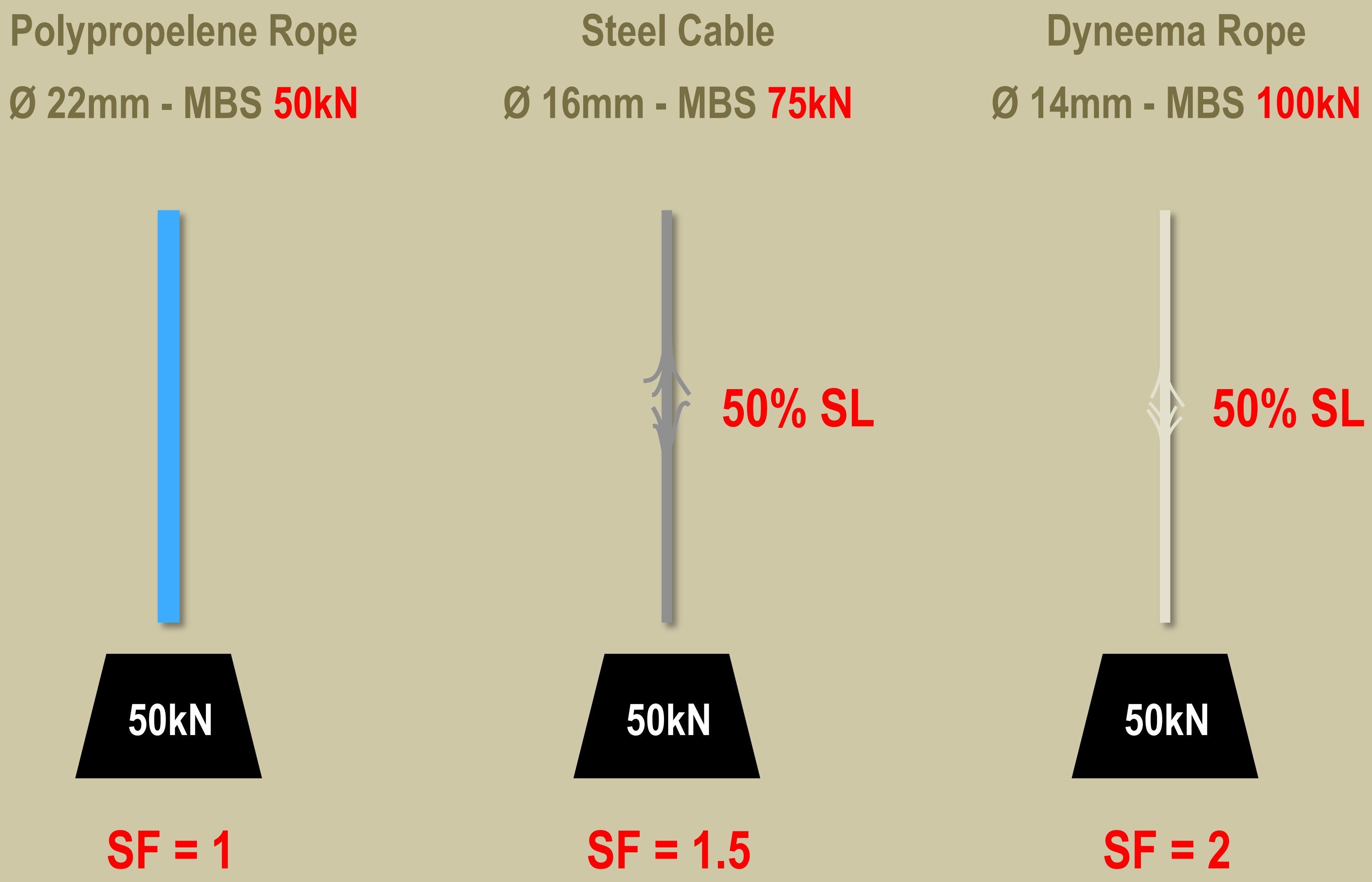


Safety Factor

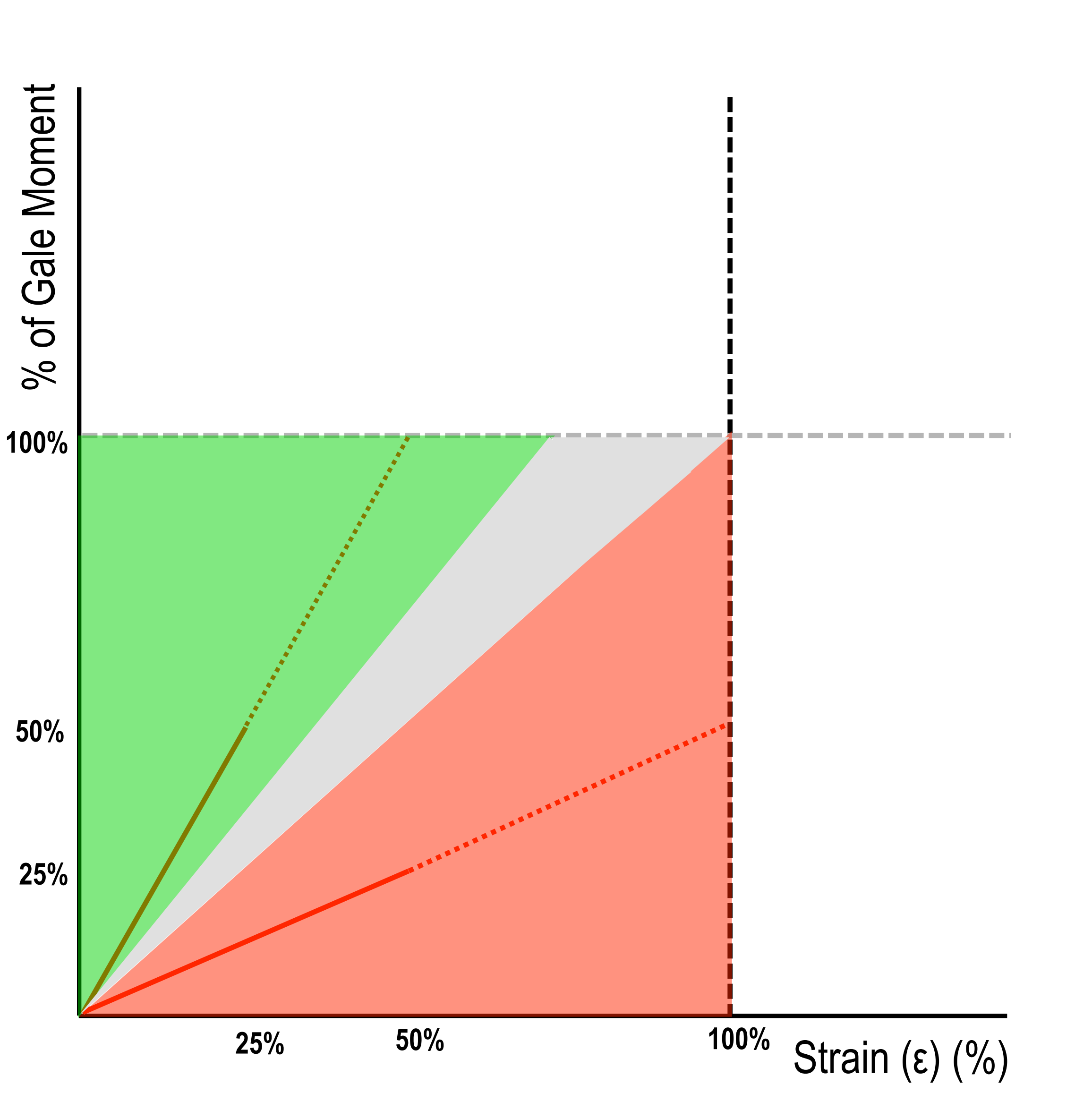
Polypropelene Rope	Steel Cable	Dyneema Rope
Ø 22mm - MBS 50kN	Ø 16mm - MBS 75kN	Ø 14mm - MBS 100kN



Safety Factor



Safety Factor For Stem Fracture



Safety Factor < 1.0

Safety Factor > 1.5

Safety Factor > 1.0-1.5

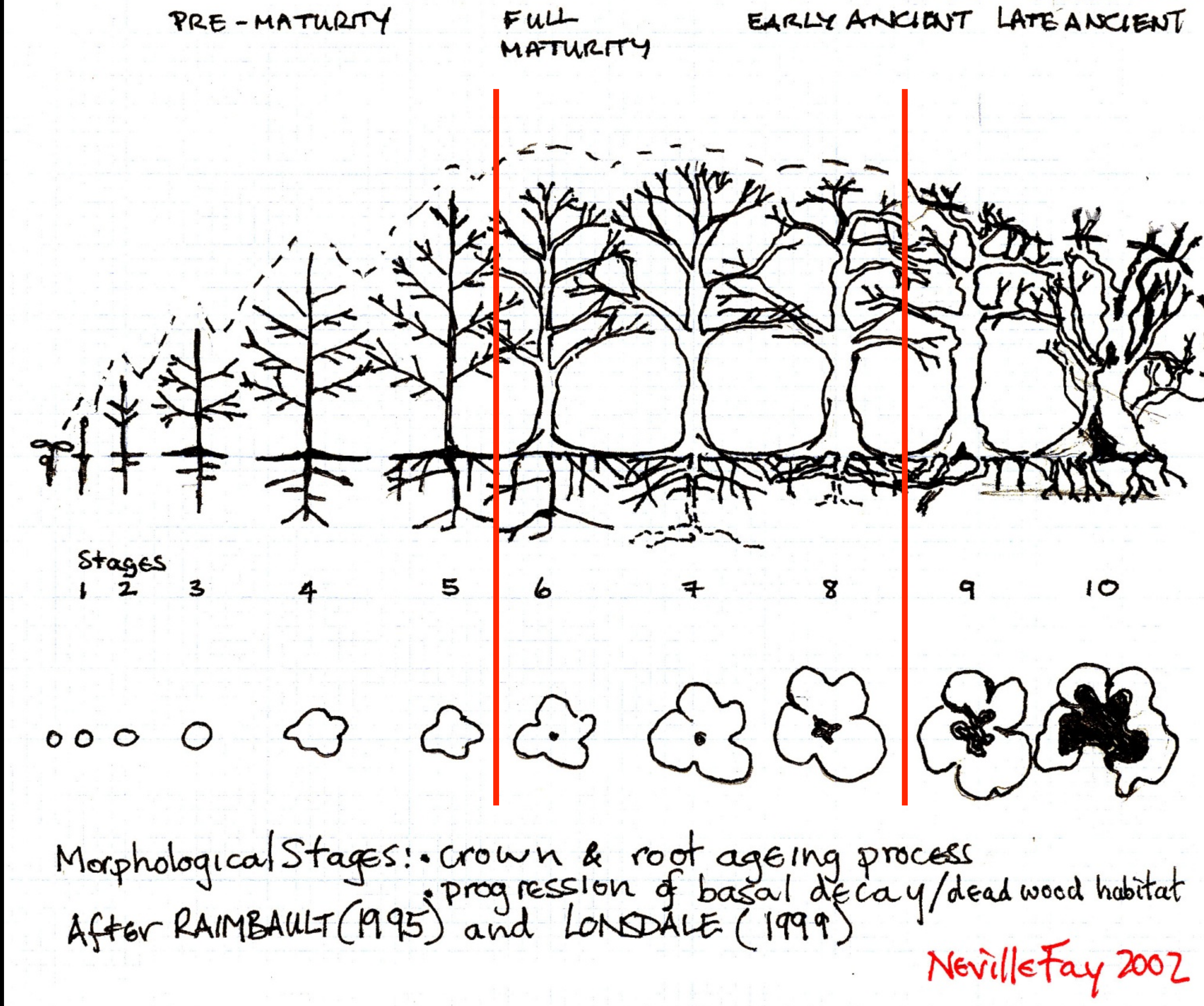
Safety Factors For Trees – Early Mature

Safety Factors For Trees - Mature

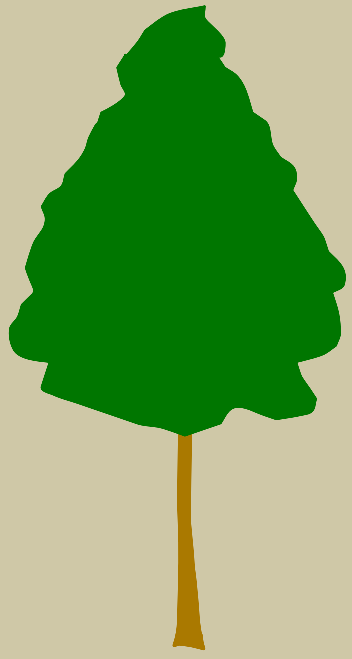
Safety Factors For Trees – Late Mature

Height = 22m
Stem Diameter = 110cm
Safety Factor = 7

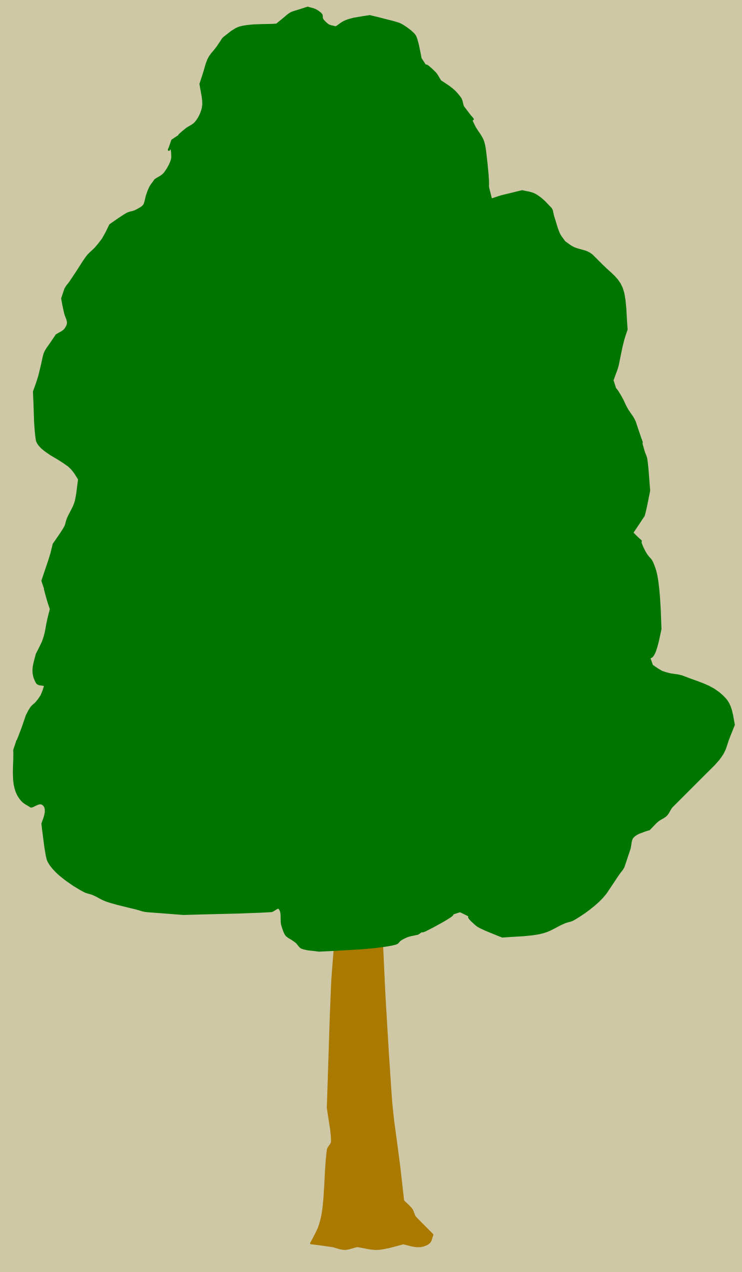
Safety Factors For Trees – Late Mature


PRE-MATURITY
FULL MATURITY
EARLY ANCIENT
LATE ANCIENT
Stages
1 2 3 4 5 6 7 8 9 10
Morphological Stages: • crown & root ageing process
• progression of basal decay/dead wood habitat
After RAIMBAULT (1995) and LONSDALE (1999)
Neville Fay 2002

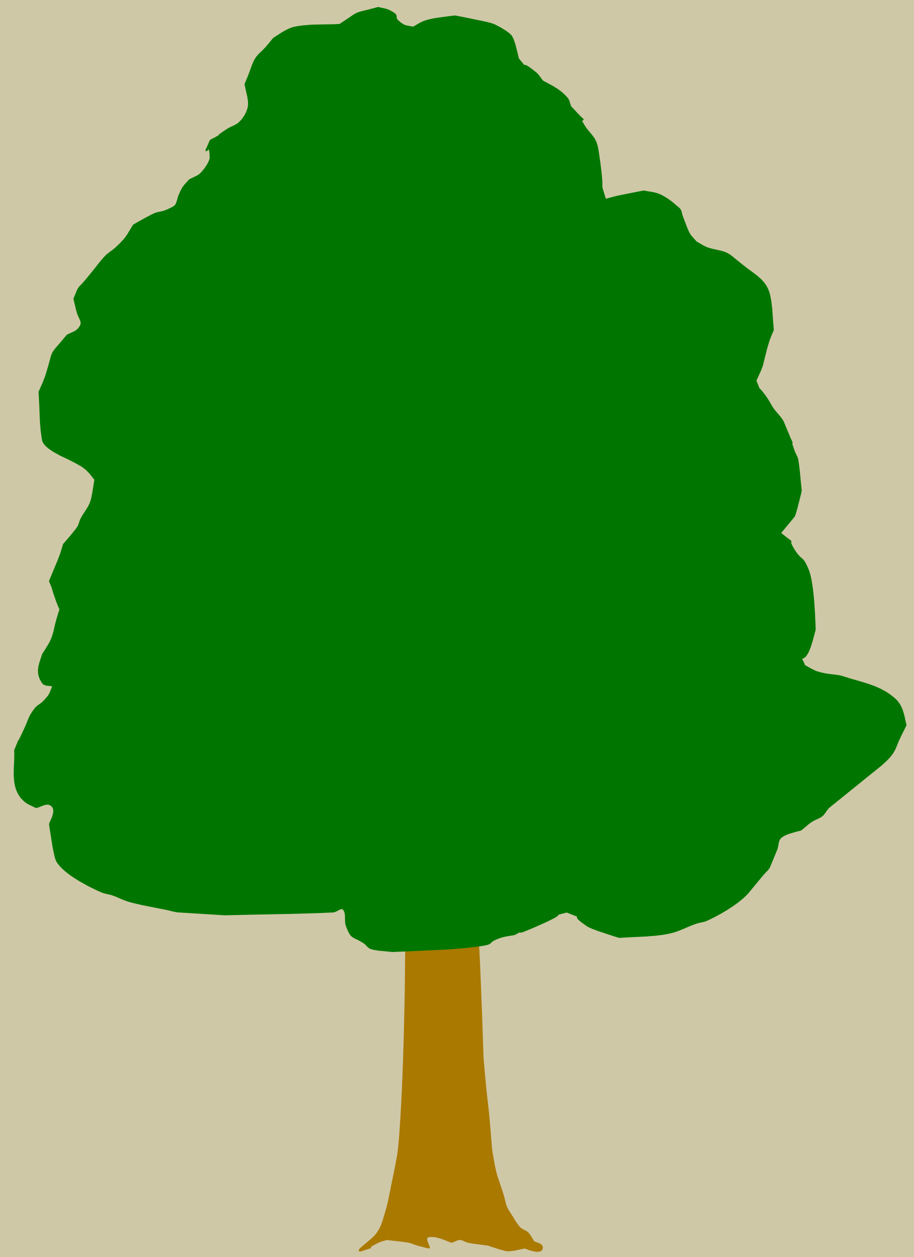
Semi-Mature



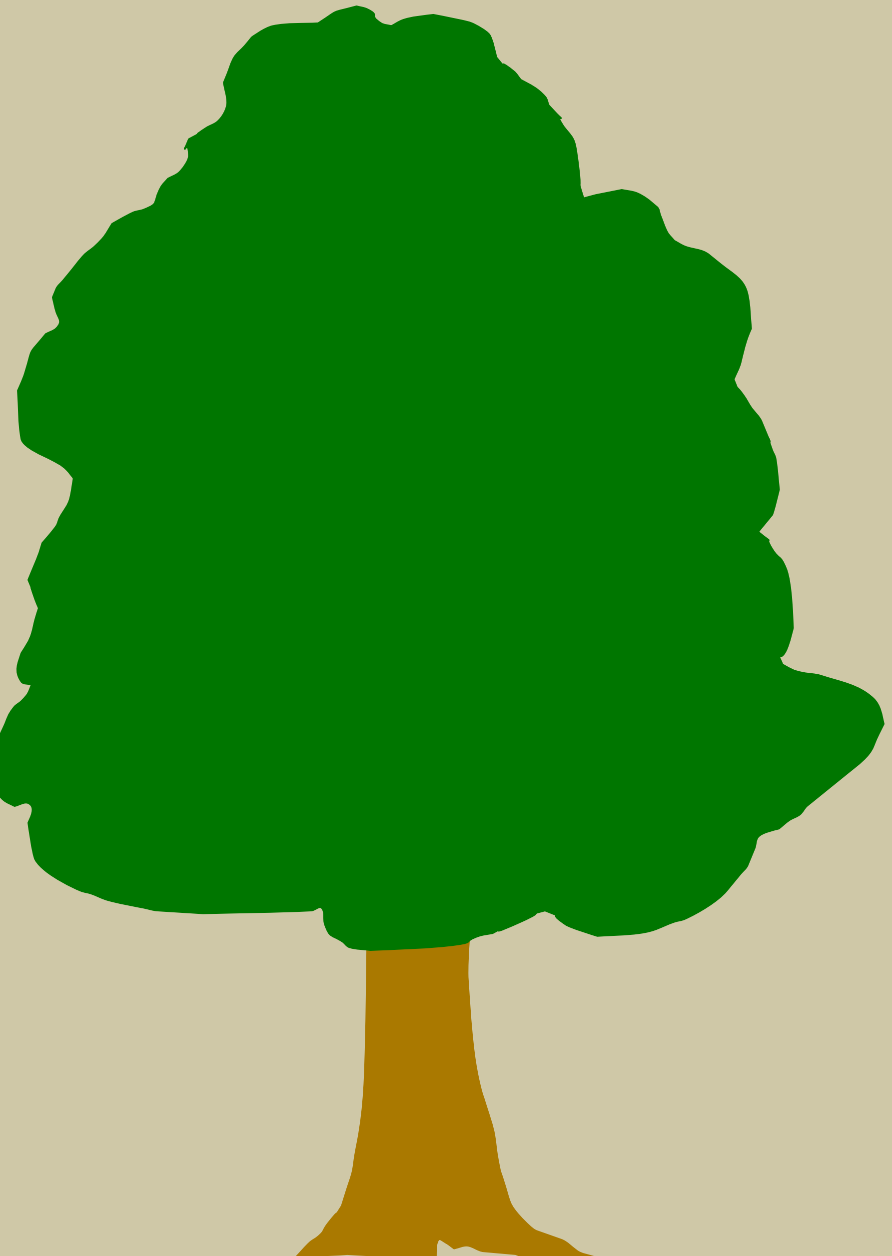
Early Mature



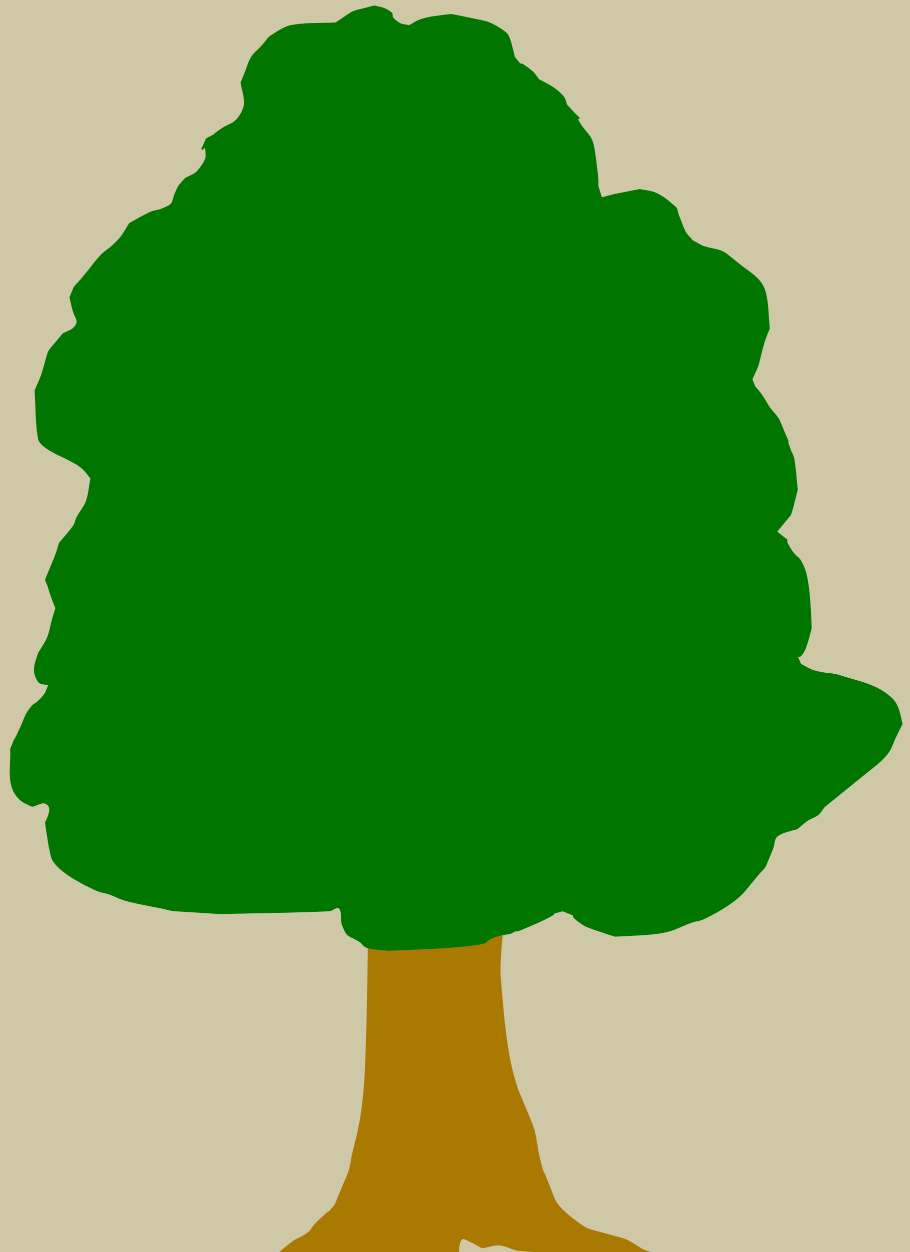
Mature



Mature



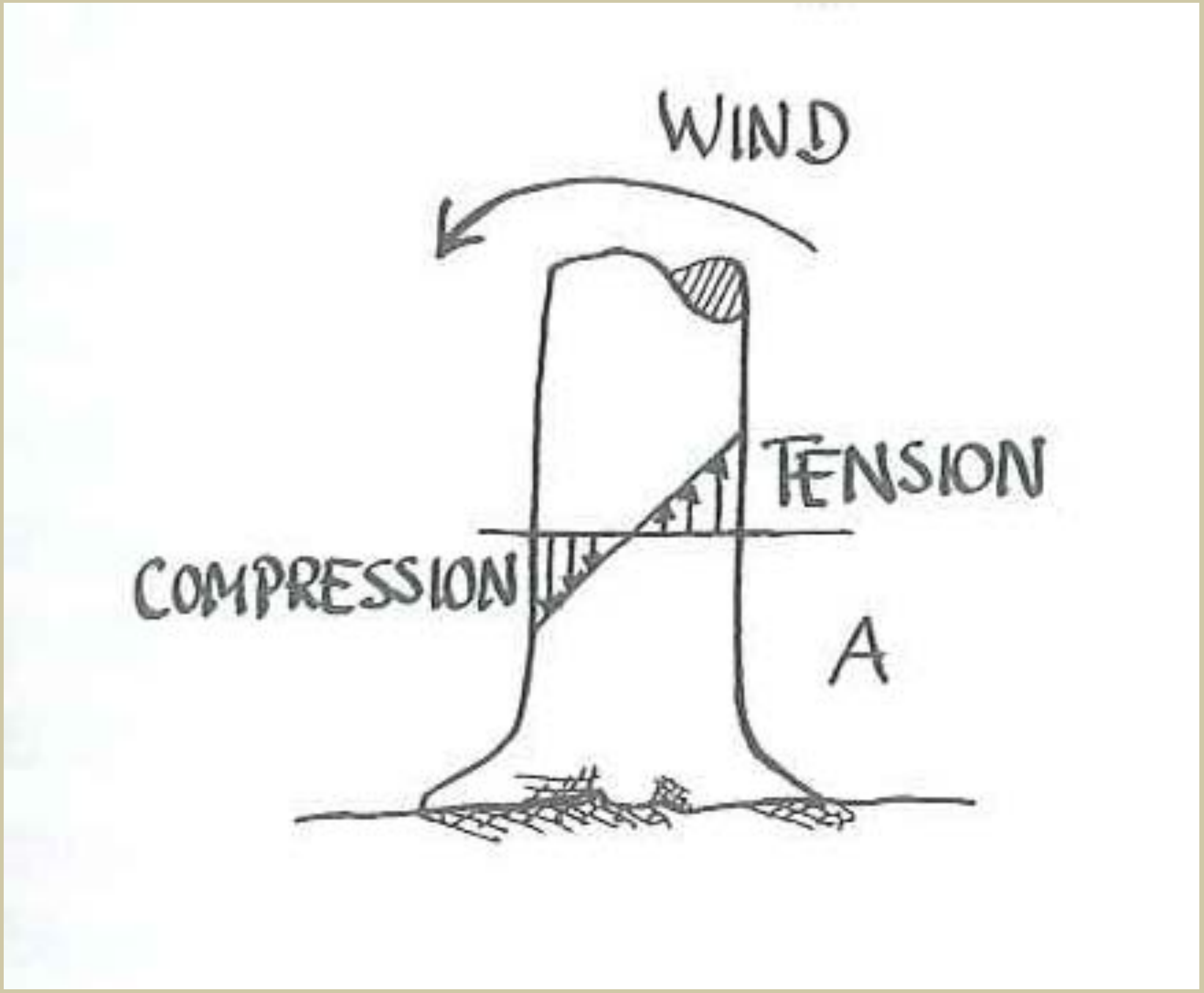
Mature



Late Mature

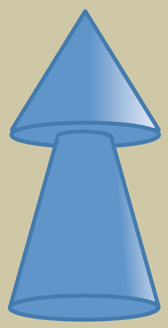
Ancient

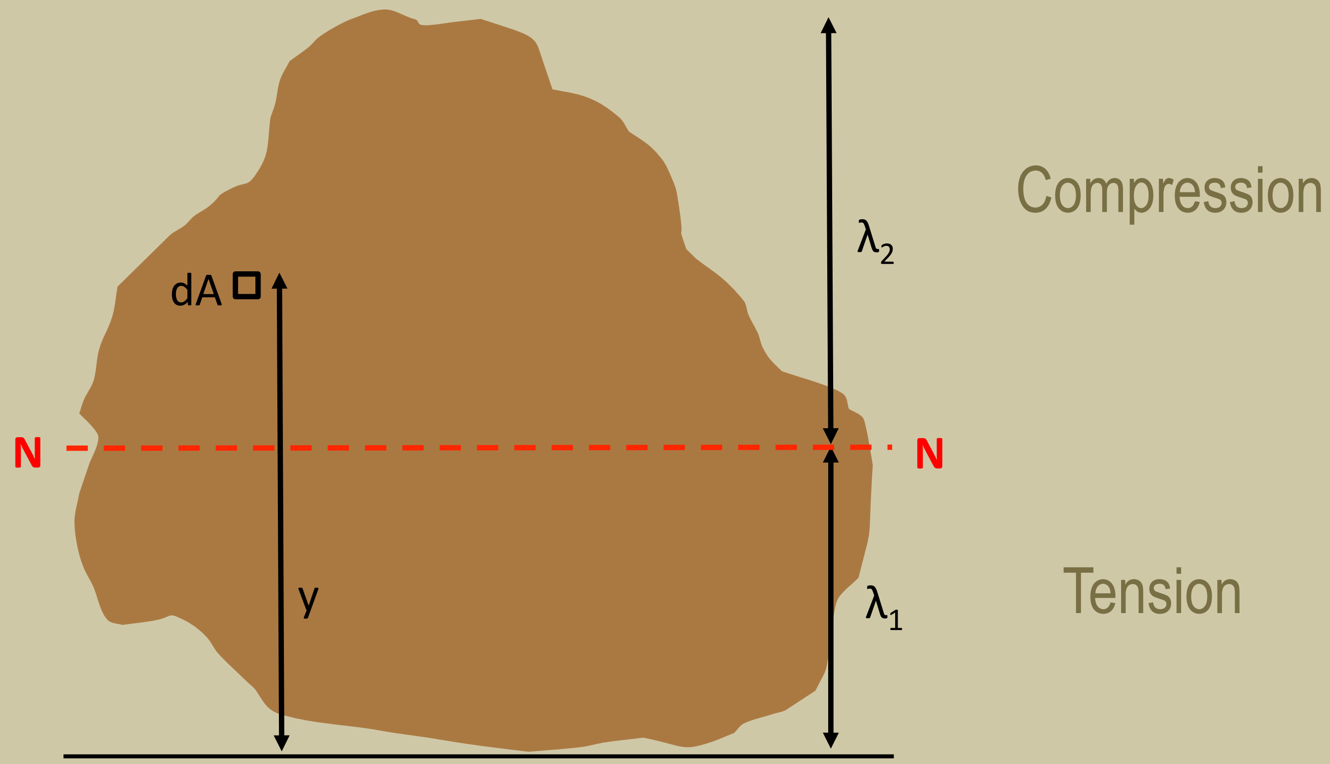
Section Modulus



Mattheck and Breloer (1994) The Body Language of Trees

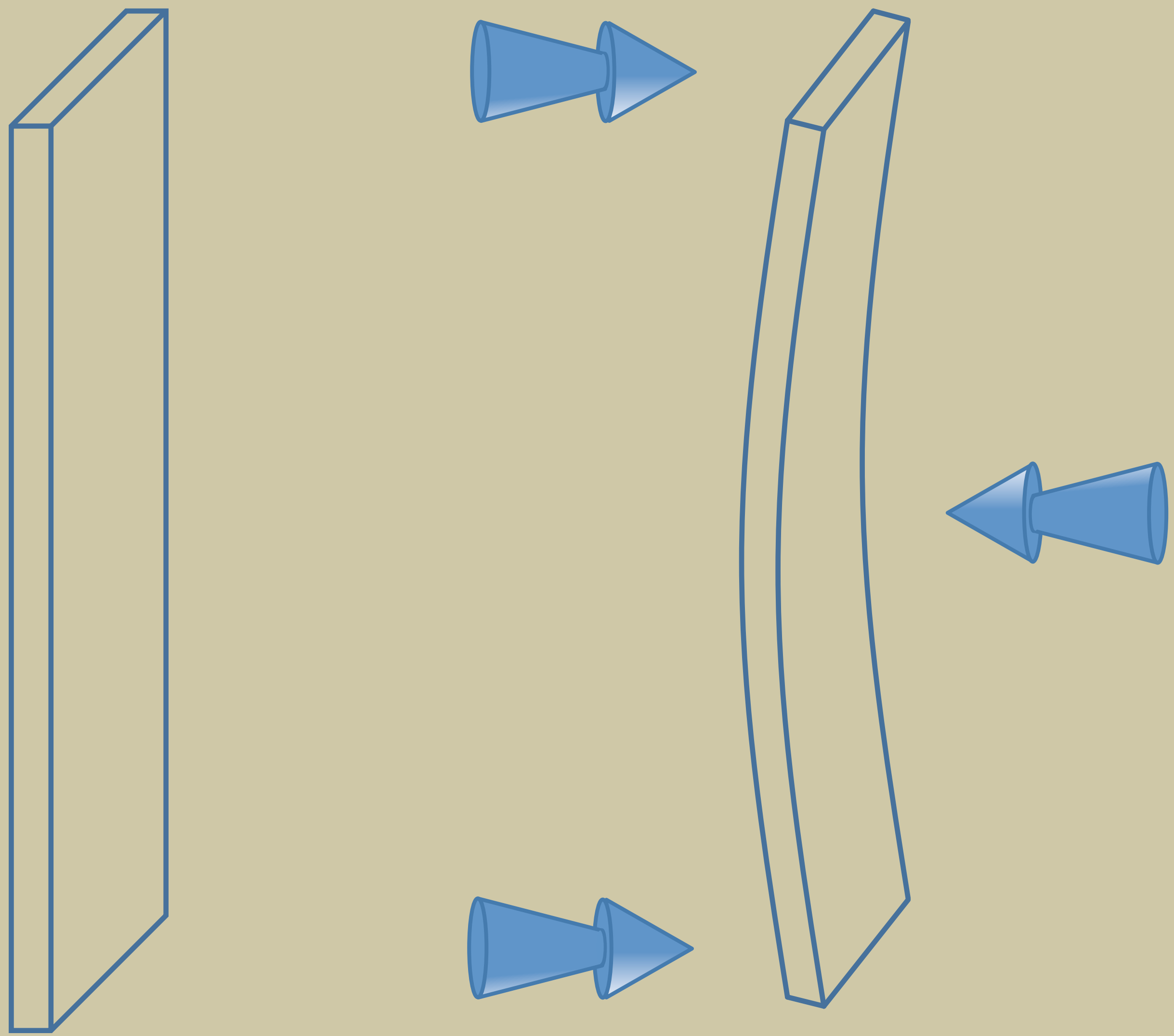
Section Modulus



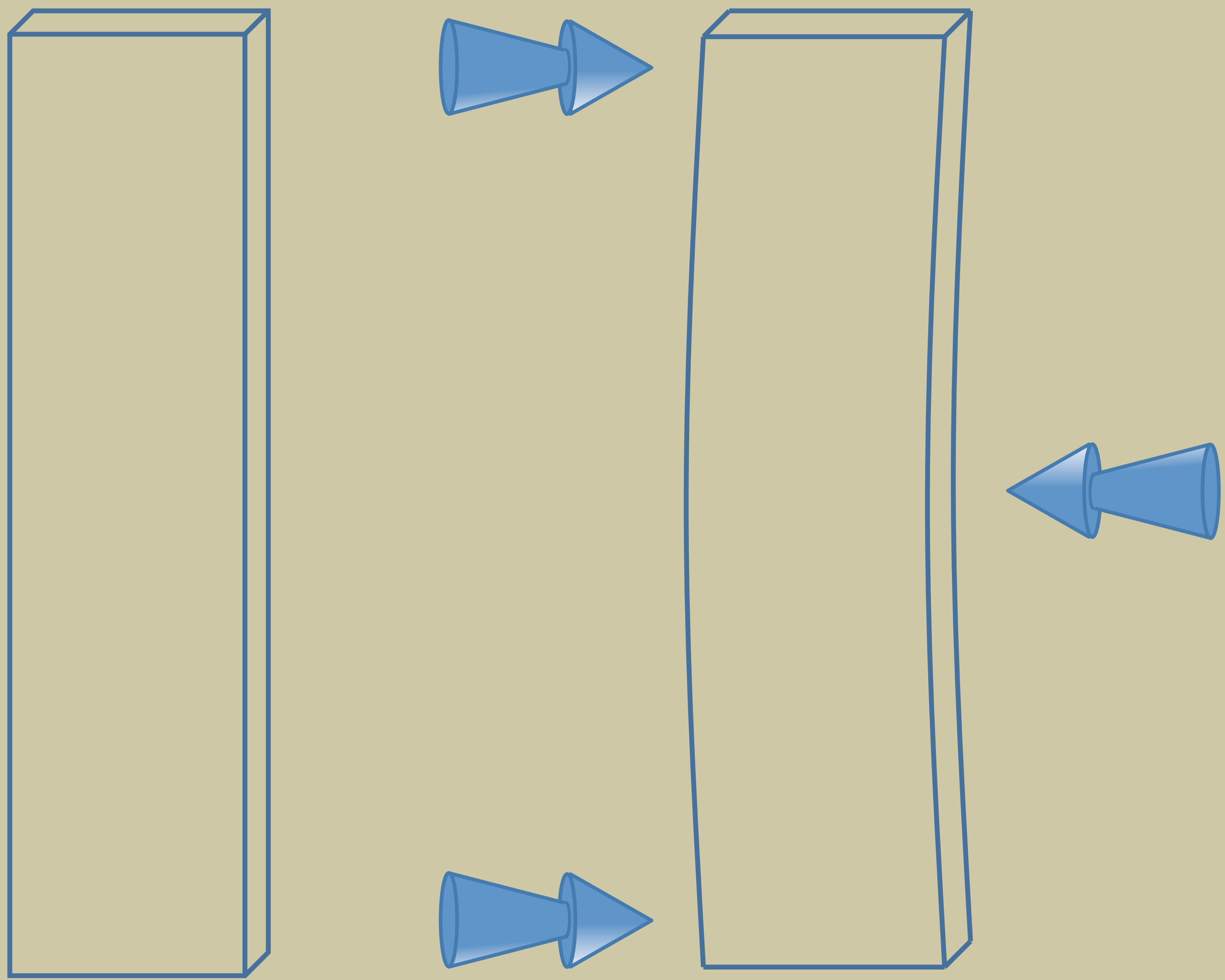


Neutral Axis	$\lambda_1 = \int y \, dA / \int dA$
Second Moment of Area	$I = \int (y - \lambda_1)^2 \, dA$
Section Modulus	$Z = I / Max(\lambda_1, \lambda_2)$

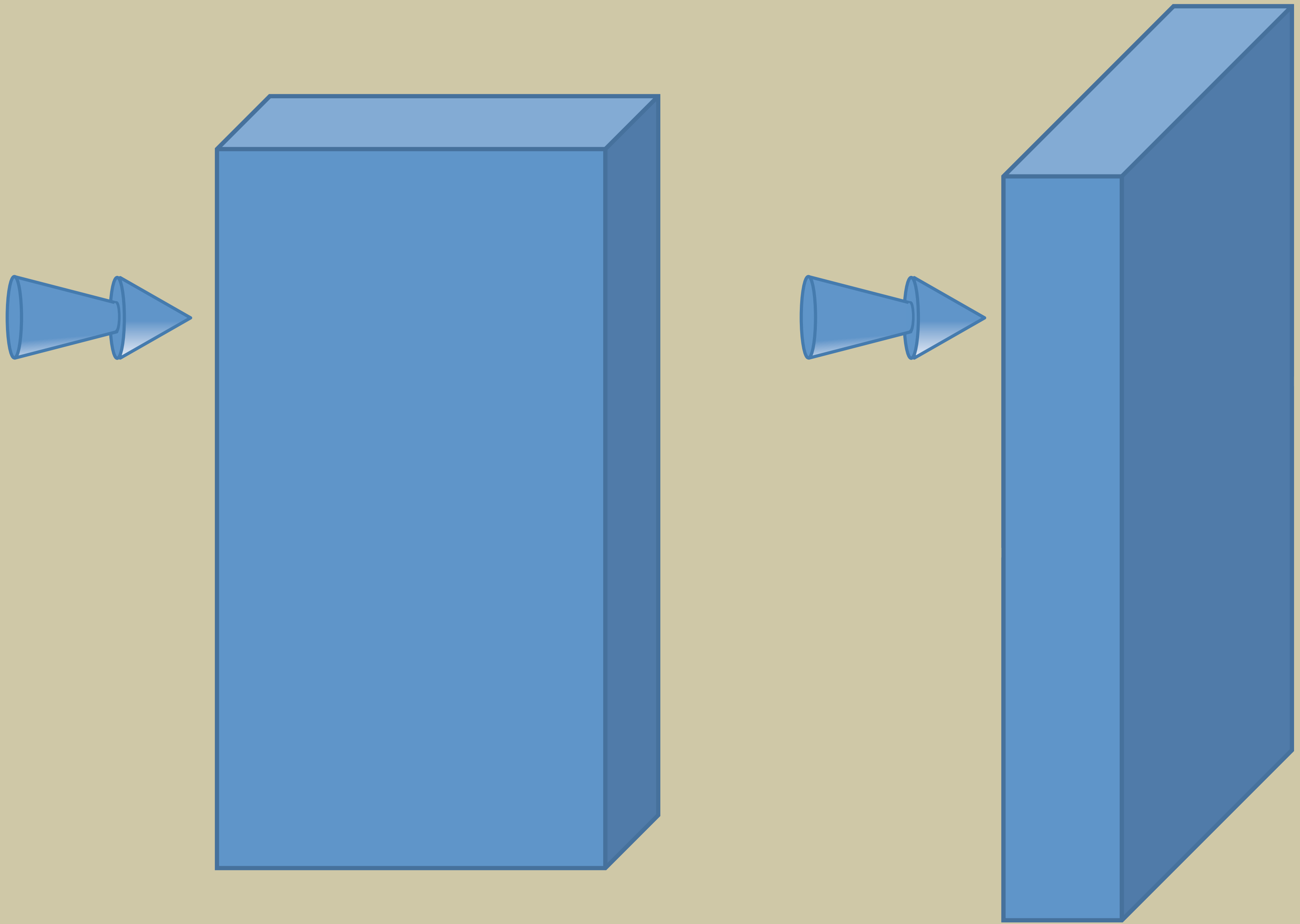
Section Modulus



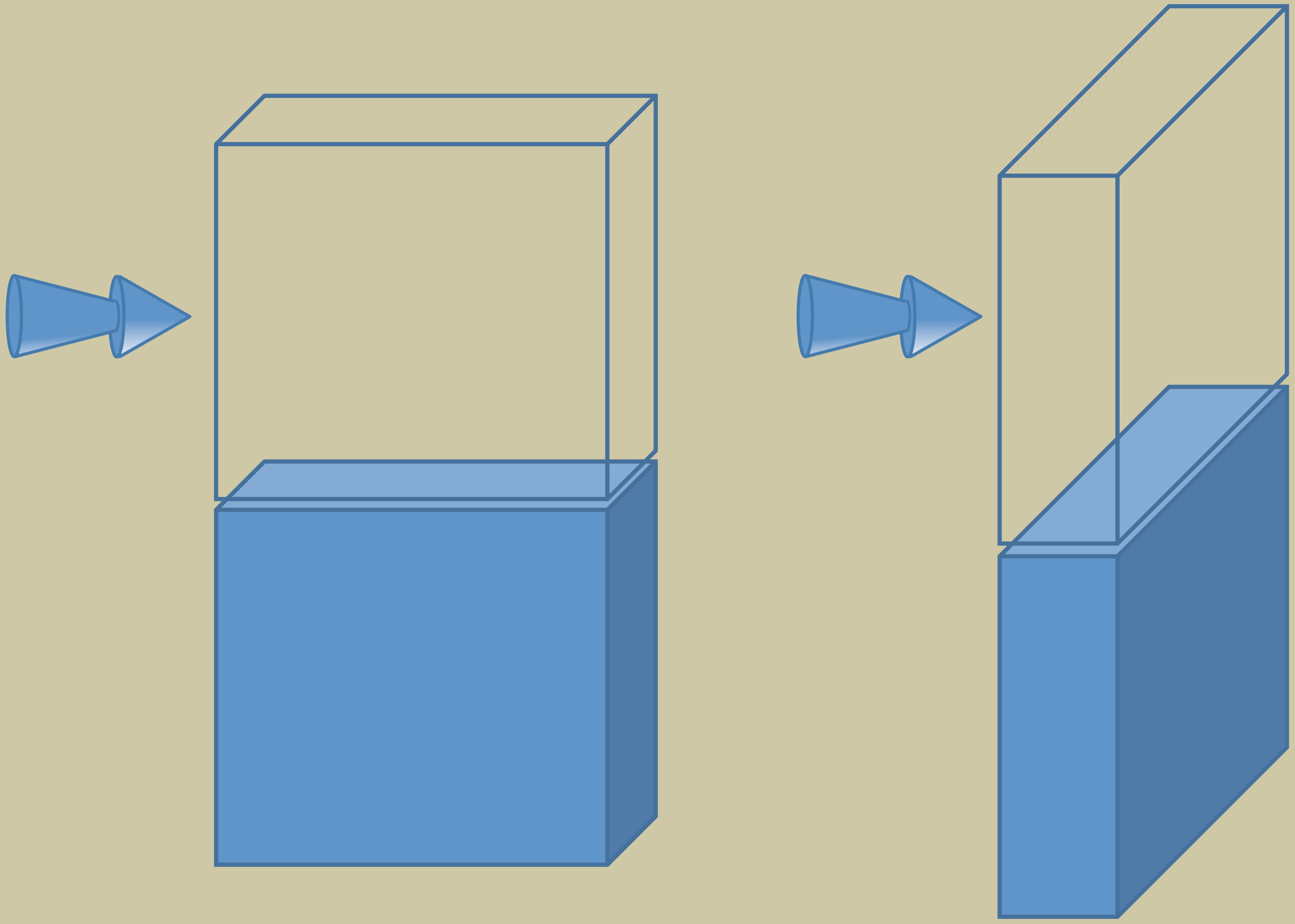
Section Modulus



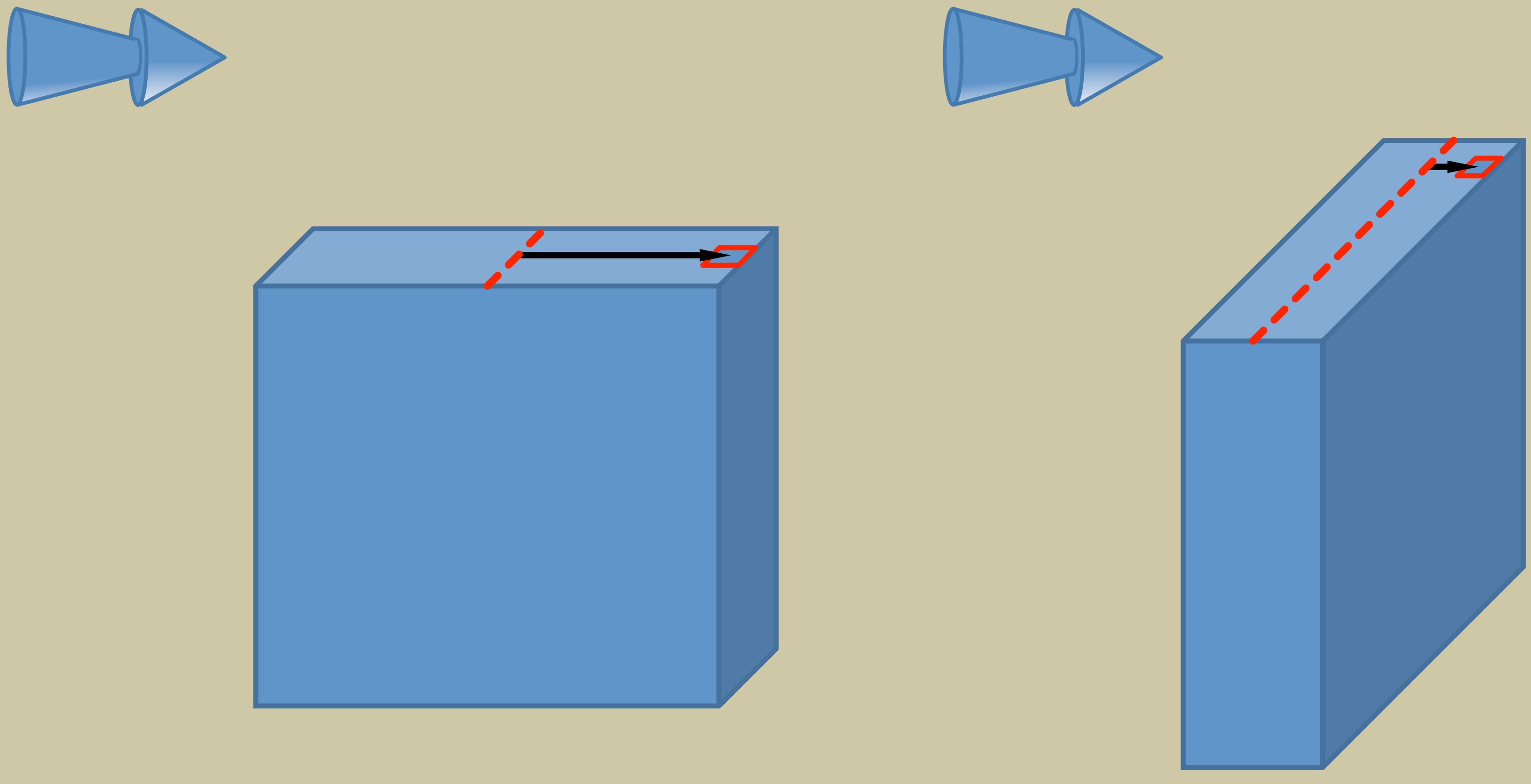
Section Modulus



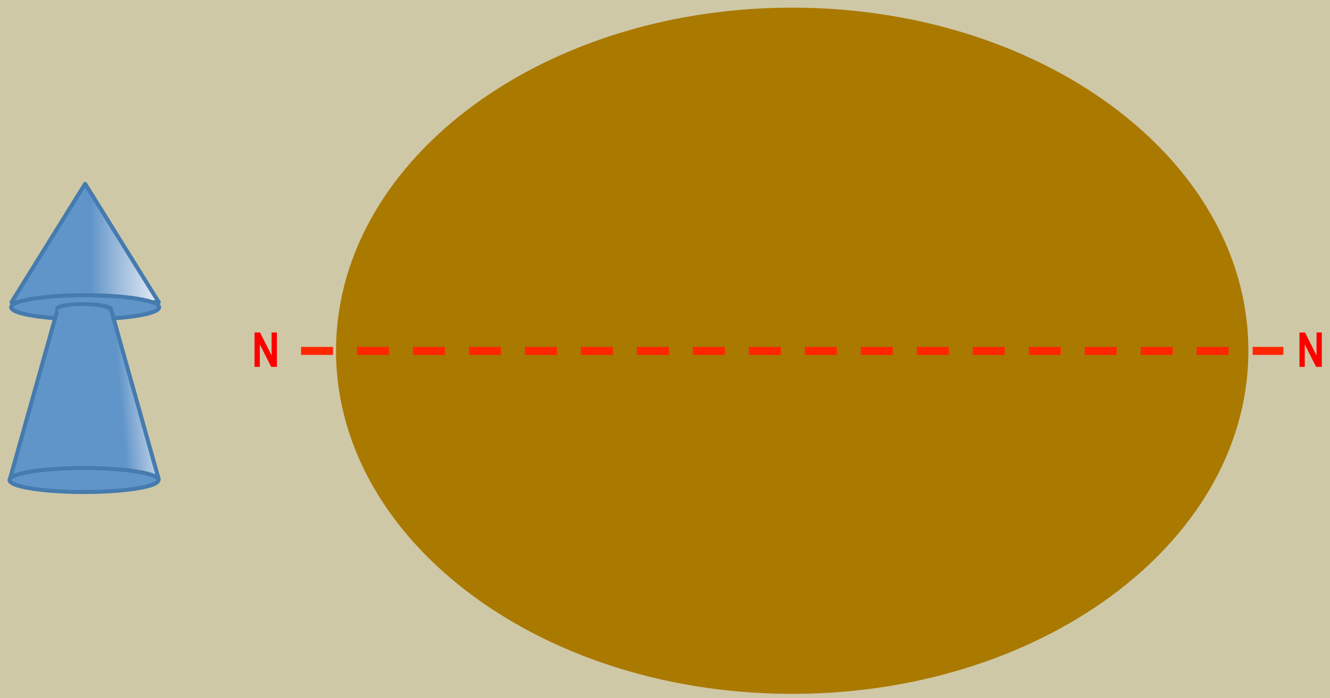
Section Modulus



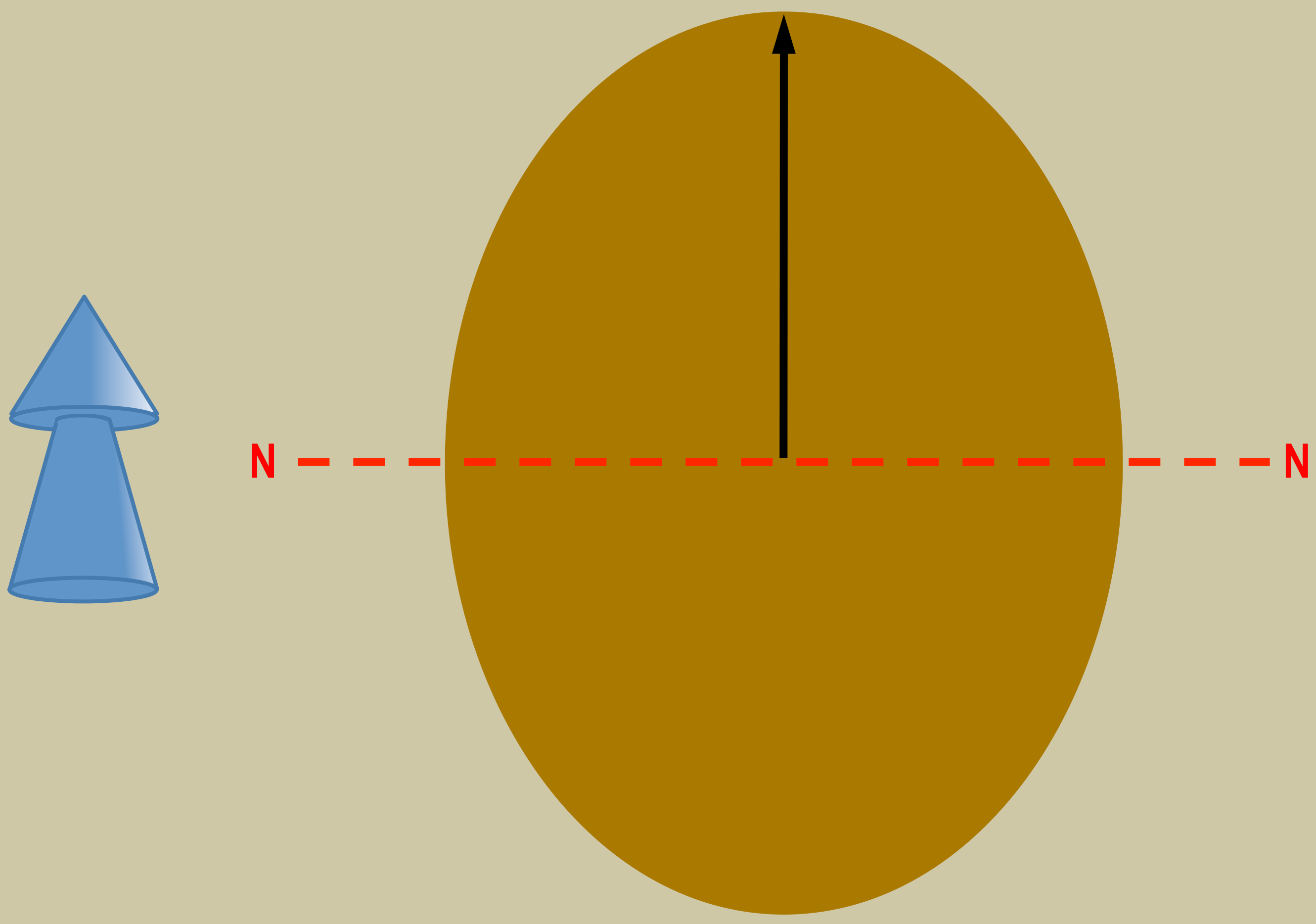
Section Modulus



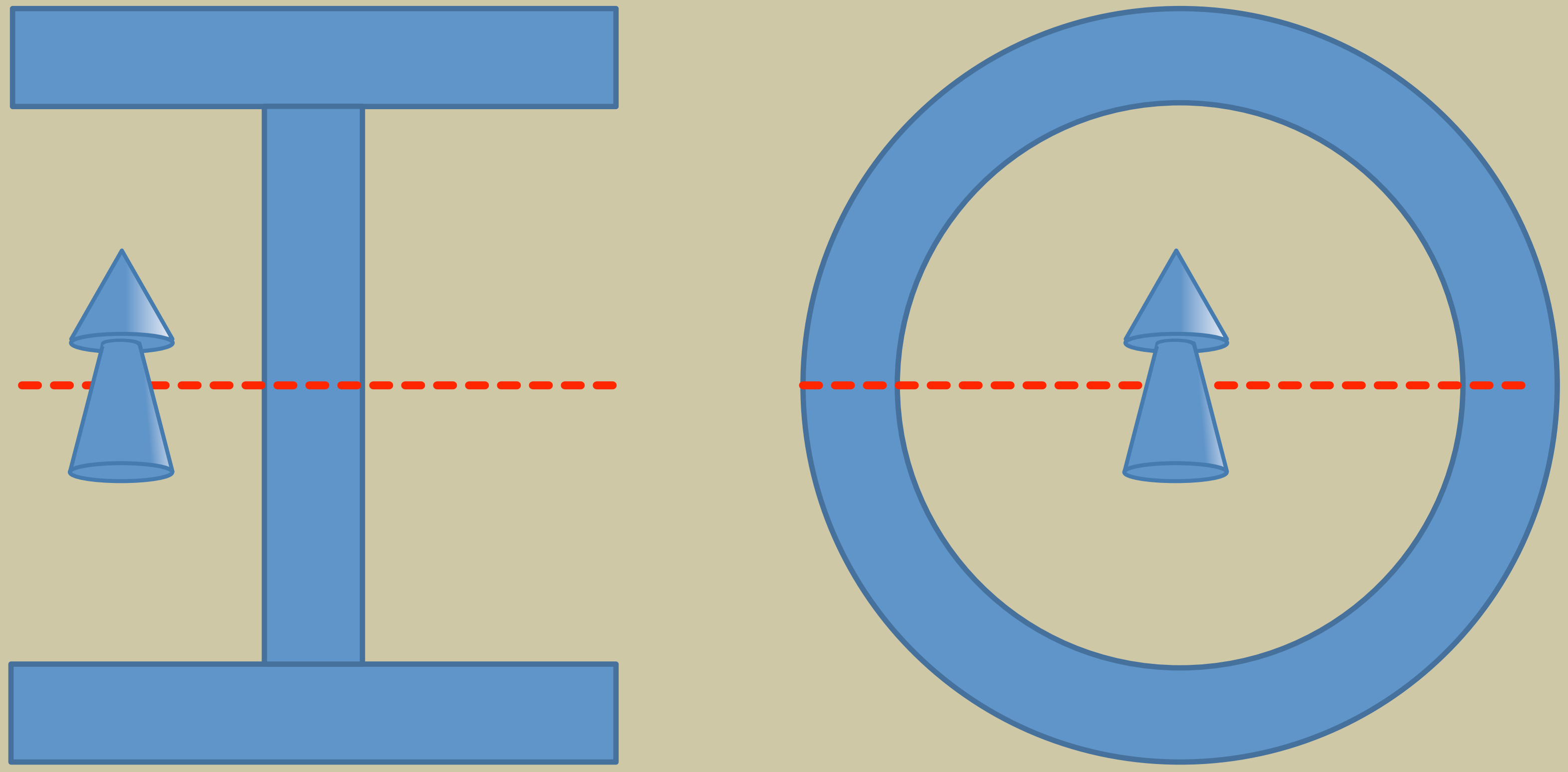
Section Modulus



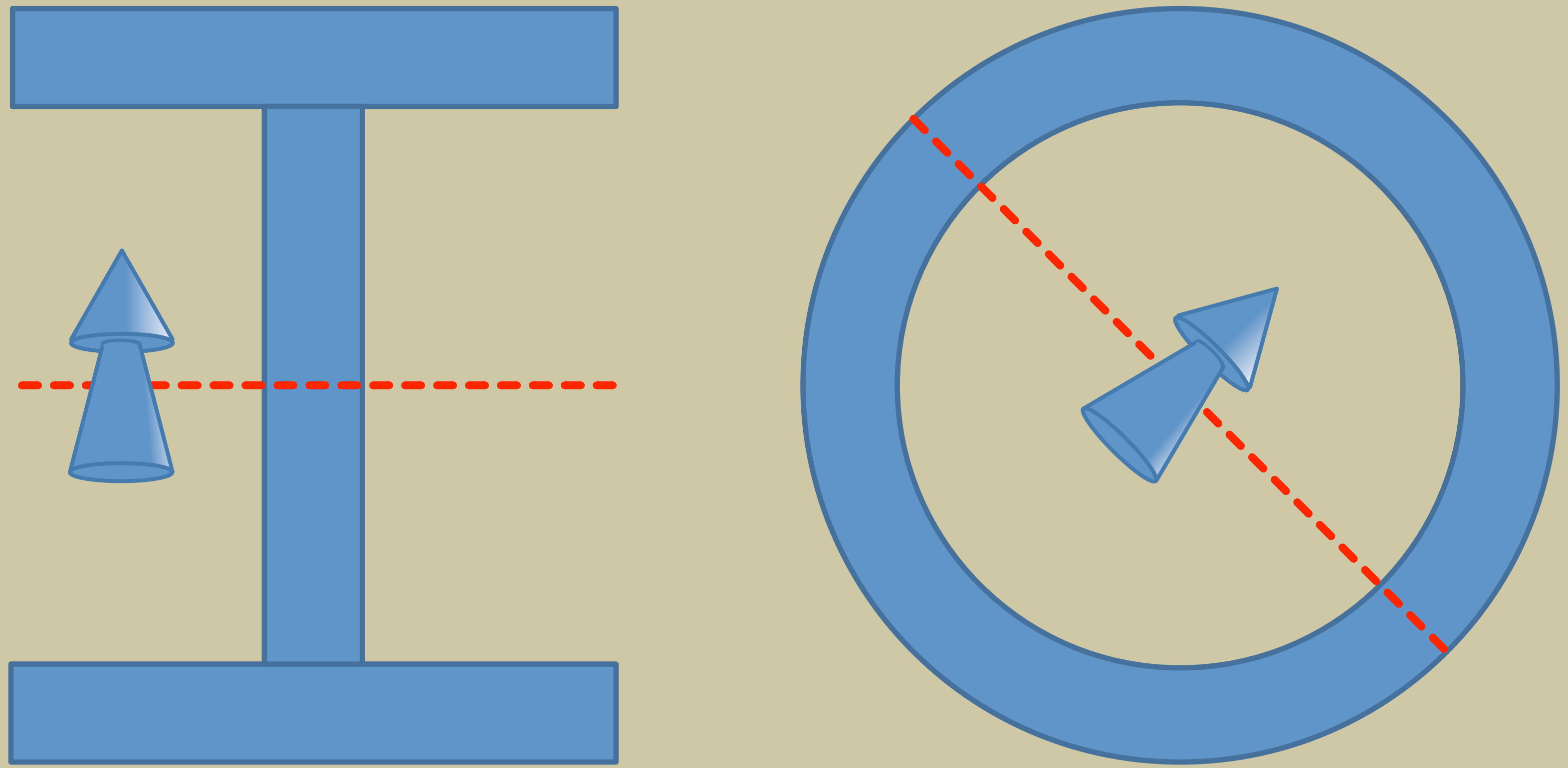
Section Modulus



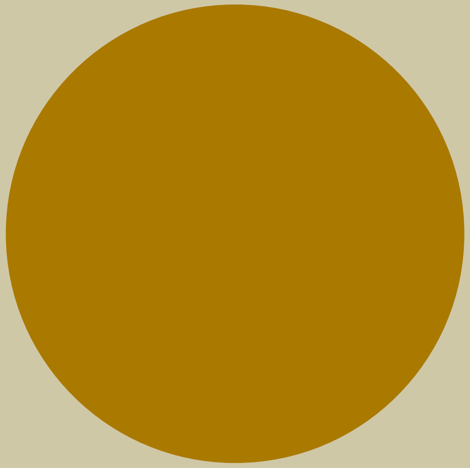
Section Modulus



Section Modulus



Section Modulus



Cross Section Area $A = (\pi/2)\ d^2$

Section Modulus $Z = (\pi / 32)\ d^3$

Section Modulus

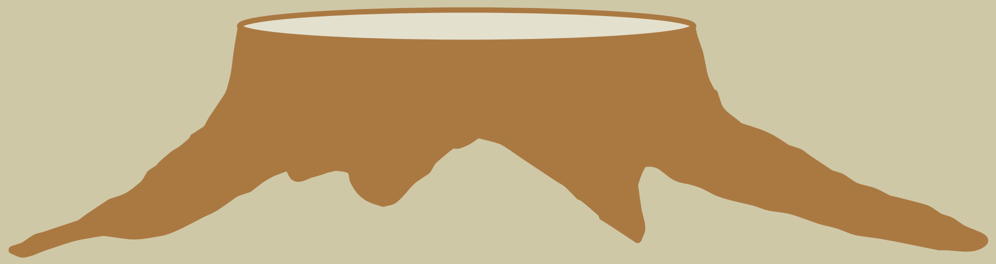
Stem Diameter	Cross-sectional Area	Section Modulus
50cm	1,963cm^2	12,226cm^3

Section Modulus

Stem Diameter	Cross-sectional Area	Section Modulus
50cm	1,963cm^2	12,226cm^3
100cm	7,850cm^2	98,125cm^3

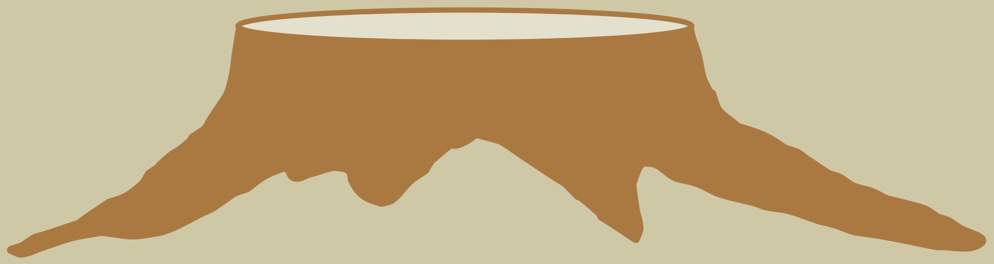
Section Modulus

Stem Diameter	Cross-sectional Area	Section Modulus
50cm	1,963cm^2	12,226cm^3
100cm	7,850cm^2	98,125cm^3
200cm	31,400cm^2	785,000cm^3



Section Modulus

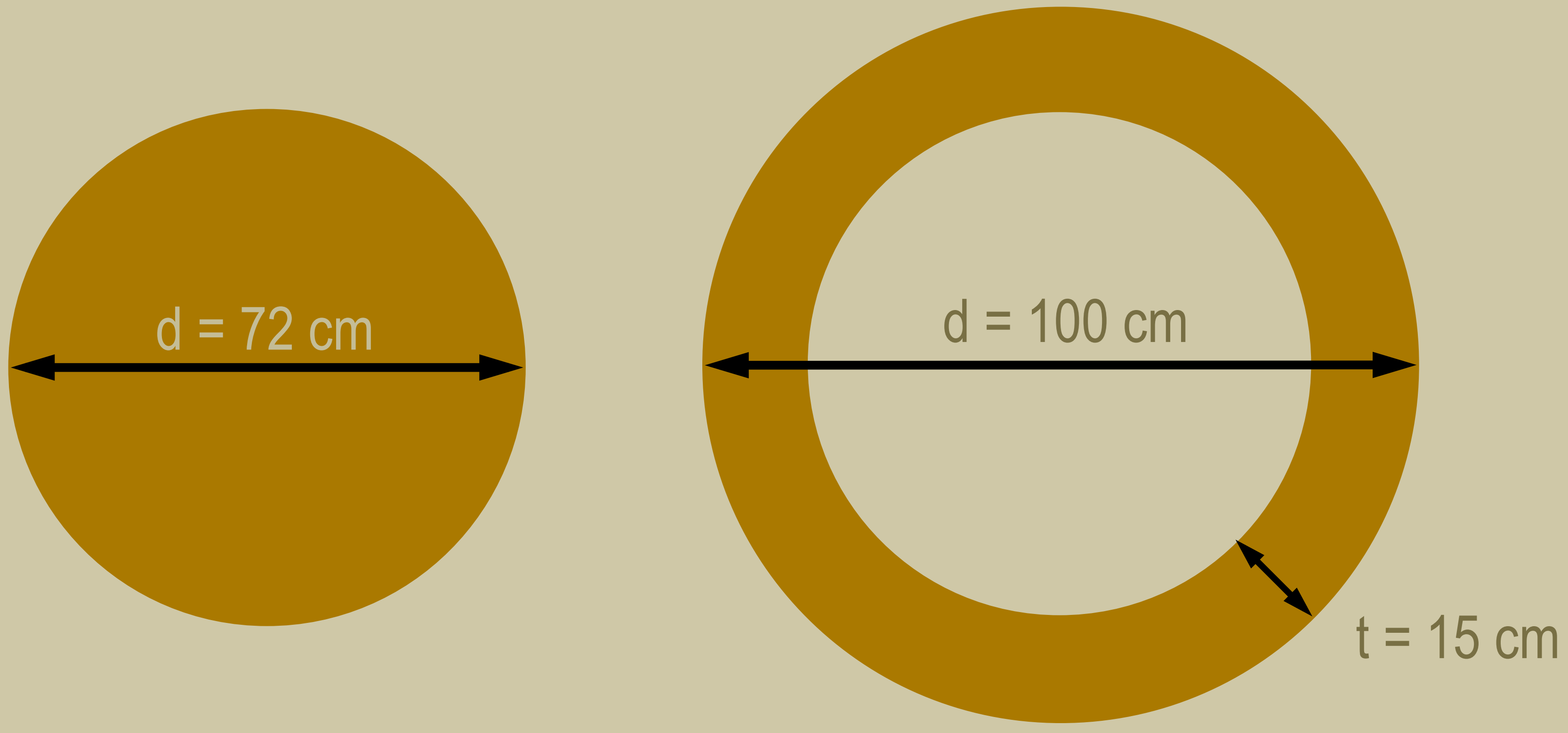
Stem Diameter	Cross-sectional Area	Section Modulus
50cm	1,963cm^2	12,226cm^3
100cm	7,850cm^2	98,125cm^3
200cm	31,400cm^2	785,000cm^3
Factor 2	**Factor 4**	**Factor 8**




Veteran trees are flexible and hollow and safe...


...but strength increases with stiffness!

Section Modulus



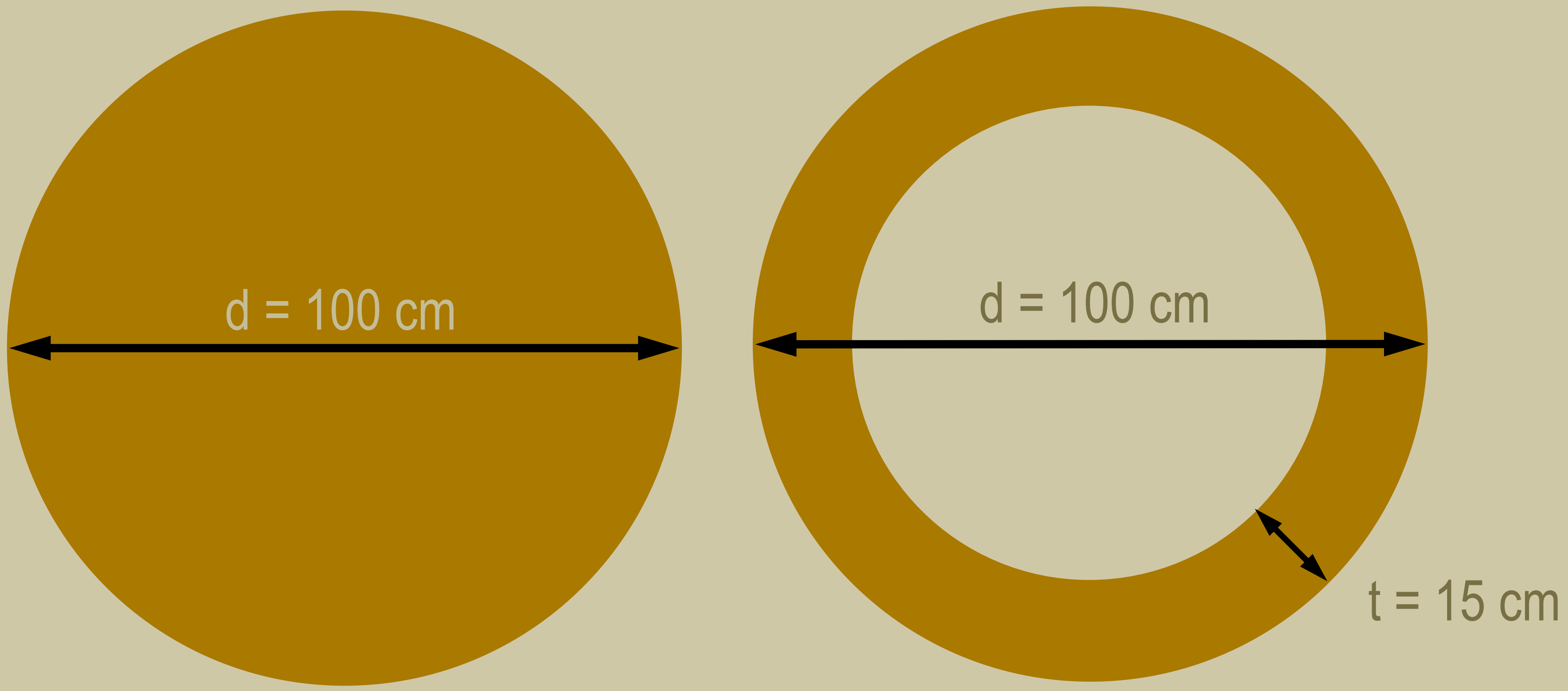
$A = 4{,}072\ cm^2$

$Z = 36{,}644 cm^3$

$A = 4{,}000\ cm^2$

$Z = 74{,}600\ cm^3$

Section Modulus



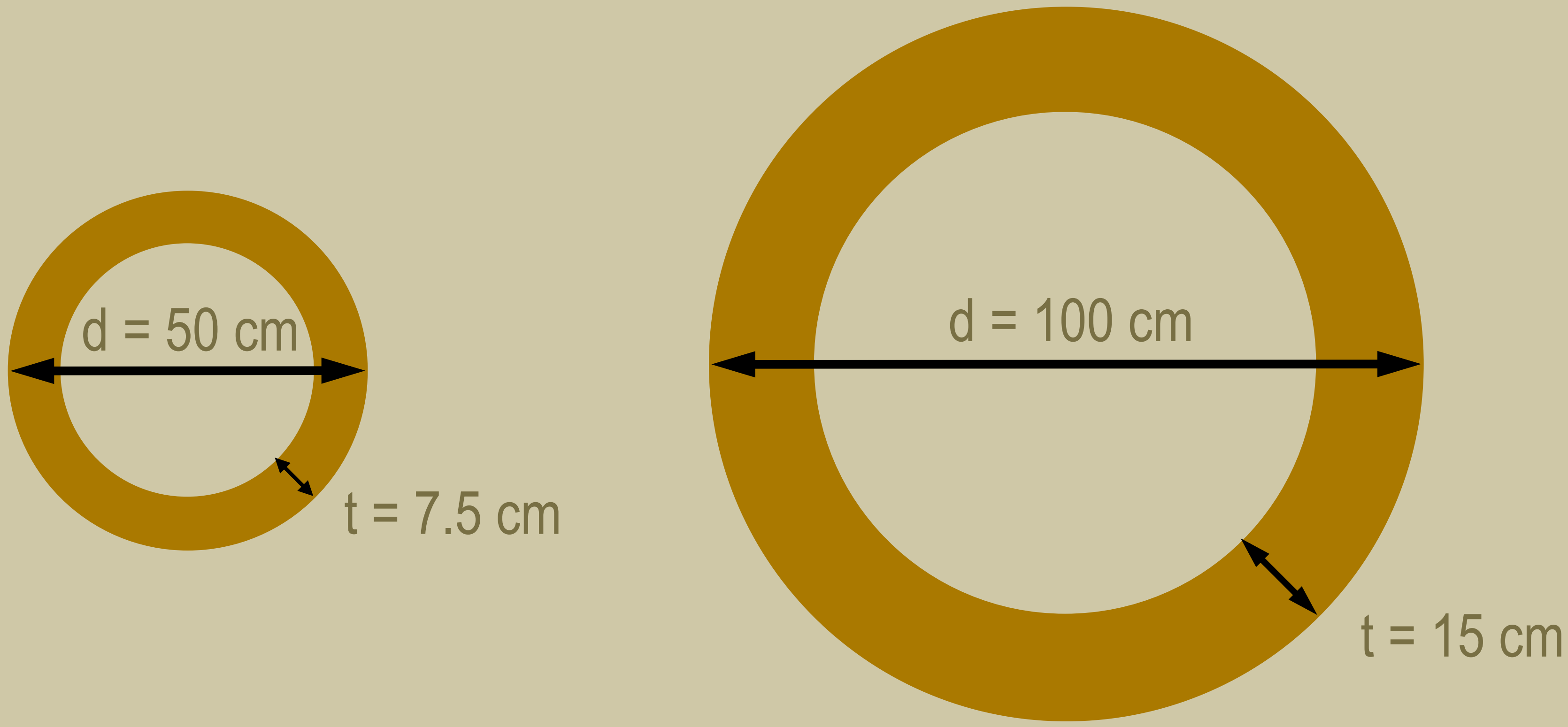
$A = 7{,}854\ cm^2$

$Z = 98{,}175 cm^3$

$A = 4{,}000\ cm^2$

$Z = 74{,}600\ cm^3$

Section Modulus



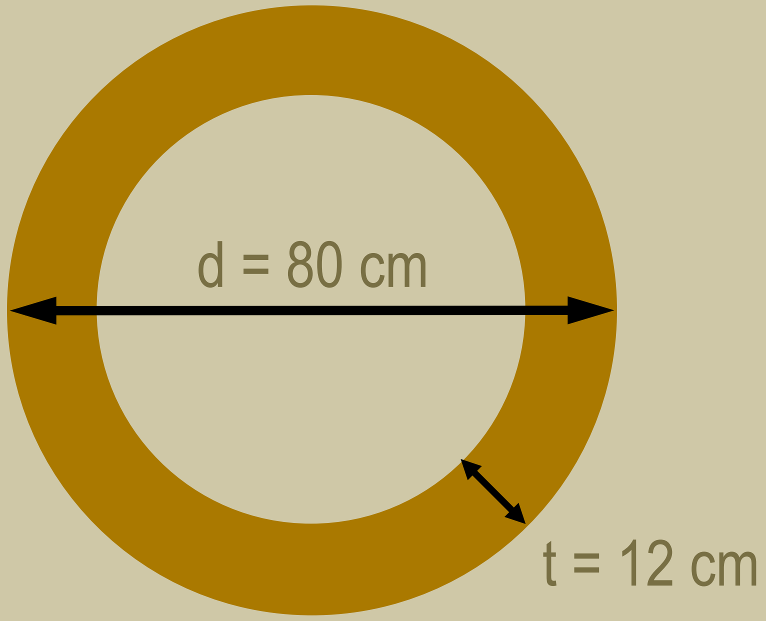
$A = 1{,}000\ cm^2$

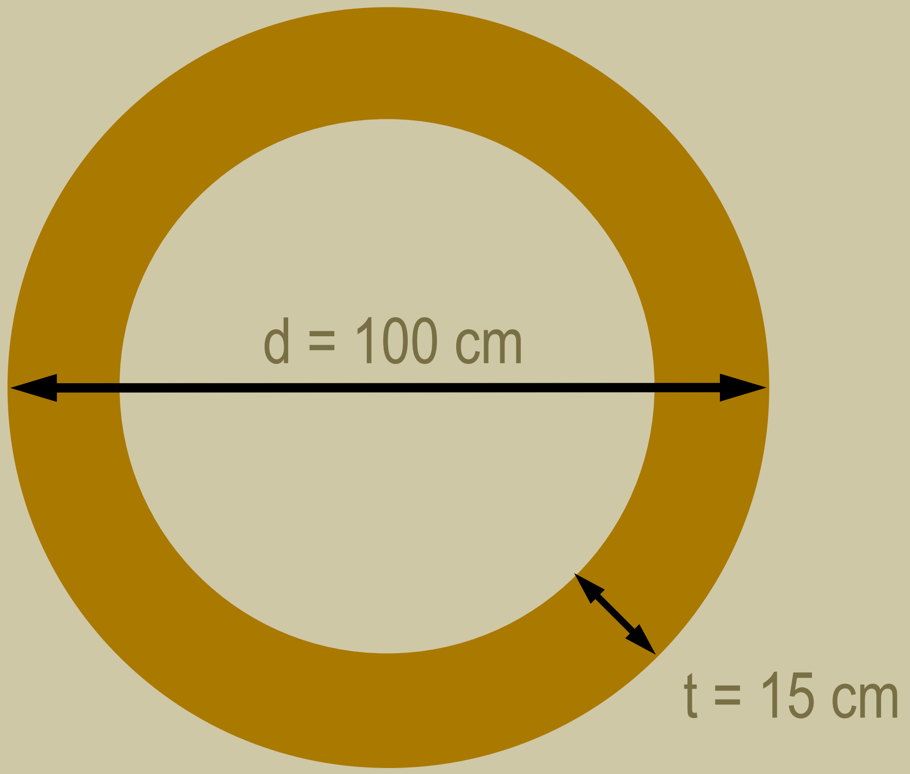
$Z = 9{,}325\ cm^3$

$A = 4{,}000\ cm^2$

$Z = 74{,}600\ cm^3$

Section Modulus





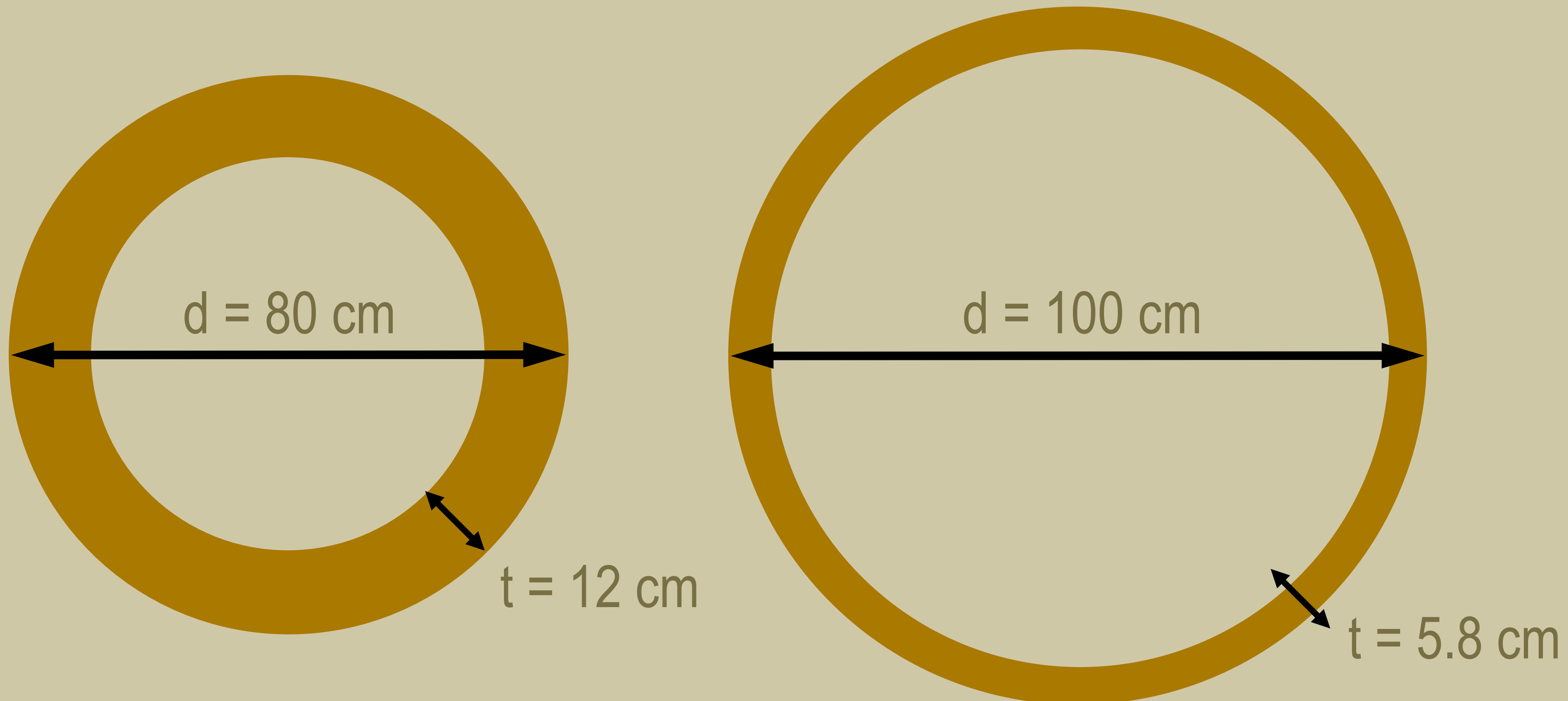
$A = 2{,}560\ cm^2$

$Z = 38{,}200\ cm^3$

$A = 4{,}000\ cm^2$

$Z = 74{,}600\ cm^3$

Section Modulus



$A = 2{,}560 \text{ cm}^2$

$Z = 38{,}200 \text{ cm}^3$

$A = 1{,}716 \text{ cm}^2$

$Z = 38{,}200 \text{ cm}^3$

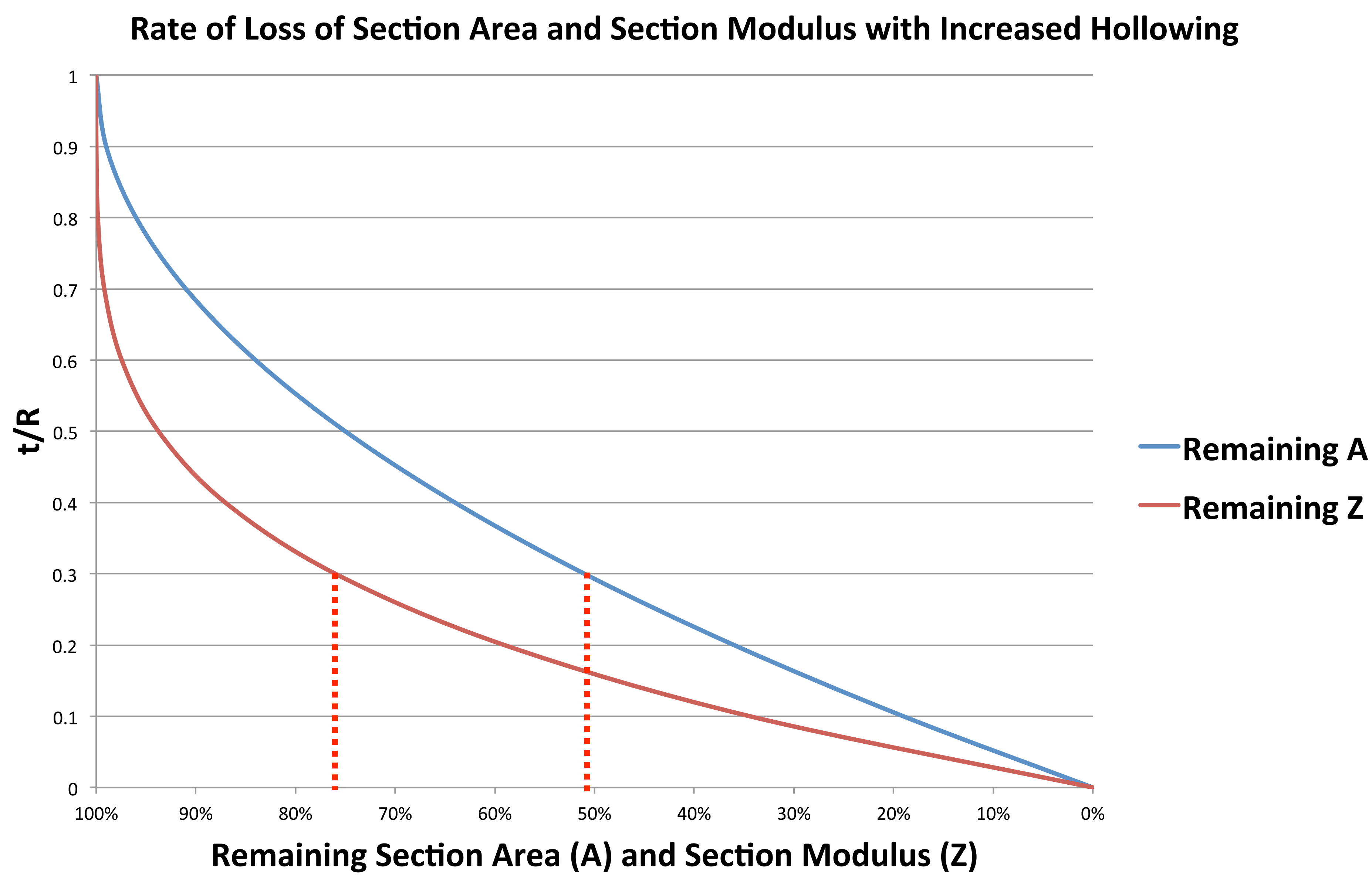
Section Modulus

There is an increasing mechanical advantage derived from an increase in stem diameter

Trees with larger stem diameters can carry proportionally greater loads

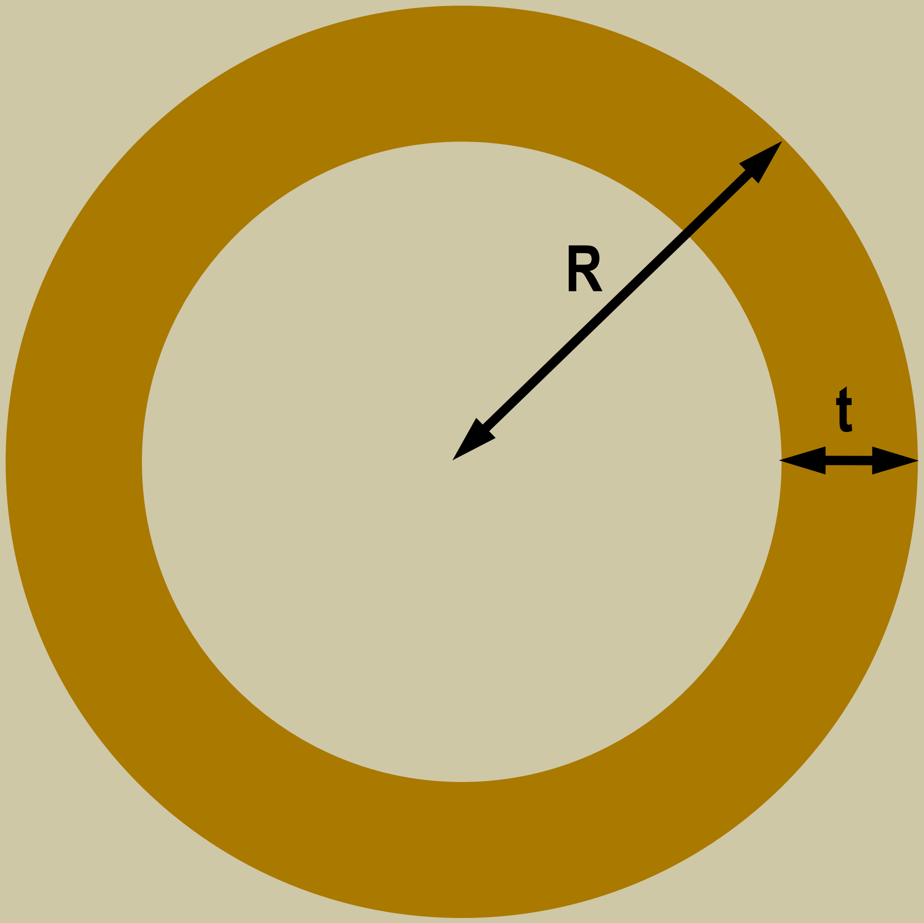
Trees with larger stem diameters have greater safety factors for a given wind load

Trees with larger stem diameters can afford more decay and thinner residual walls for a given wind load


Rate of Loss of Section Area and Section Modulus with Increased Hollowing
t/R
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Remaining Section Area (A) and Section Modulus (Z)
Remaining A
Remaining Z

t/R =0.3 - A Useful Failure Criteria?

70% Hollow



t/R = 0.3


Poulton (2008)


Poulton (2008)

Phillips (2008)


Phillips (2008)


LET ME BE

Wind Load Analysis analogous to DIN 1055-4

Project

Project Name	Henhayes Recreatior
Project Number	B276
Test Date	11/06/2012

Site — Tree Number T1

Henhayes Recreation Ground
Bryants Row, Crewkerne
TA18 8DA , UK

Altitude a. sea level	65	m

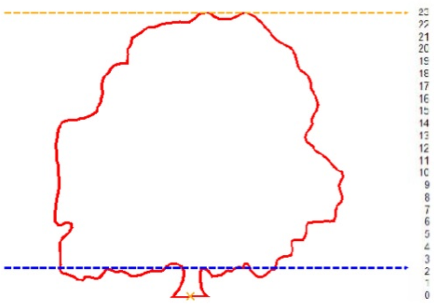
Tree Data

Tree Species	hispanica 'Lucombeana'		
Stem circumference		565	cm
Stem Diameter	||	180	cm
in 1m height	_|_	180	cm
Bark Thickness		5	cm
Tree Height		**23**	**m**

Applied Material Properties

as for	Quercus robur	
Source	Stuttgart	
Compressive Strength	28	MPa
Modulus of Elasticity	6900	MPa
Limit of Elasticity	0.41	%
Green Density	1.03	g/cm³

Crown Outline



Load Direction	SE/145°	

Surface Area Analysis

Crown Base	2.3	m
Effective Height	14.7	m
Total Surface Area	403	m²
Crown Eccentricity	0.46	m

Applied Structural Parameters

Drag Factor	0.25	
Natural Frequency	0.75	Hz
Damping Decrement	0.6	
Form Factor for Dead Weight	0.8	

Applied Site Parameters

Windzone	GB 22	
Speed of Applied Design Wind Speed	23.1	m/s
Air Density	1.28	kg/m³
Roughness Catagory	Suburb	
Exponent for Wind Profile	0.22	
Proximity Factor for Effects in Near Ground Wind Flow	1.2	
Factor for Crown Exposure	1.00	

Results

Wind Load Analysis

Mean Wind Pressure	31.7	kN
Gust Reaction Factor	2.4	
Load Centre	12.1	m
Torsion Moment	35	kNm
Design Wind Load	**918**	**kNm**

Tree Static Analysis

Dead Weight Tree	43	t
Critical Degree of Hollowness	95	%
Critical Residual Wall Thickness	4	cm

Assuming an Uncompromised Residual Wall

Basic Safety Factor	**14.7**

General

Comments

Calculated Fracture Stability according to Pull Test

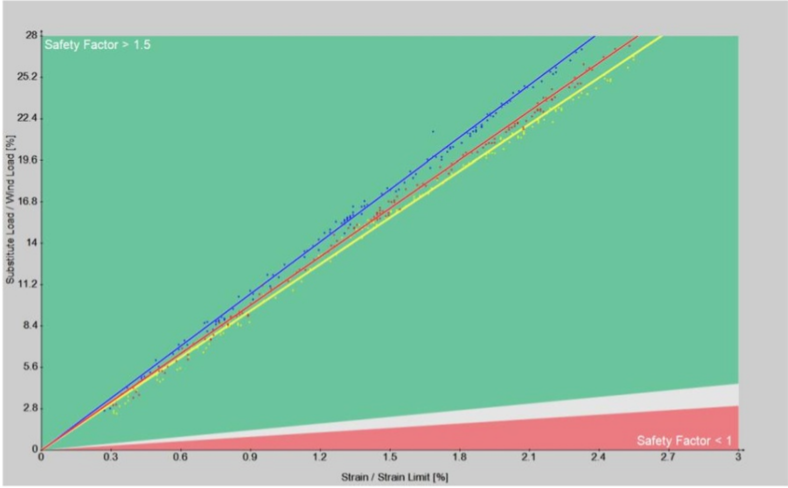
Tree Data

Project	Henhayes Recreation Ground	**Tree Number**	**T1**
Tree Species	Quercus x hispanica 'Lucombeana'	Date	11/06/2012

Setup Pulling Test

Height of the Stem Anchor	13.5 m	**Measurement No.**	**1**
Rope Angle	22.5 •	Load Direction	ENE/60°

Graphic Display (test data and best linear fit)



Elastometer Measurement	in	90	91	92
Measurement Height	**m**	**1.8**	**0.2**	**1**
Position		COM	TEN	TEN
Stem Diameter 1	cm	161	251	180
Stem Diameter 2	cm	161	251	180
Bark Thickness	cm	5	5	5
Load part	%	100	100	100
Breaking Stability (derived from the gradient of the best linear fit)				
Safety Factor		**11.76**	**10.5**	**10.91**
Control Value				
Coefficient of Determination R^2		0.9977	0.9963	0.9975
Residual Stiffness	%	97.8	25	68.7
Degree of Hollowness	%	28.1	90.9	67.9
Compression originating from				
Dead Weight	%	0.8	1.9	1.2
Substitute Load	%	27.2	26.7	27.4

Calculated Tipping Stability according to Pull Test

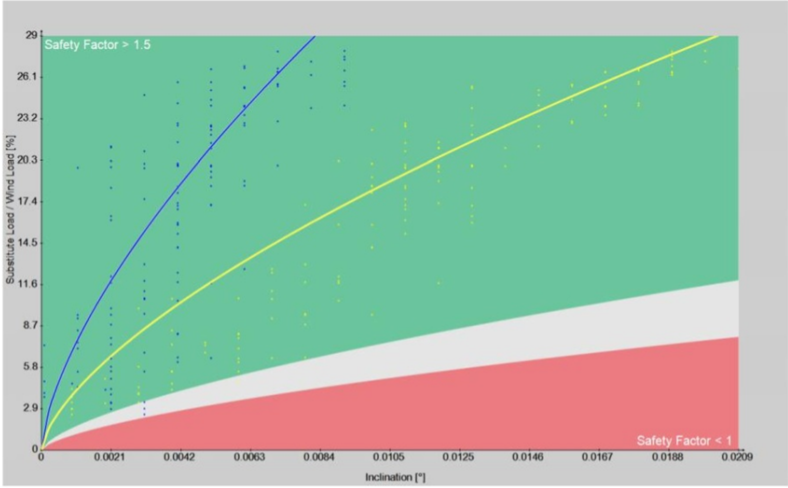
Tree Data

Project	Henhayes Recreation Ground	**Tree Number**	**T1**
Tree Species	Quercus x hispanica 'Lucombeana'	Date	11/06/2012

Setup Pulling Test

Height of the Stem Anchor	13.5 m	**Measurement No.**	**5**
Rope Angle	17 •	Load Direction	SE/145°

Graphic Display (test data and best fit to tipping curve)



Inclinometer Measurement	80	81
Position	x-axis/E	x-axis/NNE

Tipping Stability (based on Generalized Tipping Curve)

Safety Factor	**6.72**	**3.73**

Control Value	in		
Standard Deviation	%	5.26	3.33
Substitute Load	%	28	28
Load Direction at Inclinometer		x-Axis	x-Axis

General for Pull Test

Consultant	Paul Muir
Witness / Assistant	Jedd Dunn

Measurement Comments

Wind Load Analysis analogous to DIN 1055-4

Project			Site	Tree Number	T1
Project Name	202 Newbridge Road		202 Newbridge Road		
Project Number	B321		Bath		
			BA1 3LF , UK		
Test Date	18/06/2012		Altitude a. sea level	23	m

Tree Data			Applied Material Properties		
Tree Species	Fagus Sylvatica		as for	Fagus sylvatica	
Stem circumference	345	cm	Source	Stuttgart	
Stem Diameter ‖	98	cm	Compressive Strength	22.5	MPa
in 1m height ⊥	115	cm	Modulus of Elasticity	8500	MPa
Bark Thickness	2	cm	Limit of Elasticity	0.26	%
Tree Height	**19**	**m**	Green Density	1.05	g/cm³

Crown Outline

Load Direction	SE/140°	
Surface Area Analysis		
Crown Base	4.4	m
Effective Height	13.2	m
Total Surface Area	206	m²
Crown Eccentricity	0.36	m
Applied Structural Parameters		
Drag Factor	0.25	
Natural Frequency	0.6	Hz
Damping Decrement	0.5	
Form Factor for Dead Weight	0.8	
Applied Site Parameters		
Windzone	GB 21	
Speed of Applied		
Design Wind Speed	22	m/s
Air Density	1.29	kg/m³
Roughness Catagory	Suburb	
Exponent for Wind Profile	0.22	
Proximity Factor for Effects		
in Near Ground Wind Flow	1.2	
Factor for Crown Exposure	1.00	

Results

Wind Load Analysis			**Tree Static Analysis**		
Mean Wind Pressure	14.4	kN	Dead Weight Tree	13.1	t
Gust Reaction Factor	2.56		Critical Degree of Hollowness	93	%
Load Centre	11.1	m	Critical Residual Wall Thickness	4	cm
Torsion Moment	13	kNm	Assuming an Uncompromised Residual Wall		
Design Wind Load	**412**	**kNm**	**Basic Safety Factor**	**5.2**	

General

Comments

Calculated Tipping Stability according to Pull Test

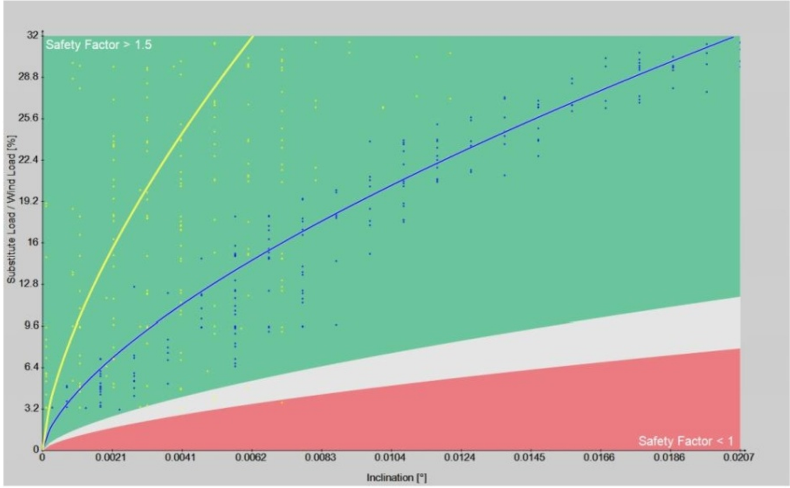
Tree Data

Project	202 Newbridge Road	**Tree Number**	**T1**
Tree Species	Fagus Sylvatica	Date	18/06/2012

Setup Pulling Test

Height of the Stem Anchor	7.3 m	**Measurement No.**	**1**
Rope Angle	10.3 •	Load Direction	SE/140°

Graphic Display (test data and best fit to tipping curve)



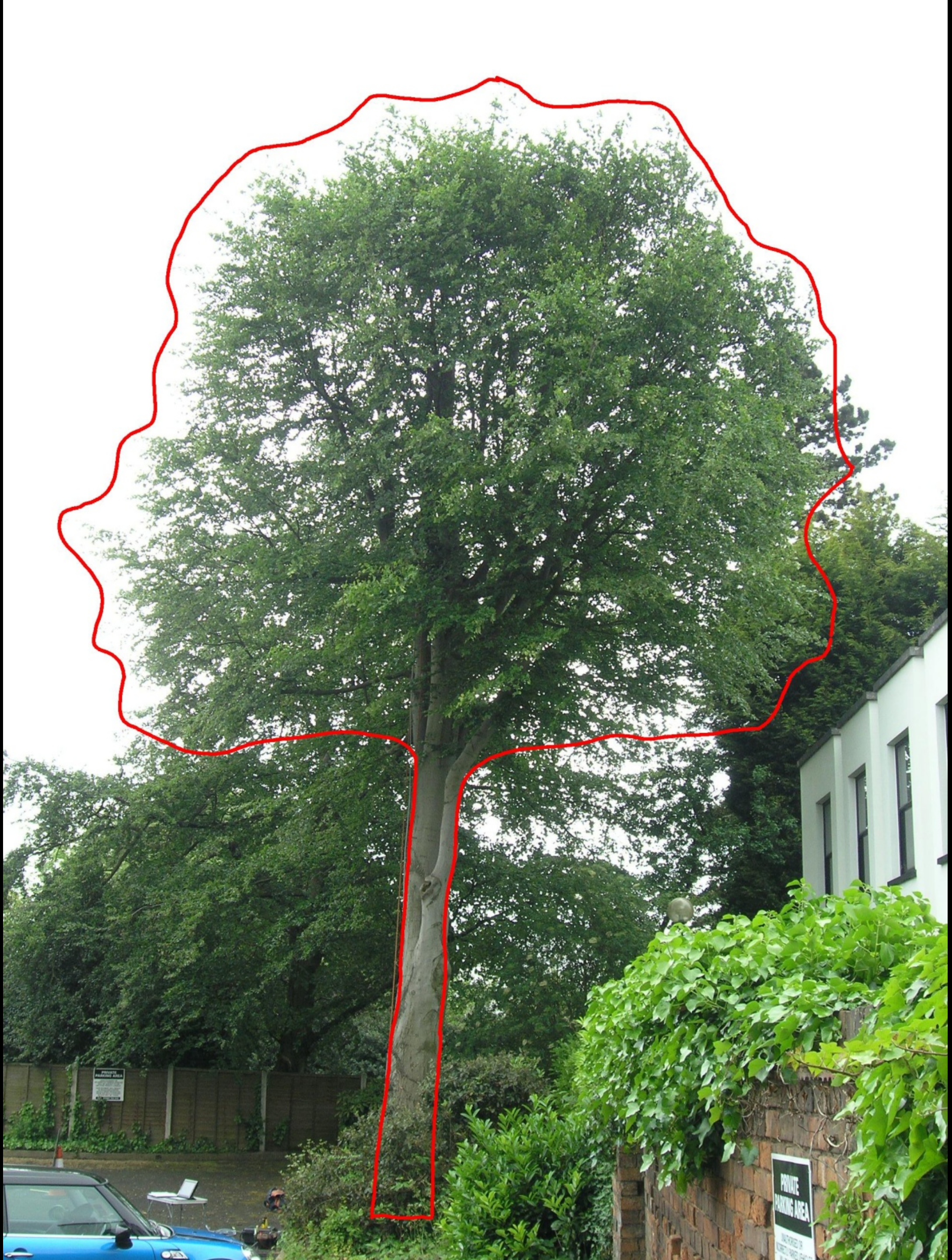
Inclinometer Measurement		80	81
Position		x-axis/NEE	x-axis/N
Tipping Stability (based on Generalized Tipping Curve)			
Safety Factor		**4.07**	**8.86**
Control Value	in		
Standard Deviation	%	2.63	11.26
Substitute Load	%	31.6	31.6
Load Direction at Inclinometer		x-Axis	x-Axis

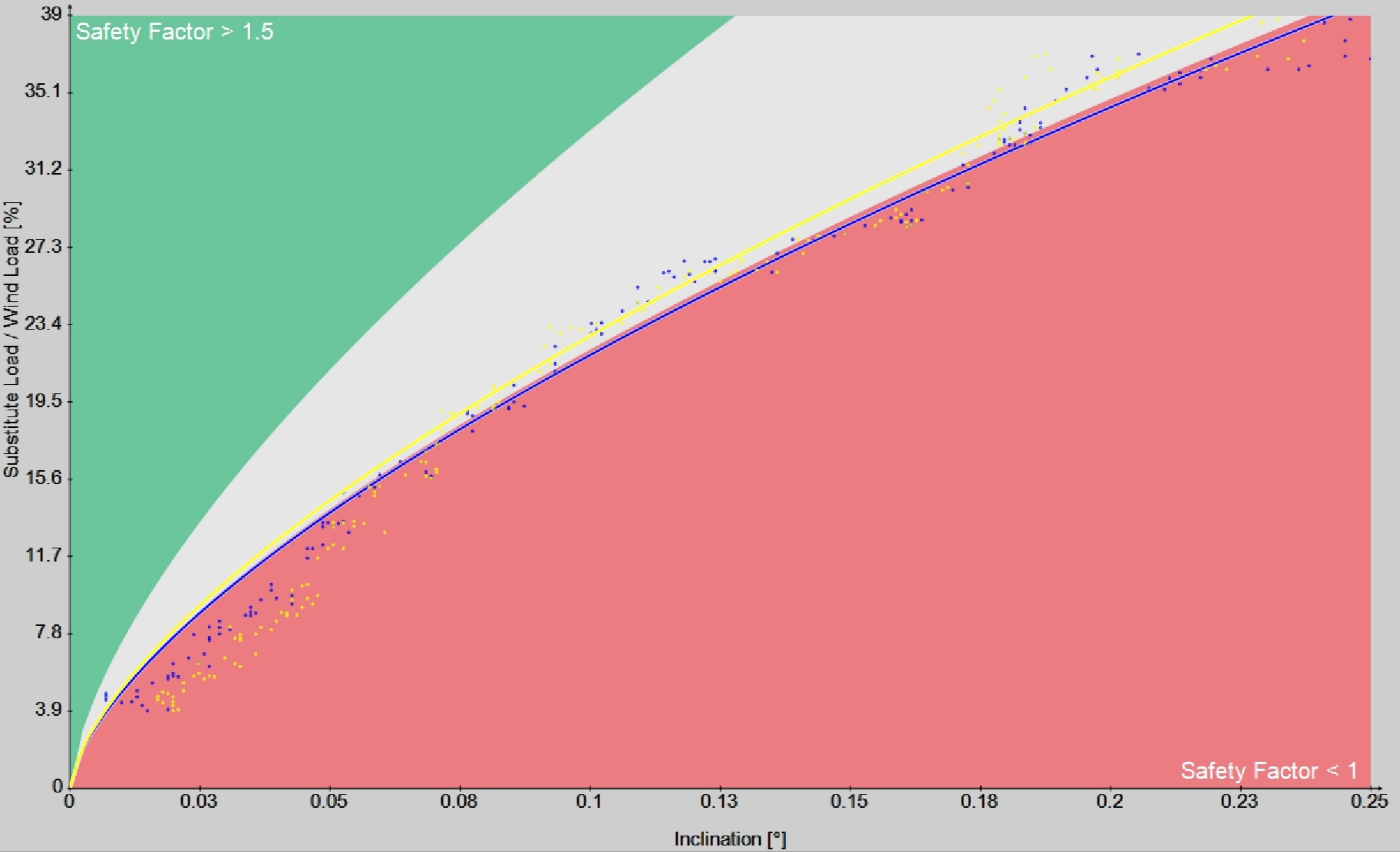
General for Pull Test

Consultant	Paul Muir
Witness / Assistant	Jim Walker

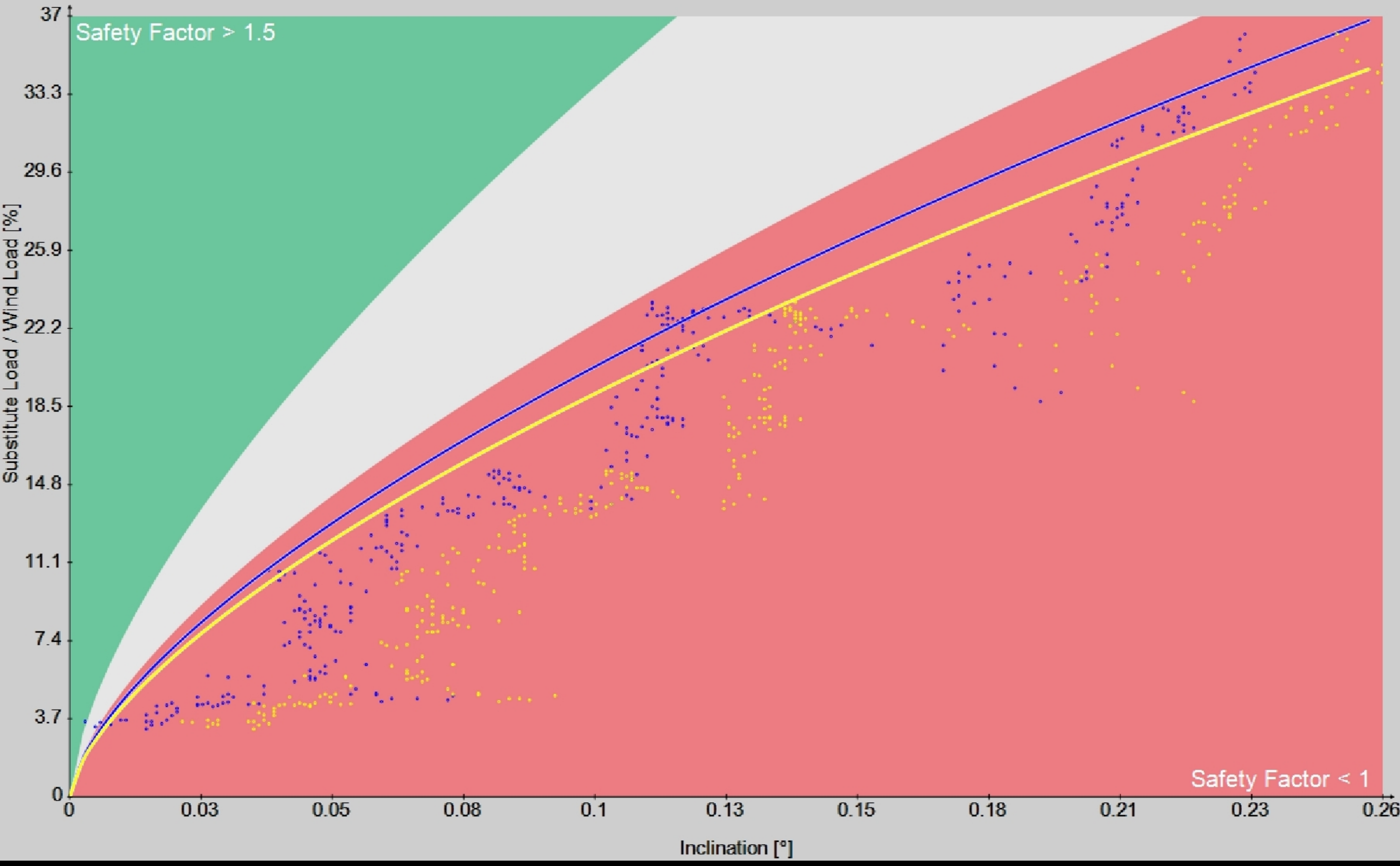
Measurement Comments


Y267 NNK

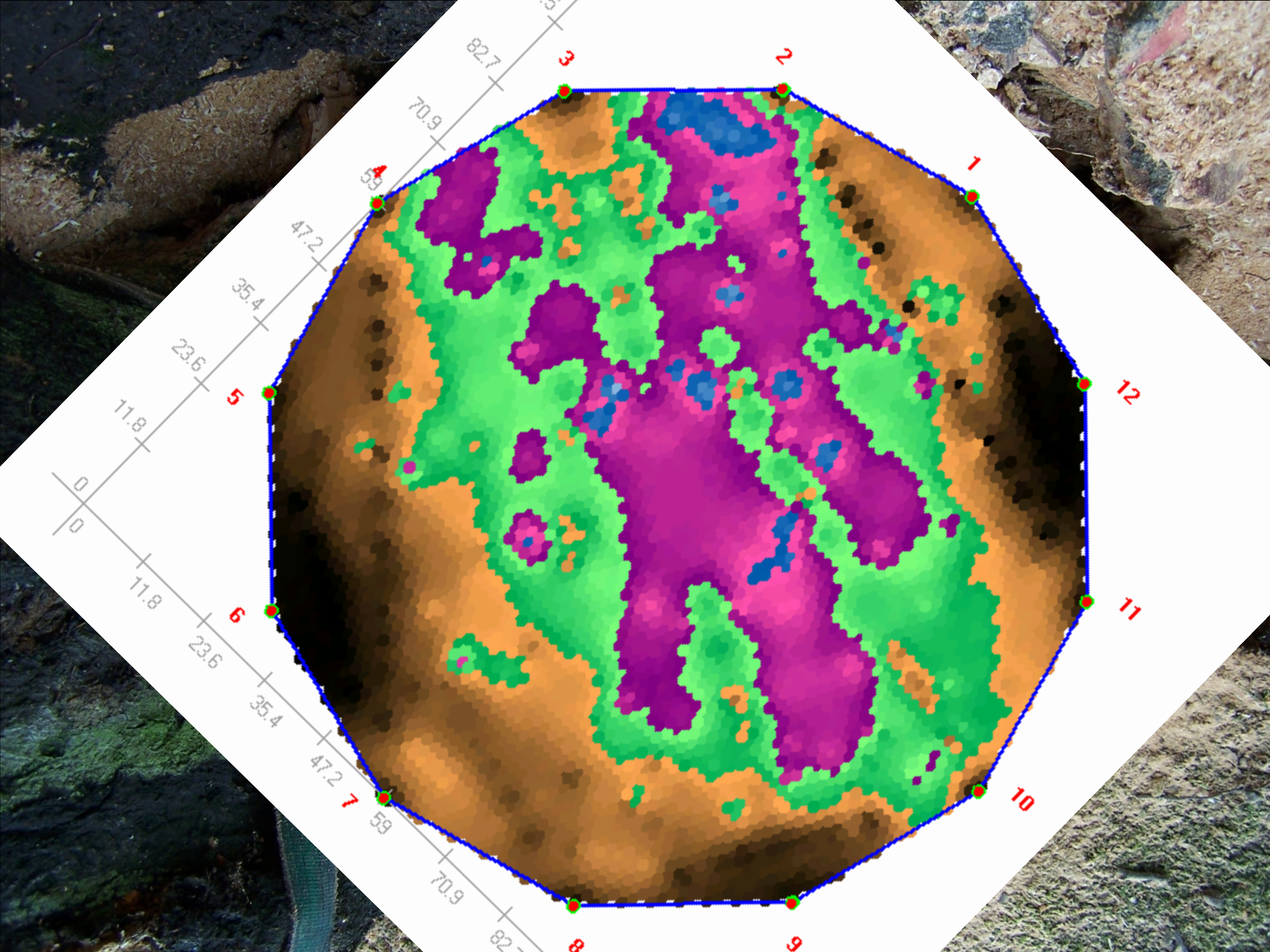

PRIVATE
PARKING AREA



Safety Factor > 1.5
Safety Factor < 1
Substitute Load / Wind Load [%]
39
35.1
31.2
27.3
23.4
19.5
15.6
11.7
7.8
3.9
0
0.03
0.05
0.08
0.1
0.13
0.15
0.18
0.2
0.23
0.25
Inclination [°]

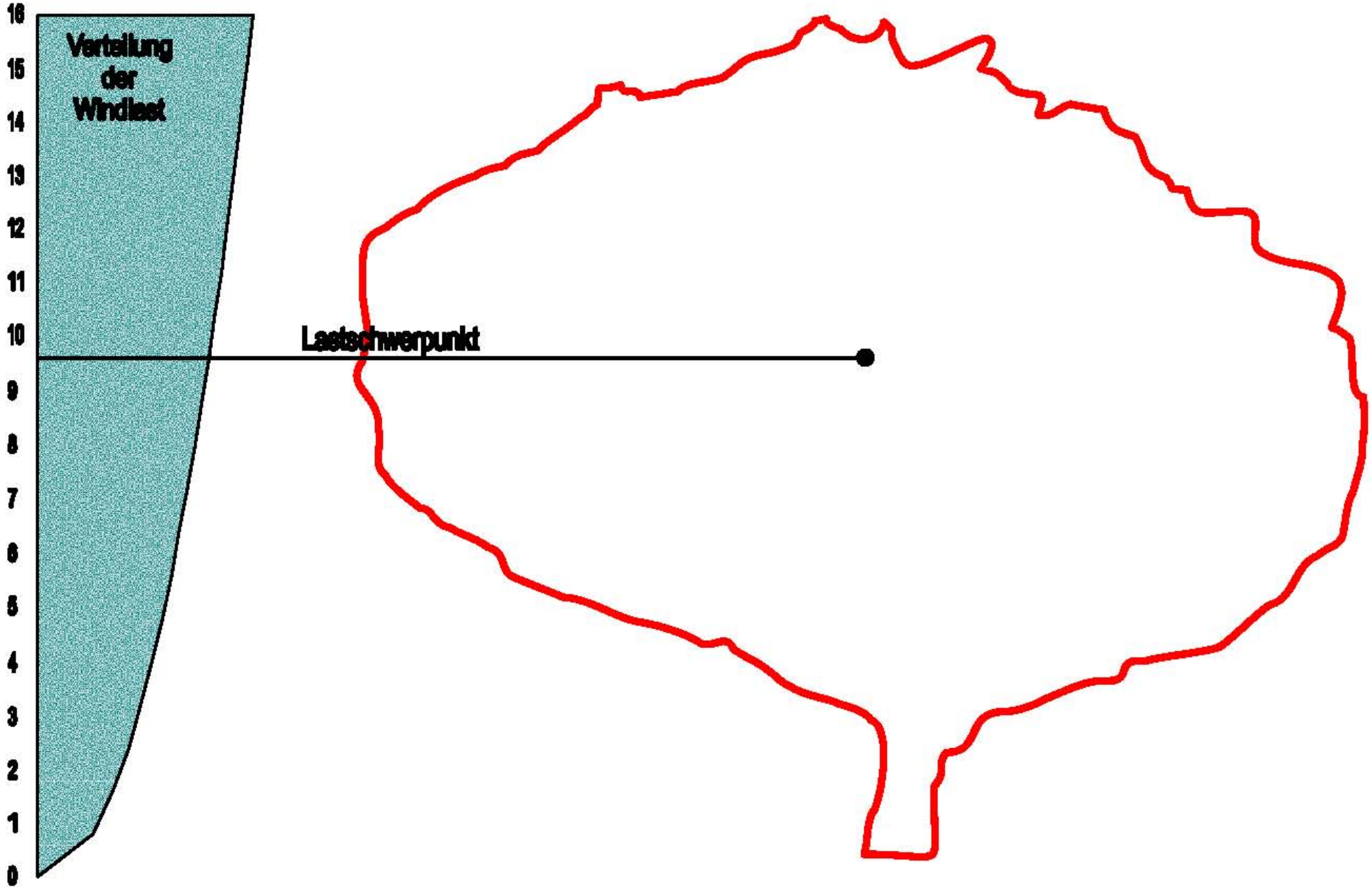


Safety Factor > 1.5
Safety Factor < 1
Substitute Load / Wind Load [%]
37
33.3
29.6
25.9
22.2
18.5
14.8
11.1
7.4
3.7
0
0.03
0.05
0.08
0.1
0.13
0.15
0.18
0.21
0.23
0.26
Inclination [°]

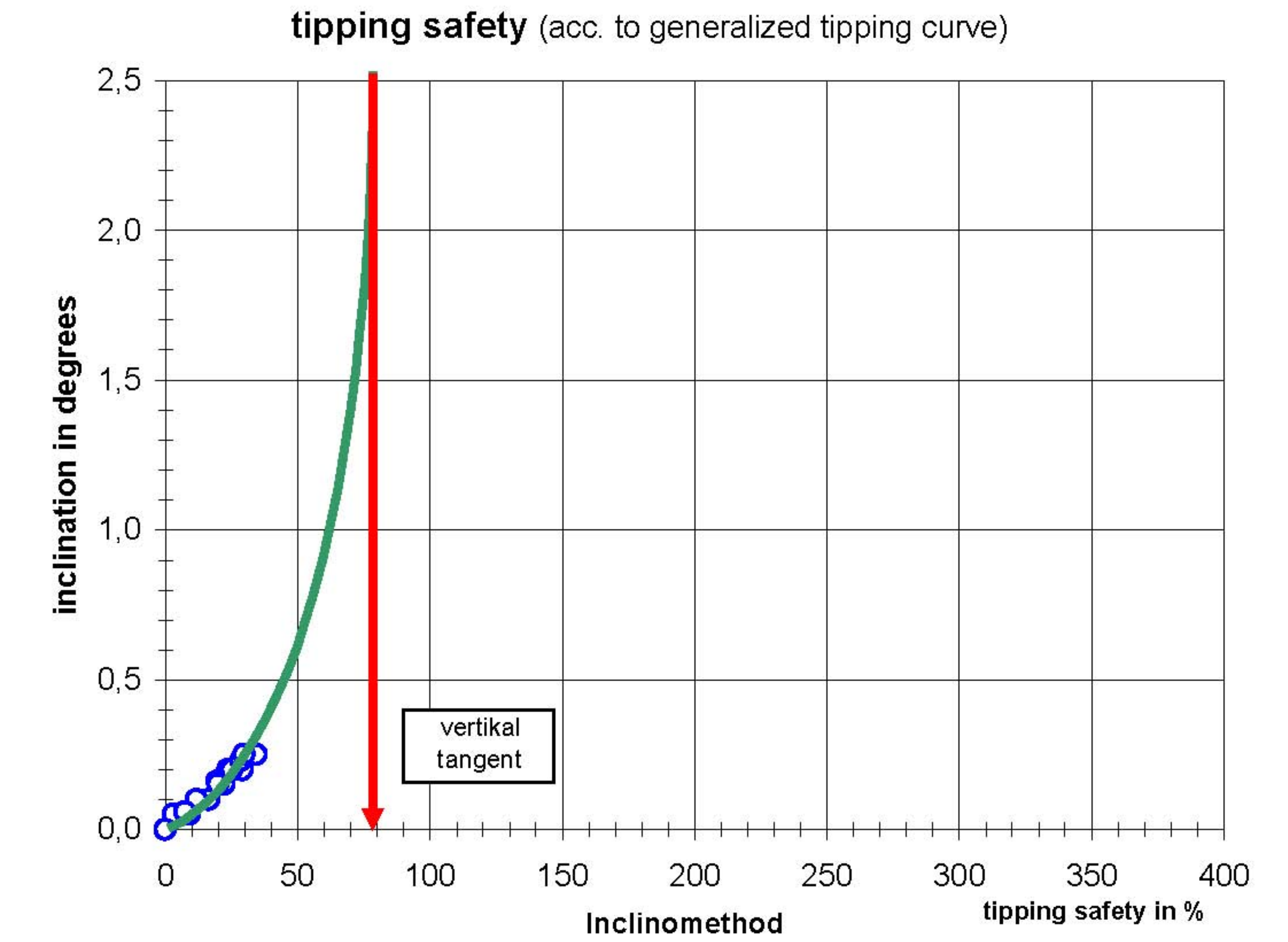


1
2
3
4
5
6
7
8
9
10
11
12
0
11.8
23.6
35.4
47.2
59
70.9
82.7

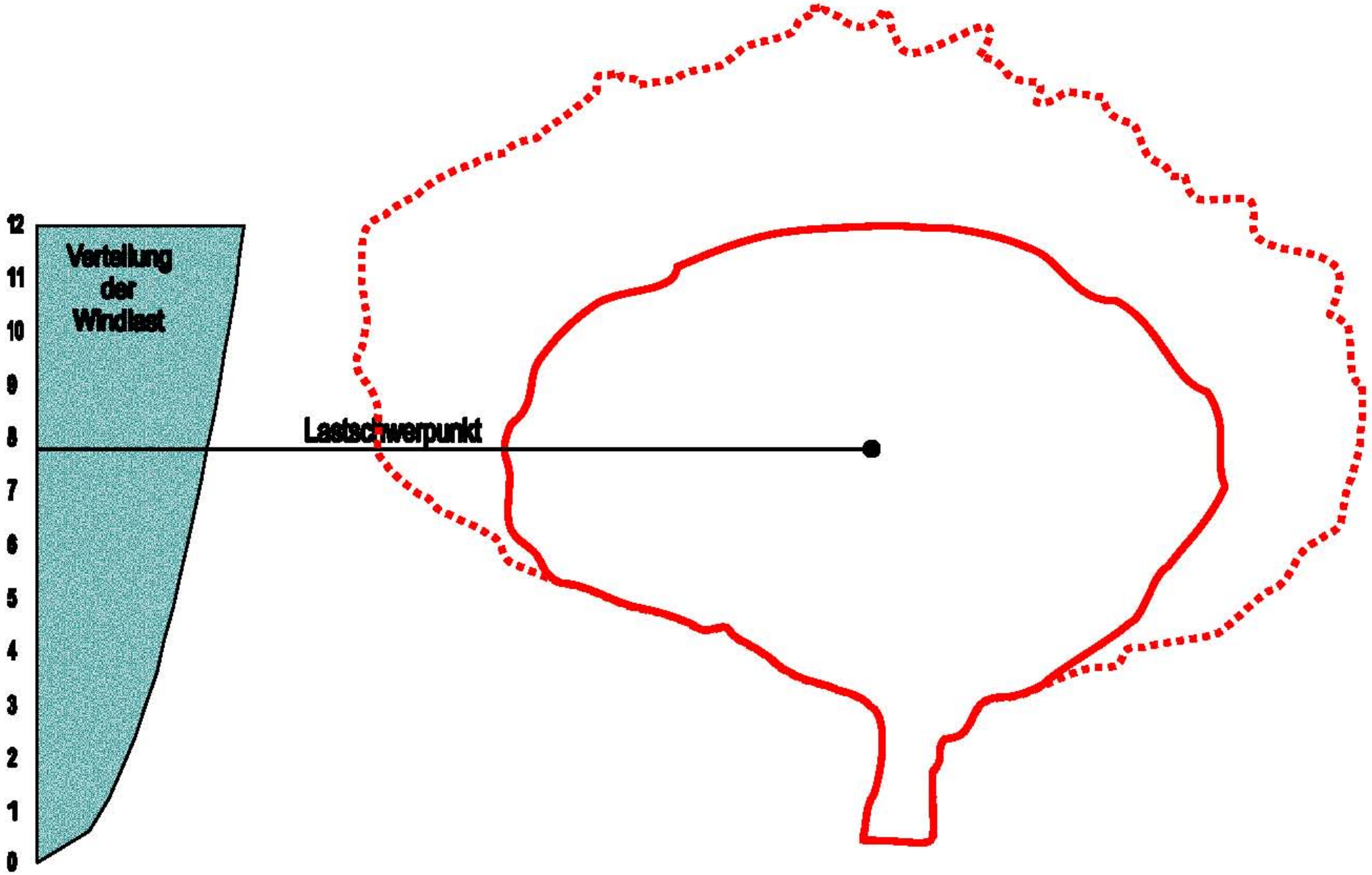
S-SE



load analysis acc. to DIN 1056 + dynamics


tipping safety (acc. to generalized tipping curve)
2,5
2,0
1,5
1,0
0,5
0,0
inclination in degrees
vertikal
tangent
0
50
100
150
200
250
300
350
400
Inclinomethod
tipping safety in %

S-SE



load analysis acc. to DIN 1056 + dynamics

Safety Factors versus Strength Loss

- We should estimate likelihood of failure not the extent of a defect
- Triangle of Statics - Load, Form and Material Properties
- Safety Factor and the role of load and absolute stem diameter
- Strength loss is relevant in relation to rate of change
- Physiological condition
- A t/R of 0.3 is not appropriate as a failure criteria
- Precautionary crown reductions are generally unnecessary/inappropriate
- Engineering terminology and concepts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