Transforming trees

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

SIRT
Strategic Integrated Research in Timber

Forest Products Research Institute

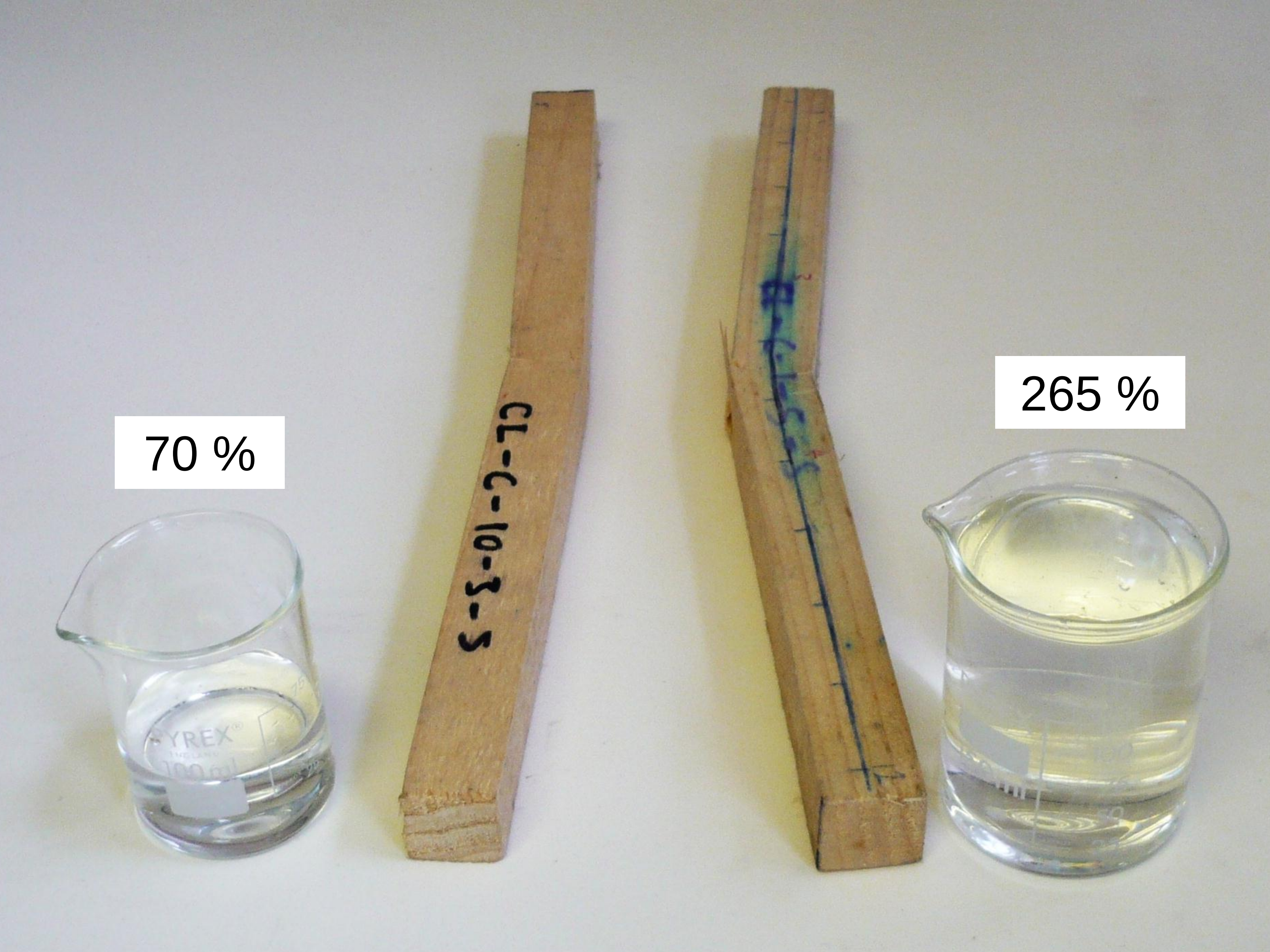
Guessing the strength of UK timber

Grading explained (a bit)

Dan Ridley-Ellis

Edinburgh Napier UNIVERSITY

Image : wood for good

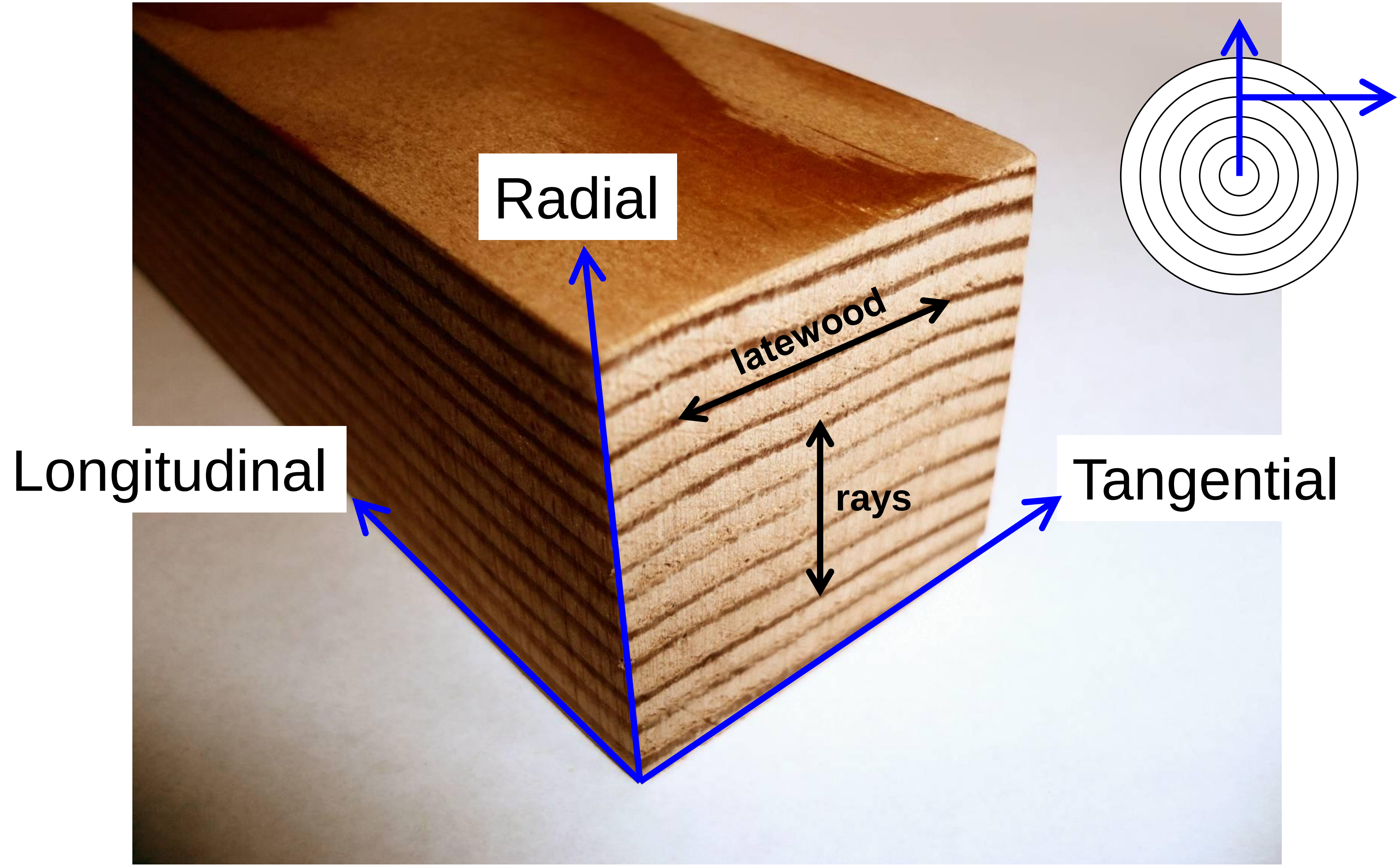

70 %
CL-C-10-3-5
265 %

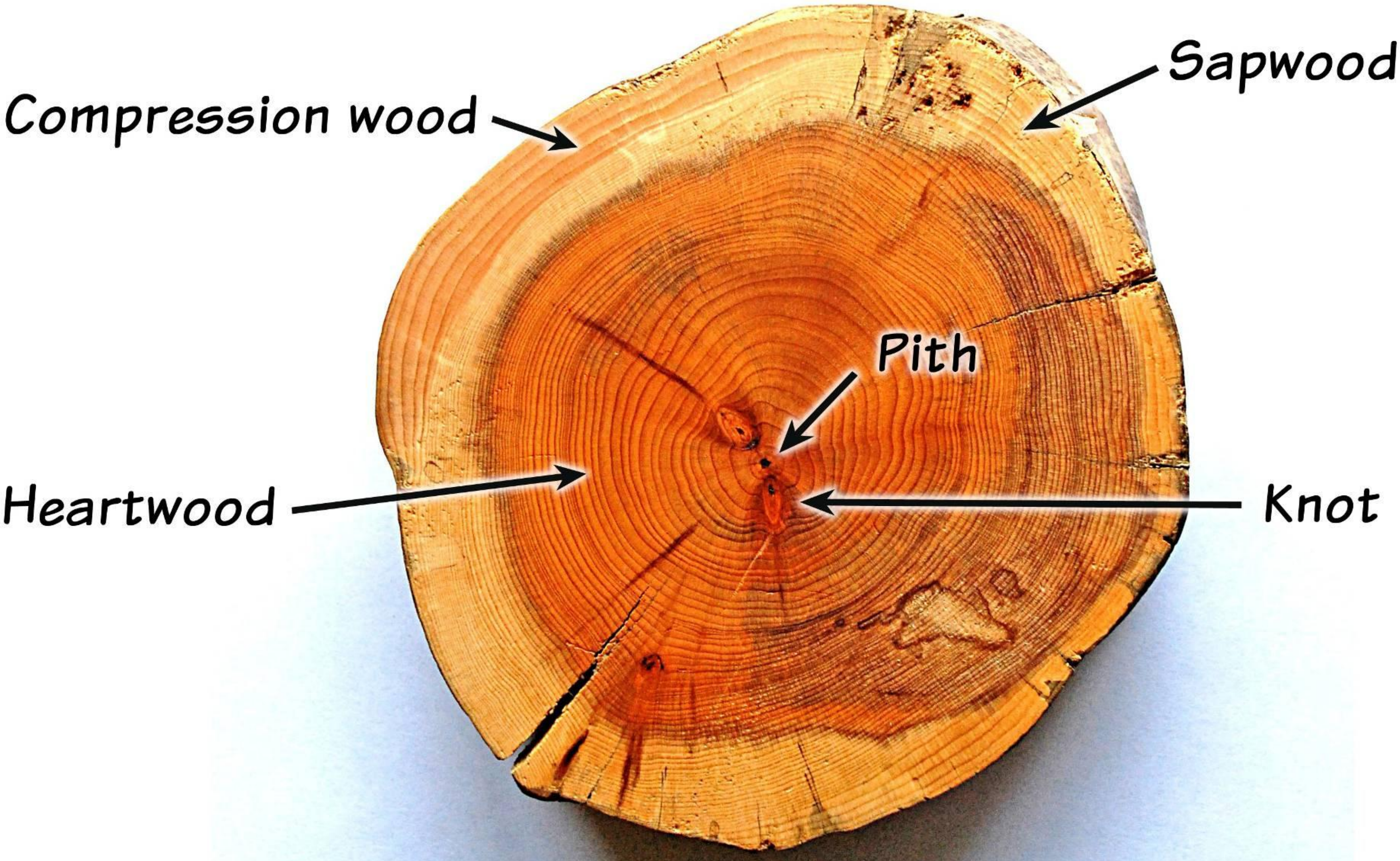
SIRT

Forest Products Research Institute

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

Edinburgh Napier UNIVERSITY

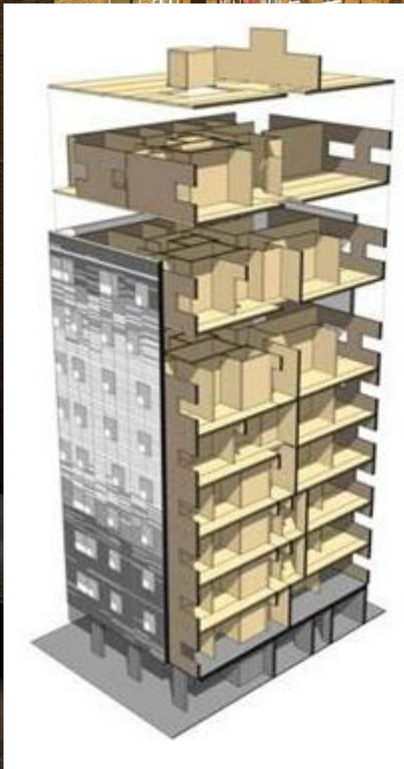

Radial
latewood
rays
Longitudinal
Tangential


Compression wood
Sapwood
Pith
Heartwood
Knot

Wood

- Strength
- Stiffness
- Density
- Shrinkage and swelling
- Distortion
- Durability
- Hardness, toughness, knots, appearance

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future



The Stadthaus, Murray Grove, London

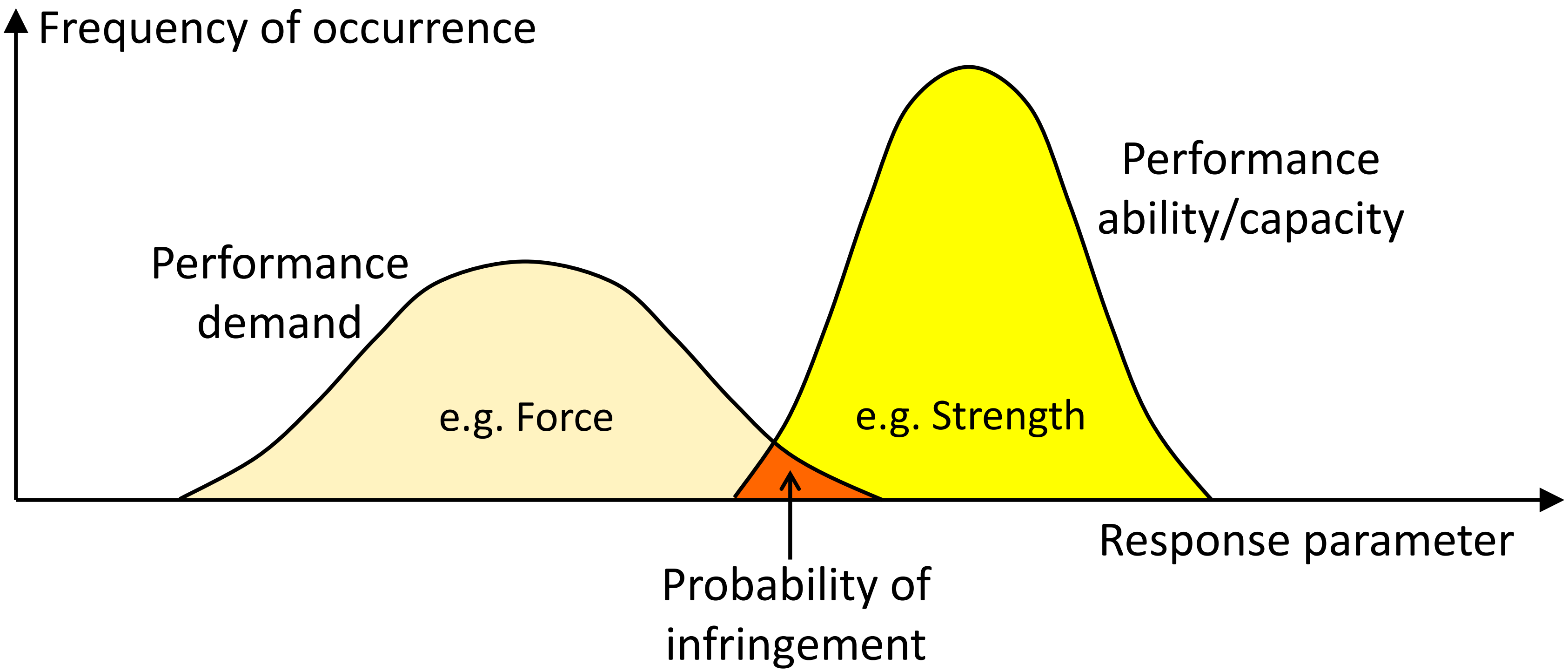
ARCHITECT: WAUGH THISTLETON ARCHITECTS **BUILDER/MAIN CONTRACTOR:** TELFORD HOMES PLC
STRUCTURAL ENGINEERS: TECHNIKER LTD **JOINERY:** KLH

Structural engineering design

- About buildings
  - Staying safe ("ultimate limit state")
  - Staying fit for use ("serviceability limit state")
- Dealing with uncertainty
  - Of material
  - Of the actions on a structure
  - Of analysis and construction
- Irrespective of the material

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

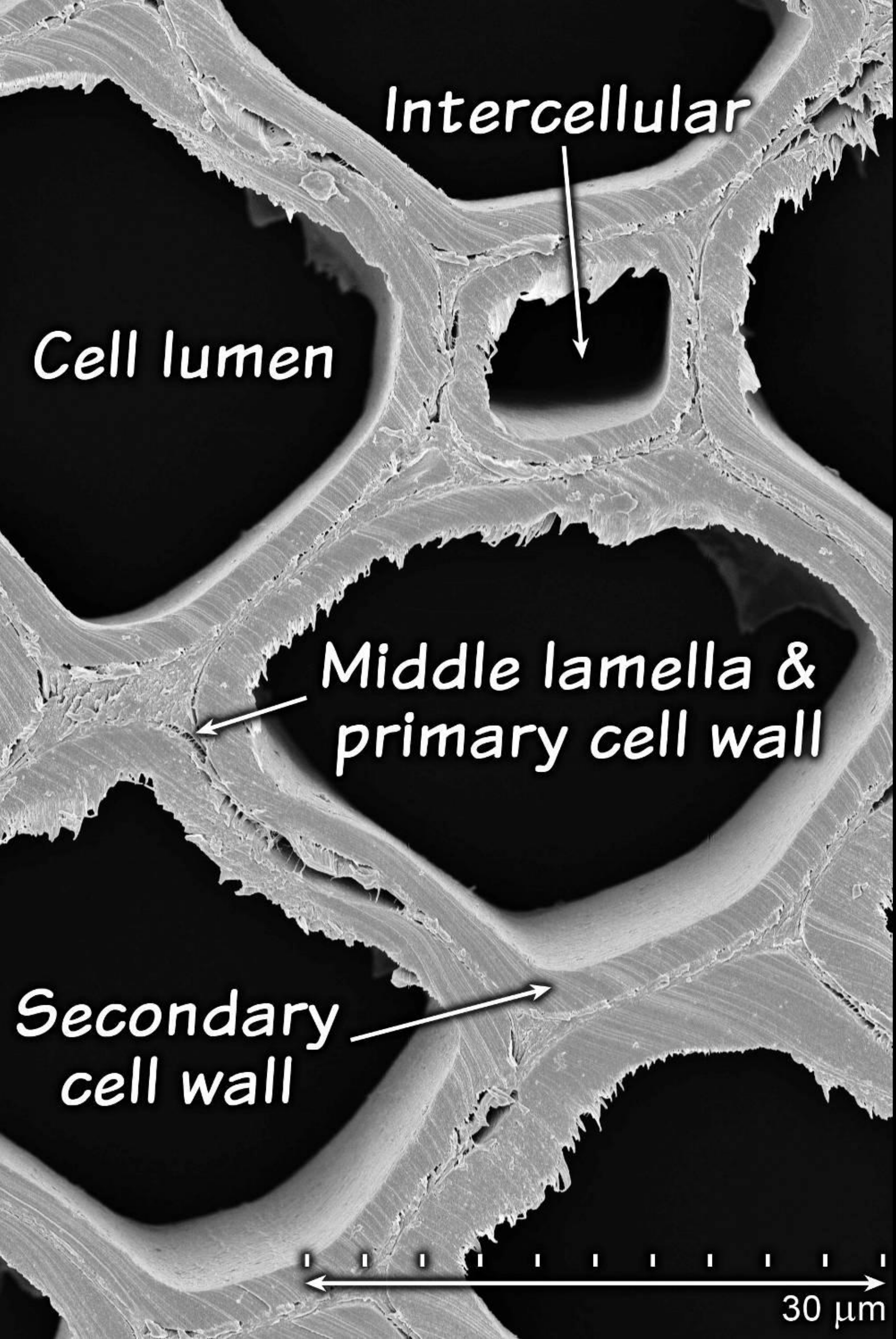
Dealing with uncertainty

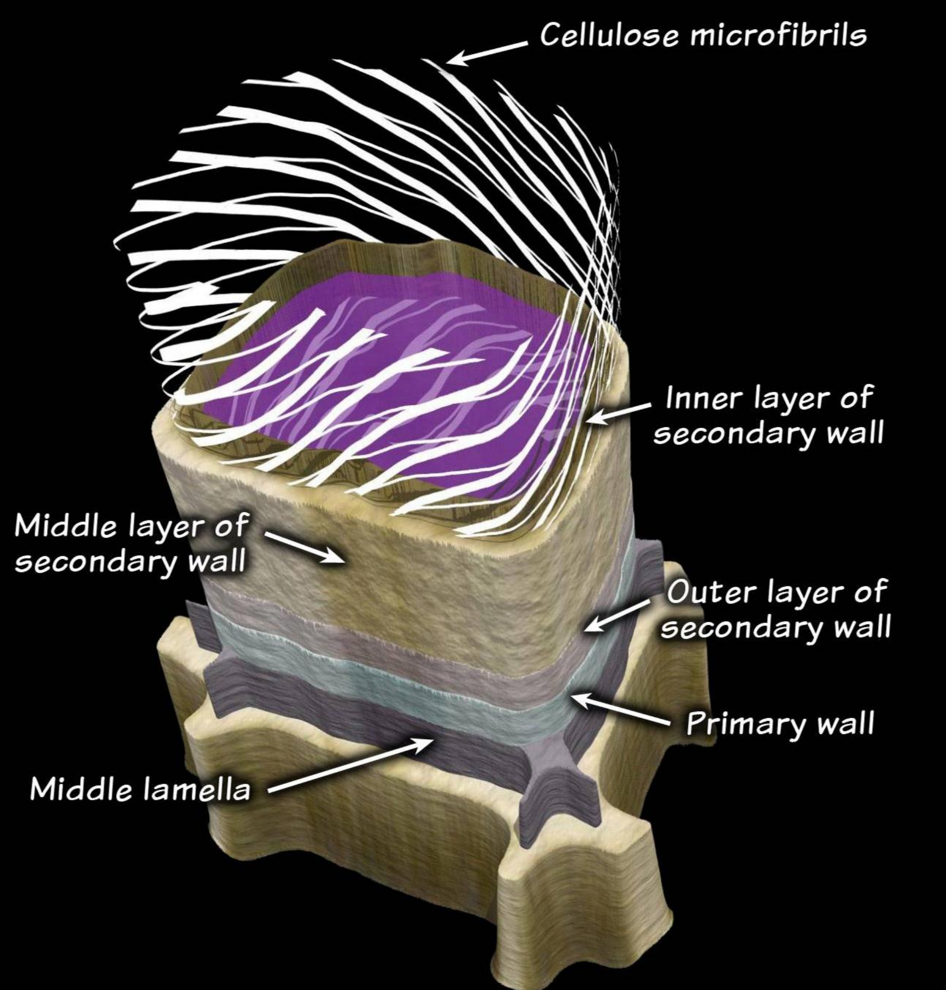


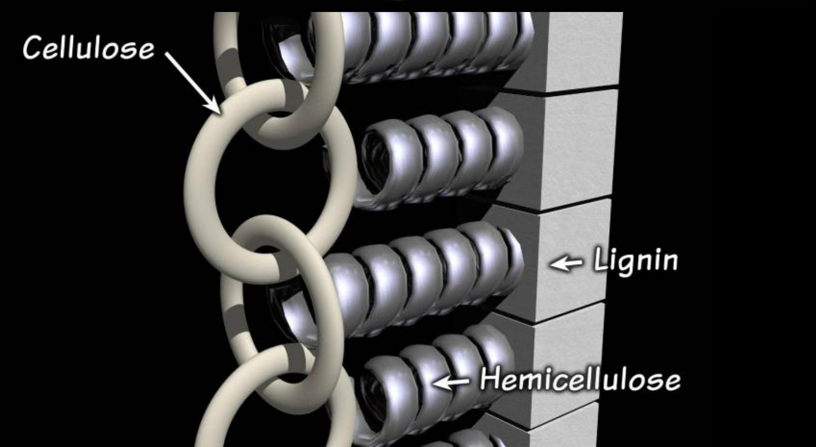
Constituents of wood

- Cellulose
  - A long polysaccharide molecule $(C_6H_{10}O_5)_n$
  - Analogous to reinforcing strand (main role tension)
- Lignin
  - A number of complex 3D biopolymers
  - Analogous to cement (main role compression)
- Hemicelluloses
  - Mixture of different sugar monomers
  - Links the cellulose and the lignin (giving flexibility)
- Extractives and water

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future


Intercellular
Cell lumen
Middle lamella &
primary cell wall
Secondary
cell wall
30 μm


Cellulose microfibrils
Inner layer of
secondary wall
Middle layer of
secondary wall
Outer layer of
secondary wall
Primary wall
Middle lamella


Cellulose
Lignin
Hemicellulose

Mechanical properties

- Amount of cell wall material
  - Wood density
- How that cell wall material is arranged
  - Grain, earlywood, latewood
- How that cell wall material is made up
  - Cellulose : lignin
  - Microfibril angle

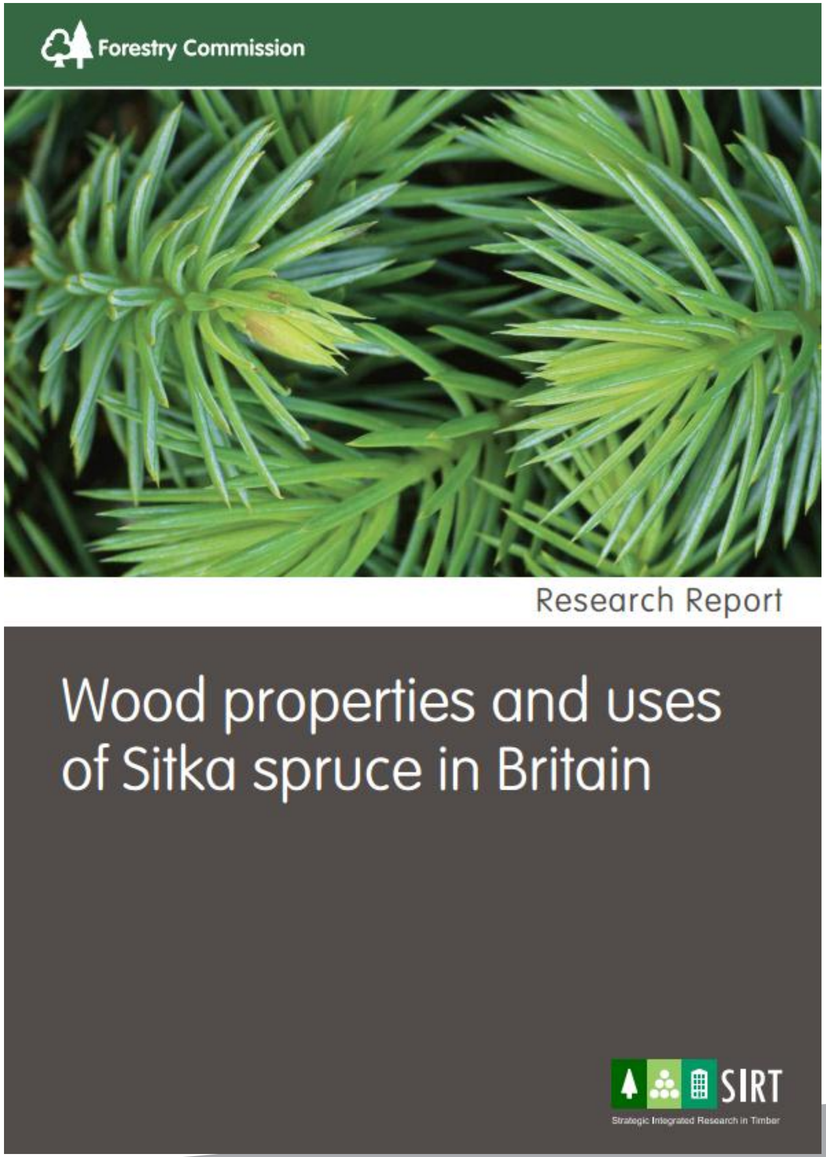
	Region
km	Forest
	Stand
	Tree
m	Log
	Sawn timber
cm	Clear wood
mm	Growth layer
	Wood anatomy
	Cell
µm	Cell wall
	Cell wall layers
	Microfibril clusters
nm	Molecular

Forest Research
Forestry Commission

Edinburgh
Napier University

The University of Glasgow

	Building
m	Assembly
	Sawn timber
cm	Details



What we know about the UK's Sitka spruce resource.

http://www.forestry.gov.uk/pdf/FCRP015.pdf/$file/FCRP015.pdf

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

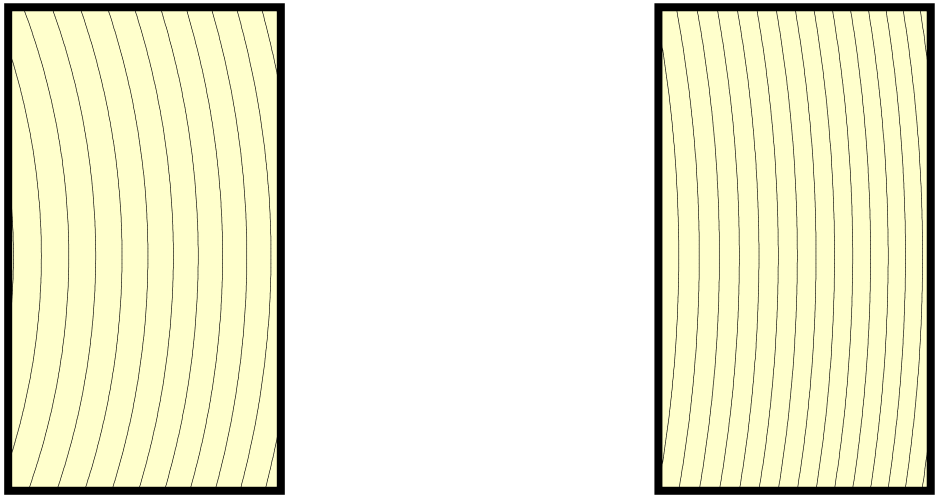
A bit of an image problem

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

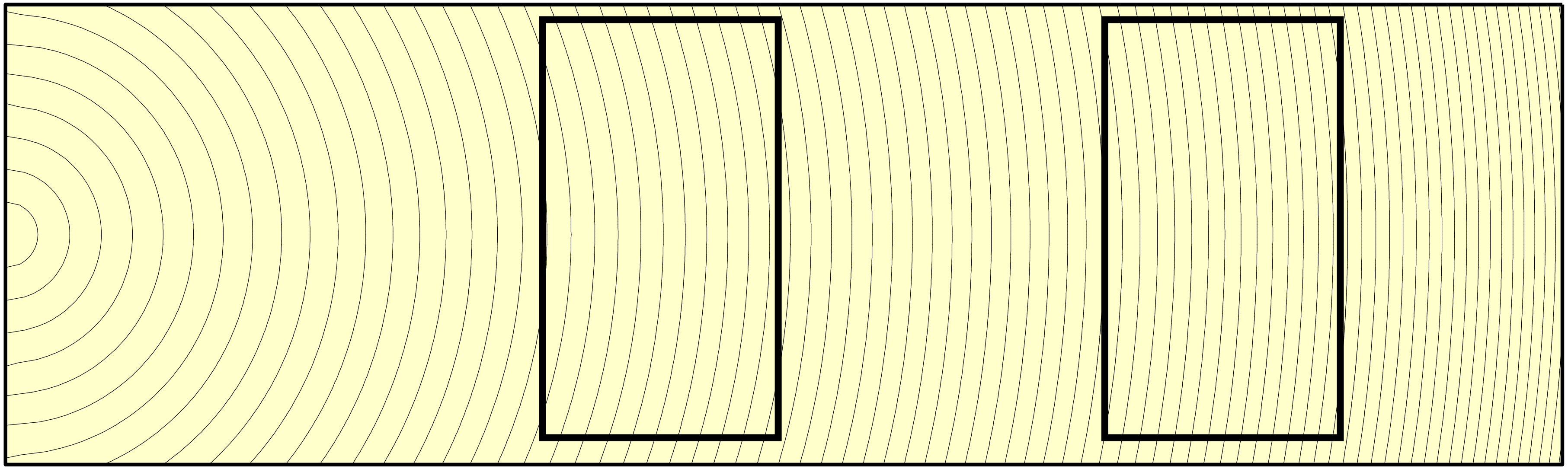
“Rate of growth”

Grew in ~11 years

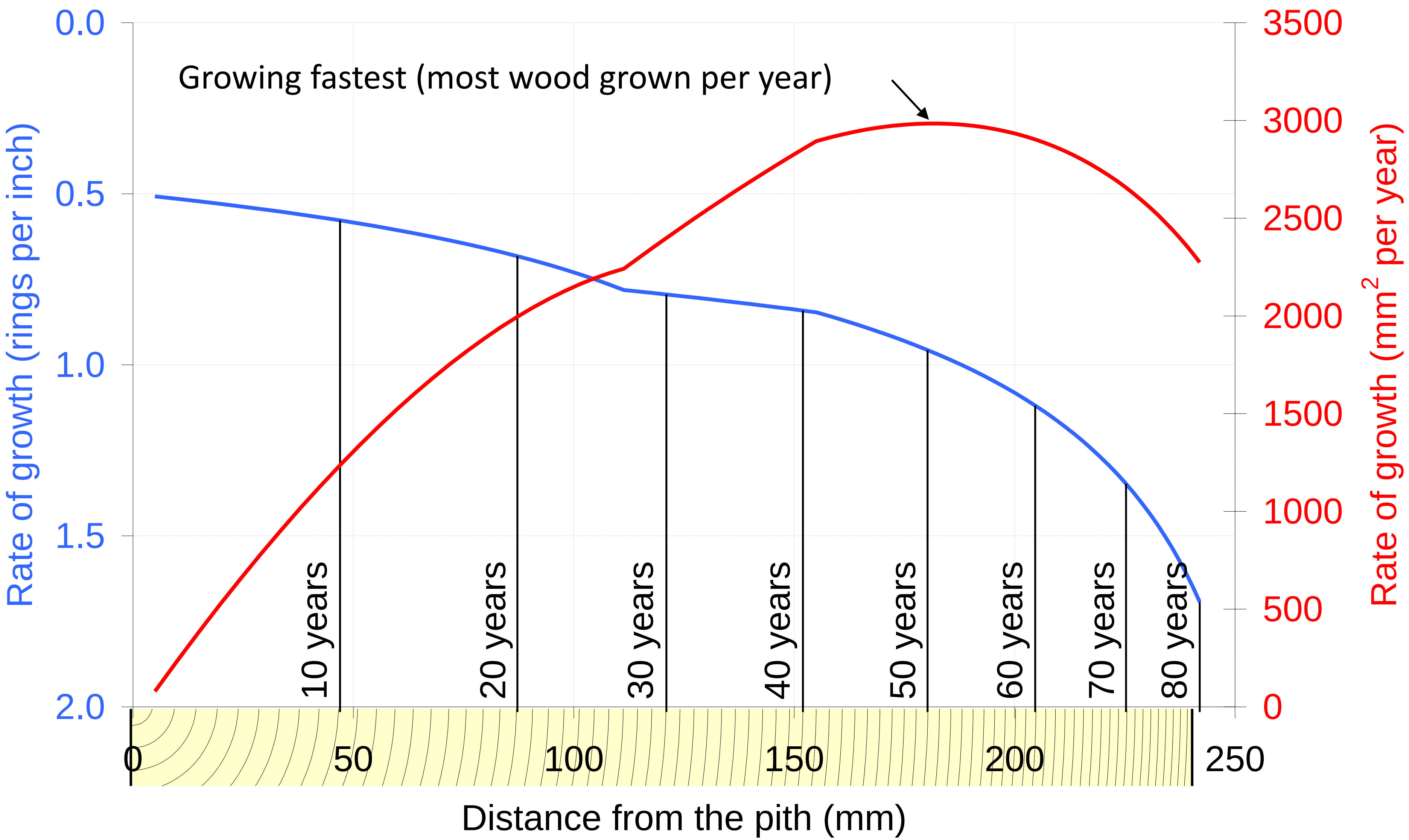
Grew in ~15 years



“Rate of growth”



EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future


Growing fastest (most wood grown per year)
Rate of growth (rings per inch)
0.0
0.5
1.0
1.5
2.0
Rate of growth (mm^2 per year)
3500
3000
2500
2000
1500
1000
500
0
10 years
20 years
30 years
40 years
50 years
60 years
70 years
80 years
0
50
100
150
200
250
Distance from the pith (mm)

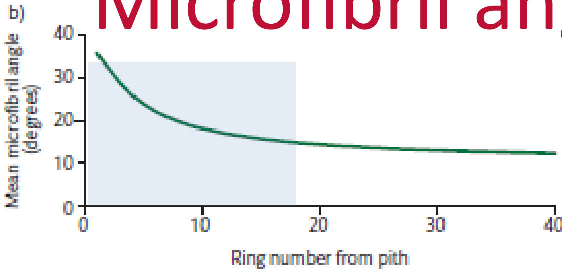
Birkley Wood Study

(83-year old Sitka spruce trees)

1162
00540
01052
1128
00764
1167
00744
00756
00726
00247
00746
1094
00895
00860
00721
00714
00910
00741
00839
1062
00888
00981
00773
00314
01003
00488
00812
00260
00202
00252
00772
00920
00268
00489
00970
00866
00915
00226
00286
00278
00600
00776
00390
00196
00422
00198
00430
00394
00782
00421
00186
00374
00448
00401
00404
00512
00507
00511
1247
1232
00494
1230
00306
1197
00317
1231
1211
1222
1252
00373

Juvenile core

Microfibril angle



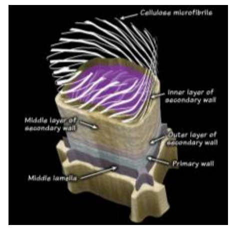


Figure 2.20 Example of the radial variation in modulus of elasticity for two specimens of Sitka spruce wood. Modulus of elasticity was estimated from data on density and microfibril angle obtained from SilviScan-3.

Stiffness, *E*

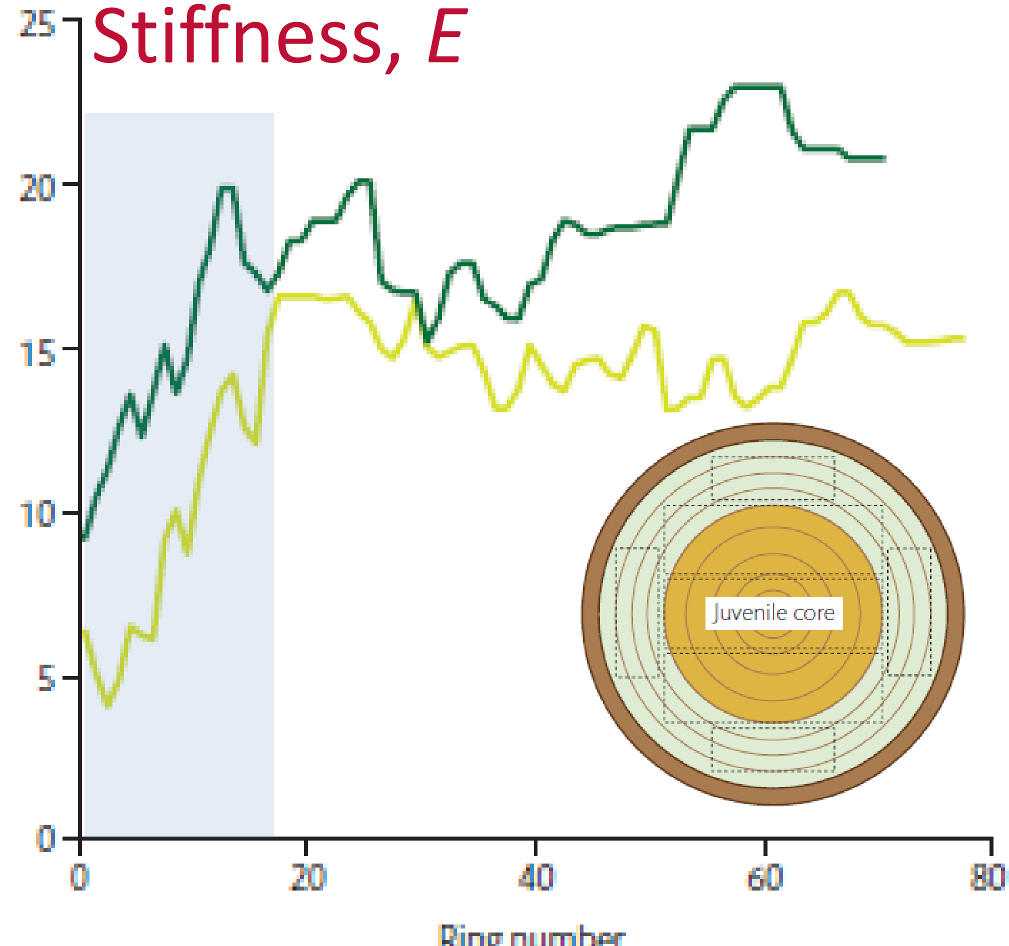
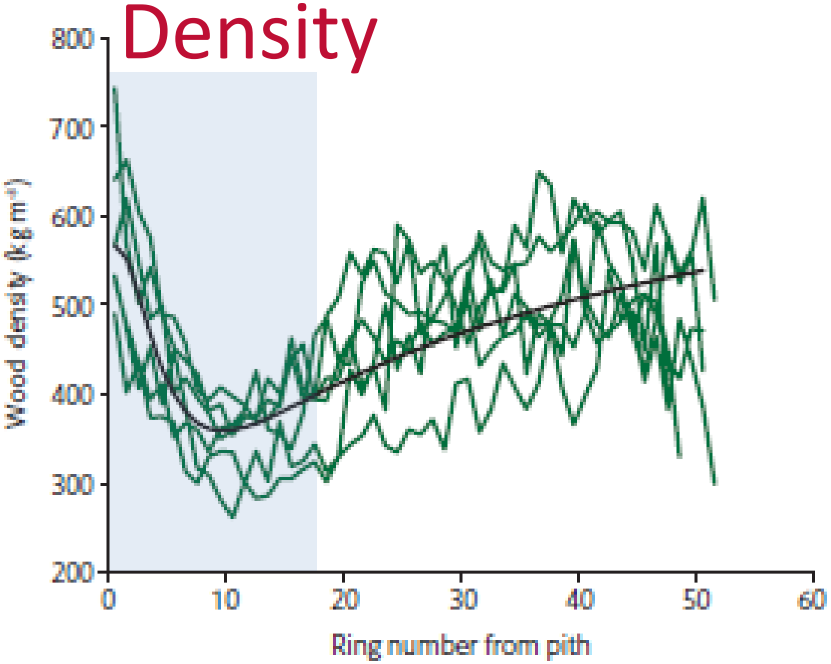


Figure 2.15 Radial profile of Sitka spruce wood density. The green lines show profiles for five individual trees sampled at Baronscourt in Northern Ireland, while the black line represents a model fitted to these data.

Density

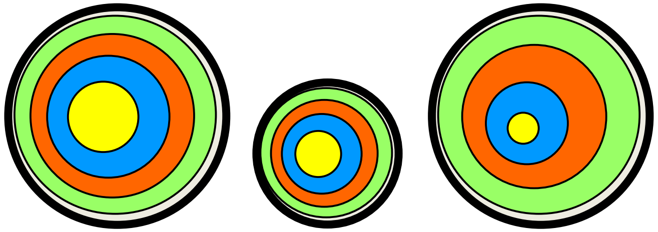


SIRT

Forest Products Research Institute

Factors affecting softwood quality

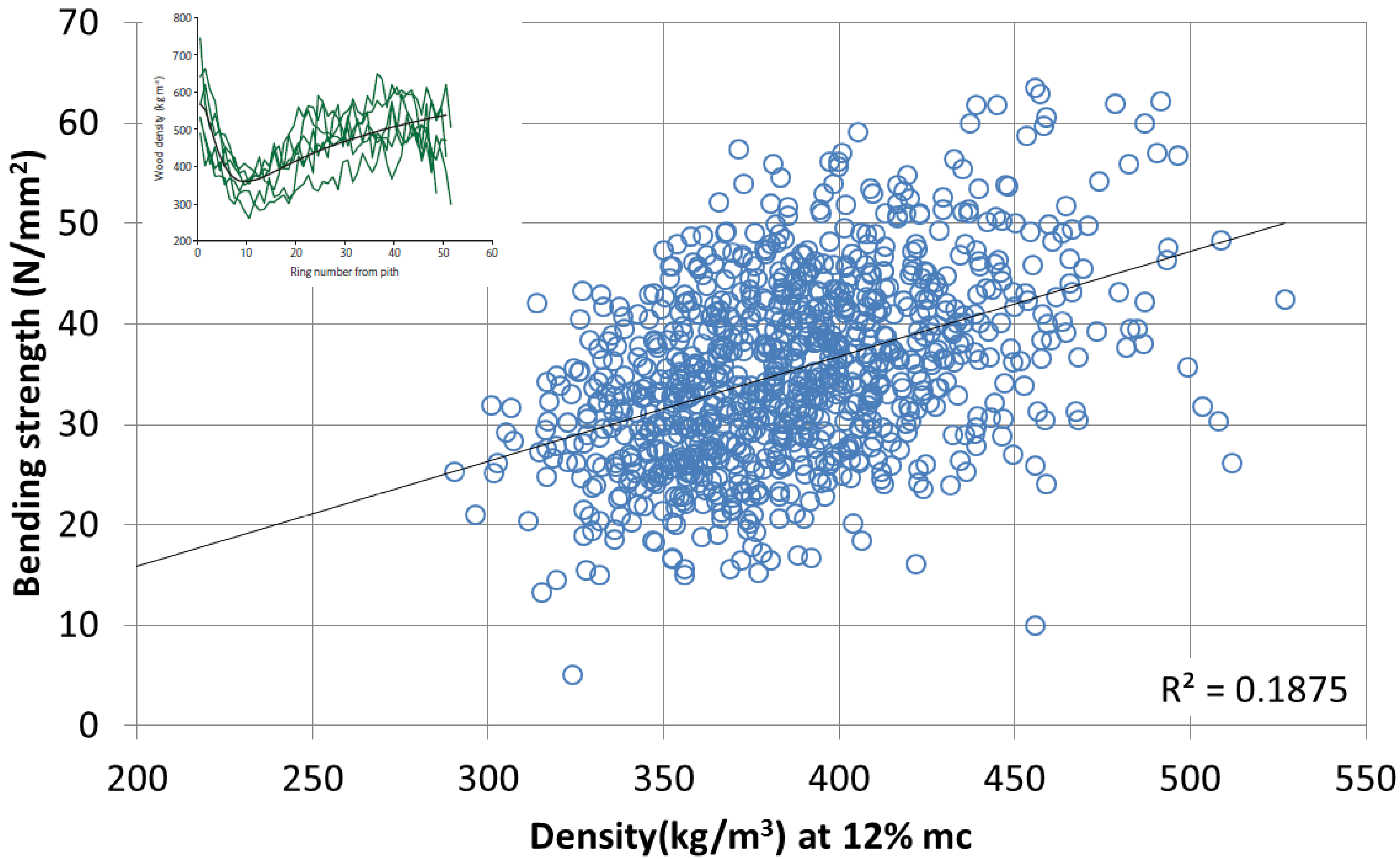
- Position within the tree
  - Radially & vertically
- Silviculture
  - Spacing, thinning, rotation length etc
- Site
  - Exposure, temperature, rainfall, soil type etc
- Genetics
  - Species, variety and individual



EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

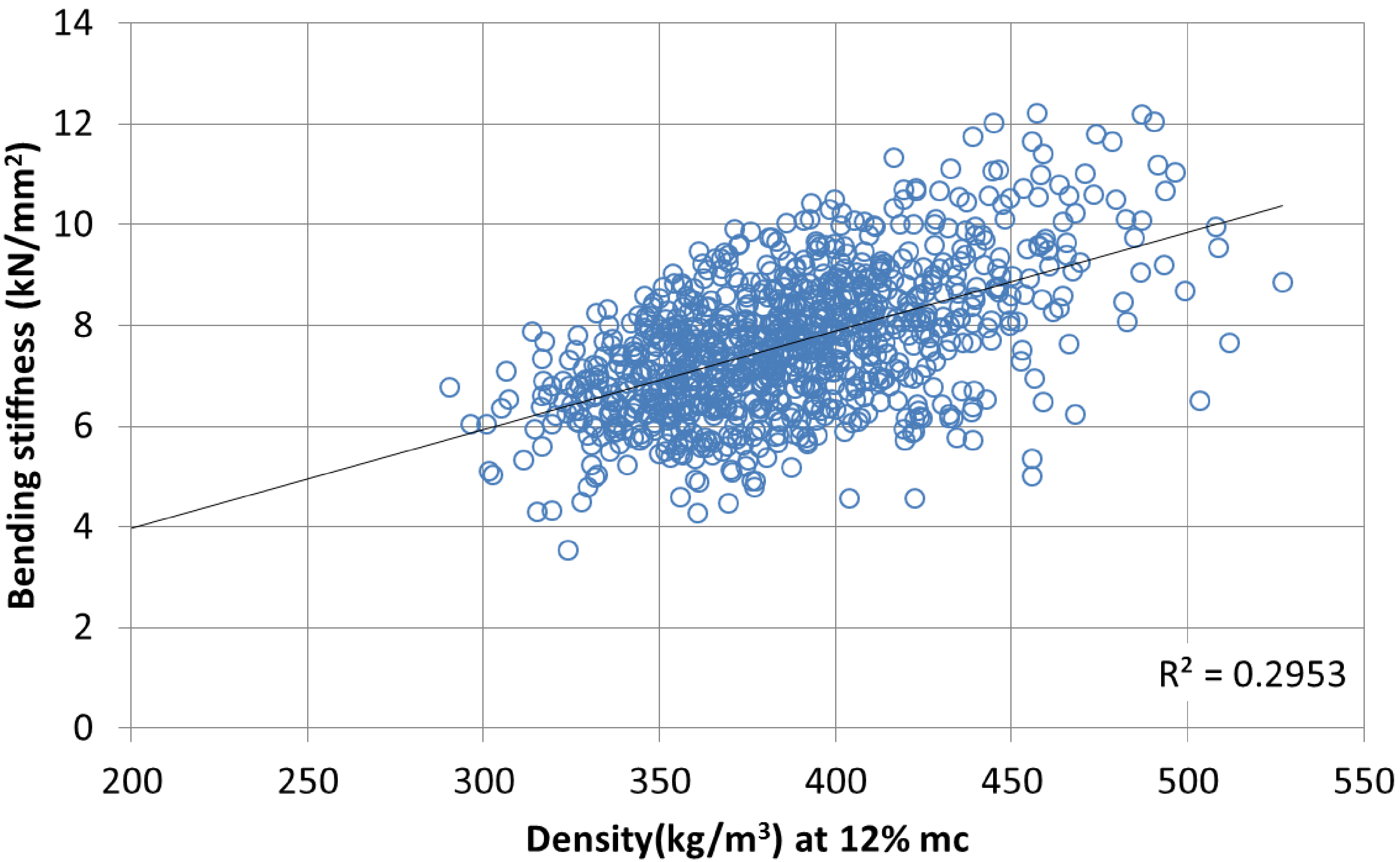
Edinburgh Napier UNIVERSITY

Density and bending strength



Raw data from SIRT benchmarking validation study

Density and bending stiffness

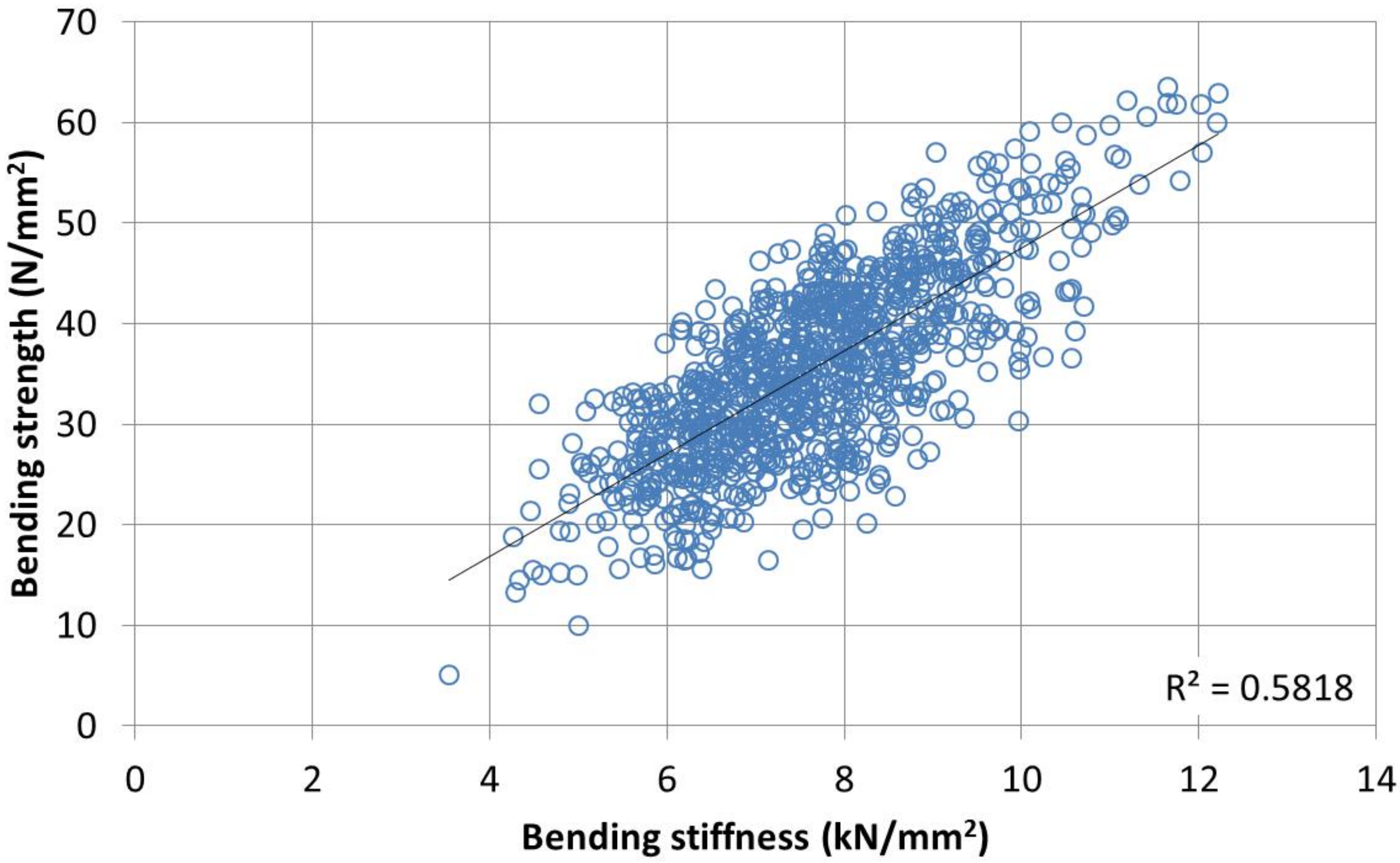


Raw data from SIRT benchmarking validation study

SIRT

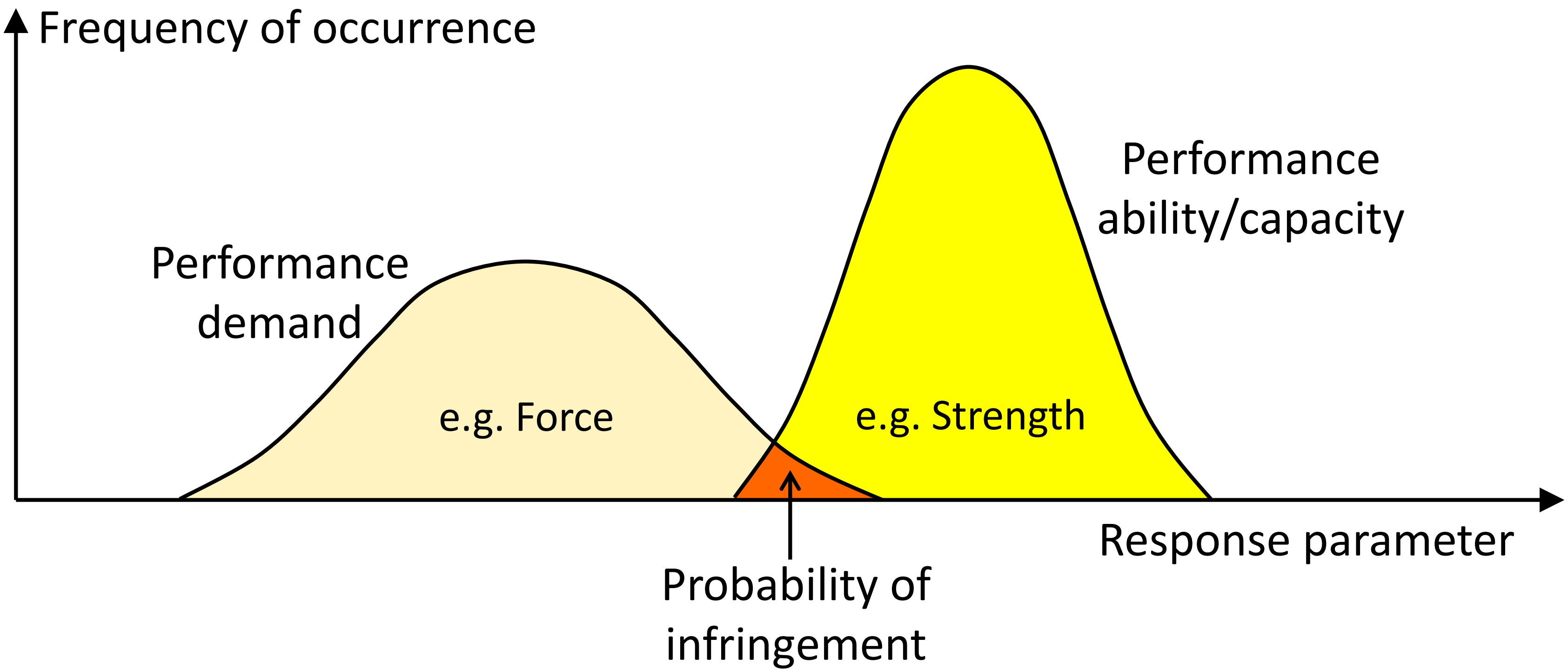
Forest Products Research Institute

Bending strength and stiffness

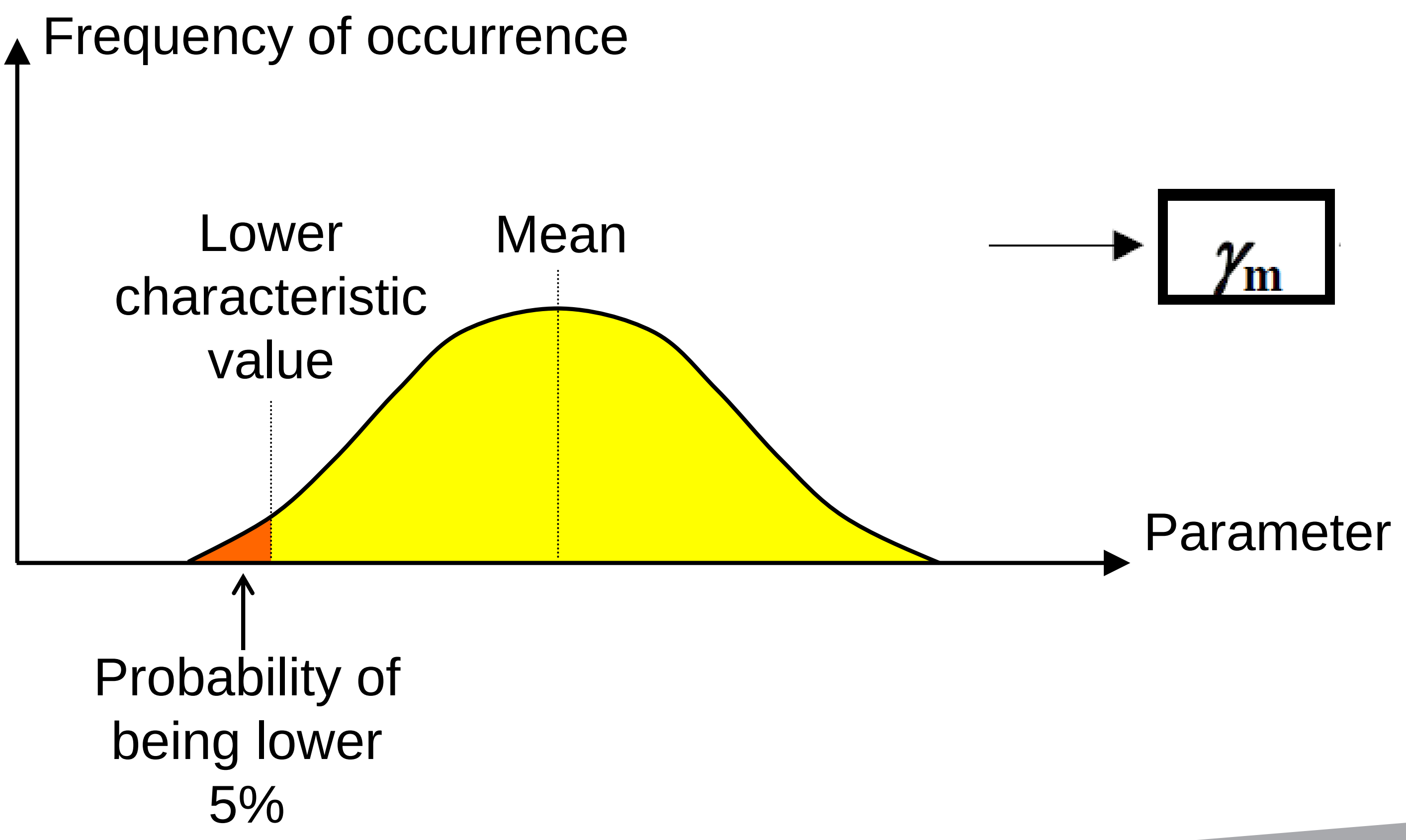


Raw data from SIRT benchmarking validation study

Dealing with uncertainty



Characteristic values



The core standards

EN 14081, Timber structures - Strength graded structural timber with rectangular cross section
Part 1: General requirements
Part 2: Machine grading, additional requirements for initial type testing
Part 3: Machine grading; additional requirements for factory production control
Part 4: Machine grading; grading machine settings for machine controlled systems

BS 4978, Visual strength grading of softwood. Specification
BS 5756, Visual strength grading of hardwood. Specification

EN 336, Structural timber - Sizes, permitted deviations
EN 338, Structural timber - Strength classes
EN 1912, Structural timber - Strength classes - Assignment of visual grades and species

EN 408, Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties
EN 384, Structural timber - Determination of characteristic values of mechanical properties and density
EN 14358, Timber structures - Calculation of characteristic 5-percentile values and acceptance criteria for a sample

+ CEN TC124 TG1 additional requirements

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

Grade-determining properties

- Strength
  - Usually major axis bending strength **ULS**
- Stiffness
  - Usually major axis bending stiffness **SLS** **(sometimes ULS)**
- Density
  - Also an indirect measure of strength in some elements of timber design
- All other properties are derived from these 3 properties

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

Critical property

- Grades are defined by characteristic
  - Strength (lower 5th percentile)
  - Stiffness (mean)
  - Density (lower 5th percentile)
- The limits are general across species
  - Softwoods (C classes...major axis bending)
  - Hardwoods (D classes...major axis bending)
  - Density (lower 5th percentile)
- Other strength class systems exist

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

EN 338

		Softwood species											
		C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
Strength properties (in N/mm^2)													
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50
Tension parallel	$f_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30
Tension perpendicular	$f_{t,90,k}$	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
Compression parallel	$f_{c,0,k}$	16	17	18	19	20	21	22	23	25	26	27	29
Compression perpendicular	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,6	2,7	2,8	2,9	3,1	3,2
Shear	$f_{v,k}$	3,0	3,2	3,4	3,6	3,8	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Stiffness properties (in kN/mm^2)													
Mean modulus of elasticity parallel	$E_{0,mean}$	7	8	9	9,5	10	11	11,5	12	13	14	15	16
5 % modulus of elasticity parallel	$E_{0,05}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,0	10,7
Mean modulus of elasticity perpendicular	$E_{90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40	0,43	0,47	0,50	0,53
Mean shear modulus	G_{mean}	0,44	0,5	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00
Density (in kg/m^3)													
Density	ρ_k	290	310	320	330	340	350	370	380	400	420	440	460
Mean density	ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550

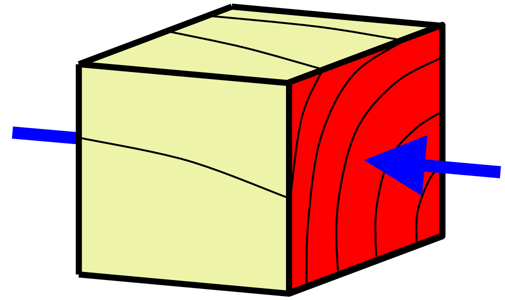
Critical property

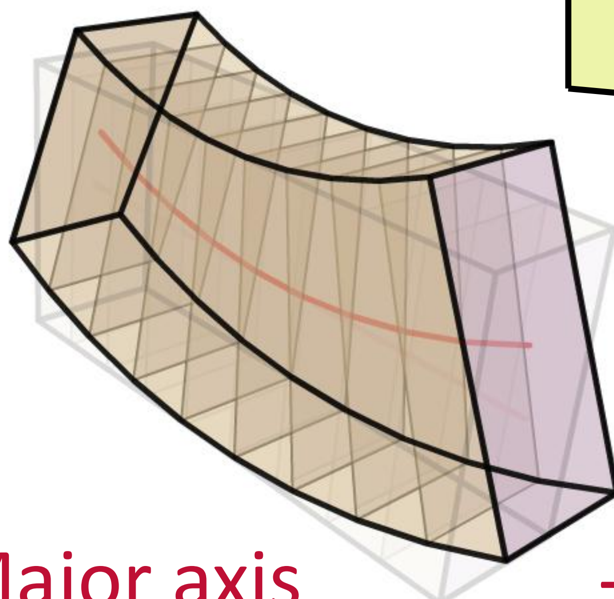
- To comply with the grade, characteristic values must be met (at least)
- For a species and grade combination usually one property is limiting
  - Strength
  - Stiffness
  - Density
- So strength grading isn't *always* about predicting strength

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

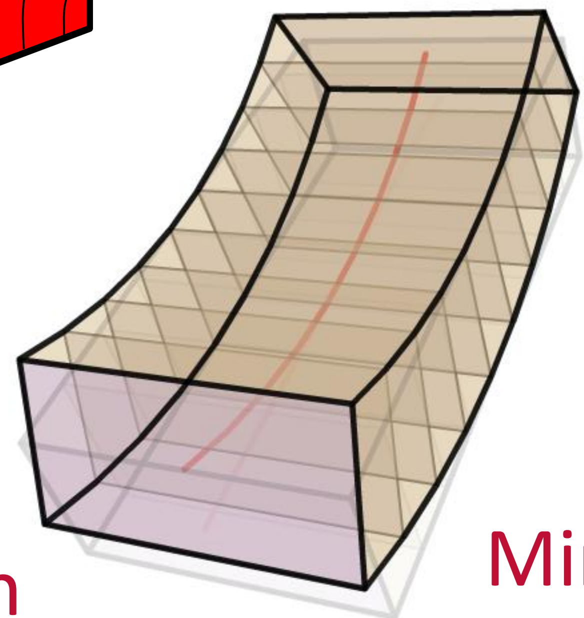
Bending

Compression



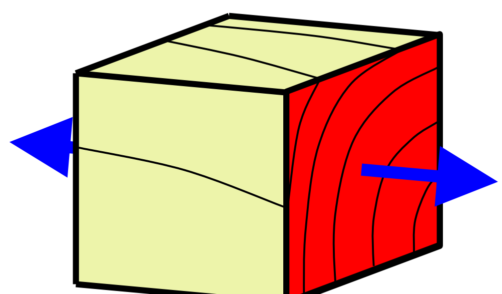


Major axis
(as a joist)

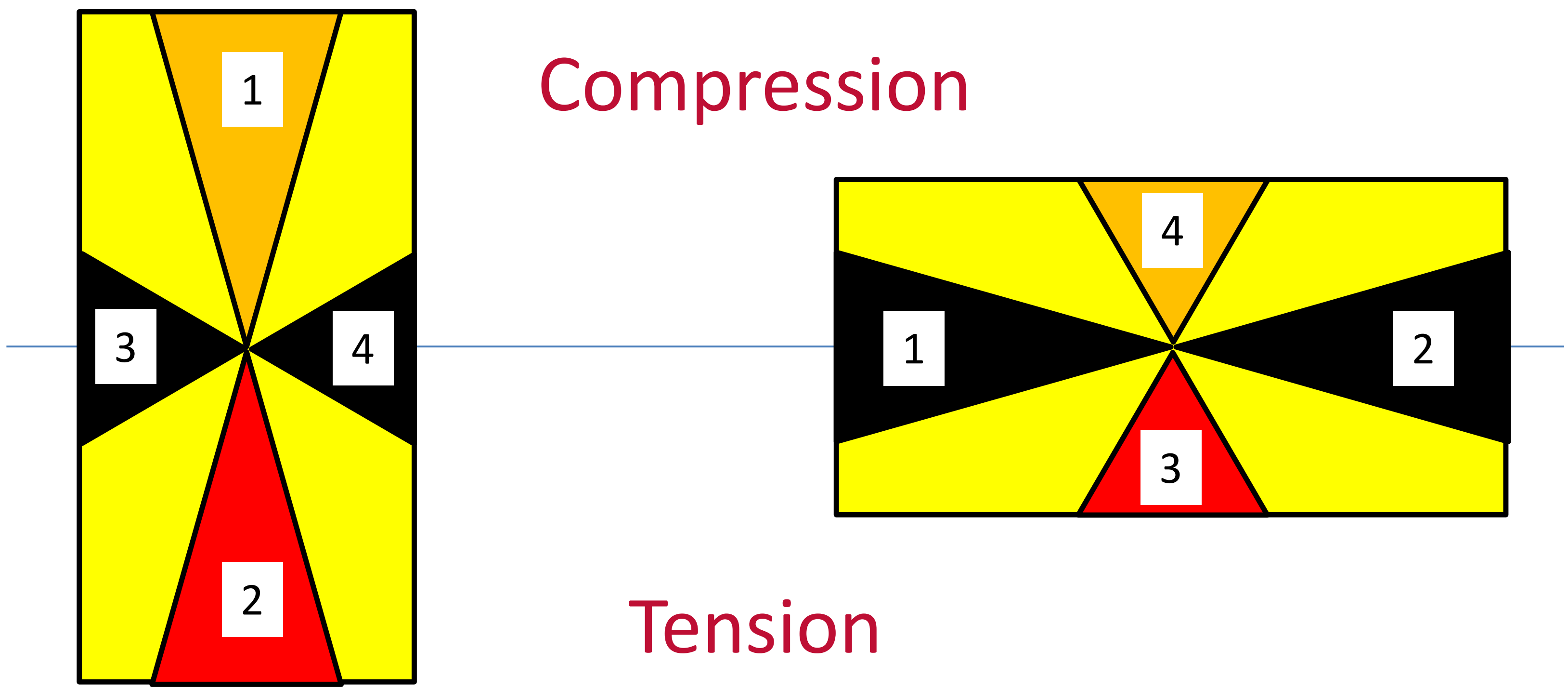


Minor axis
(as a board)

Tension



Bending



Major axis
(as a joist)

Minor axis
(as a board)

How do we predict strength?

- Can only be measured destructively
- But strength is correlated with:
  - Stiffness
  - Density
  - Knots
  - Grain e.g. ring width
    - Rate of tree growth & radial position
  - Species
  - Origin

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

How do we predict stiffness?

- Stiffness can be measured non-destructively
  - Mechanical bending (within elastic range)
  - Dynamic stiffness (vibration or time of flight)
- It is also correlated with
  - Density
  - Knots
  - Grain e.g. ring width
    - Rate of tree growth & radial position
  - Species
  - Origin

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

How do we predict density?

- Density can be measured non-destructively
  - By weighing and measuring dimensions
  - Using x-rays (and similar methods)
  - Pin indent
  - But is confounded by moisture content
- It is also correlated with
  - Stiffness
  - Grain e.g. ring width
    - Rate of tree growth & radial position
  - Species
  - Origin

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

Grading methods for timber

- Visual strength grading
  - (not the same as appearance grading)
- Machine strength grading

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

Visual strength grading

- Overarching requirements in EN 14081-1
- But done according to National Standards
  - BS 4978:2007 (softwoods)
  - BS 5756:2007 (hardwoods)
  - Also German, Canadian, French, Italian, Dutch, Nordic, Spanish...
- Assignments to classes in EN 1912
- According to testing to EN 384
- Can also be assignments elsewhere

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

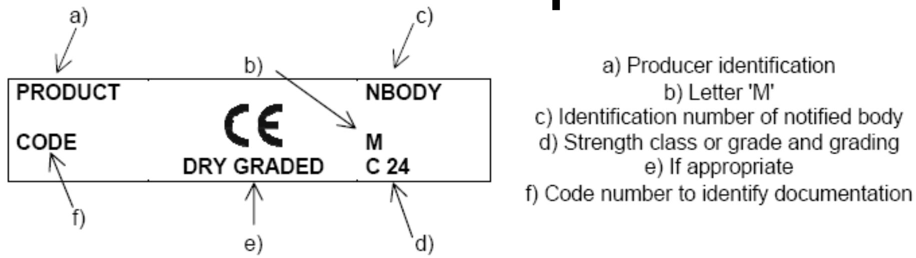
Machine strength grading

- Machine grading
  - Relates an ‘indicating parameter’ to the critical grade-determining parameter(s)
  - Better accuracy than visual grading…
  - …due to the parameters being measured
  - …and the automation
  - …so assignment to grade is less conservative
  - Fast but expensive equipment
  - Cannot really be verified afterwards

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

What? Cannot be verified?

- Timber is stamped with the grade mark



- But it is not possible to tell if an individual piece has been correctly assigned to a grade
- Because a piece can correctly belong to any grade

How can that make sense?

- Timber grading does not operate on a piece by piece basis
- Pieces are individually assigned to grades
- …but it is the population of timber in that grade that matters
- Packages of timber should meet the characteristic values

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

So does this make timber bad?

- No
- In fact this applies for all materials
- There is always some uncertainty
  - – the variability is accounted for in design
  - – by characteristic values and γ_m

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

So how do we machine grade?

- Now many types of grading machines
  - Bending stiffness
    - Bending about the minor axis
  - Dynamic (acoustic/vibration)
    - Essentially a measure of stiffness
    - May or may not include density
  - X-rays
    - A combination of knots and density
    - Perhaps with optical camera
  - Mixtures of the above

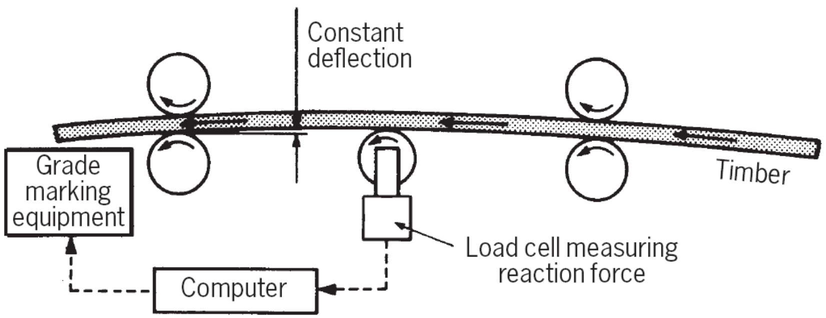
EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

Bending graders

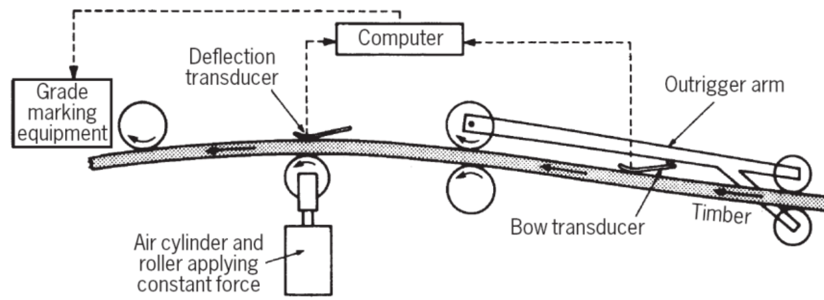
- Measure mechanical stiffness
  - Through application of defined load
  - or defined deflection
  - Minor axis
  - Accounting for pre-existing bow
- Relatively slow (with dynamic errors)
- Limited by cross-section
- Cannot measure the whole piece

Bending graders

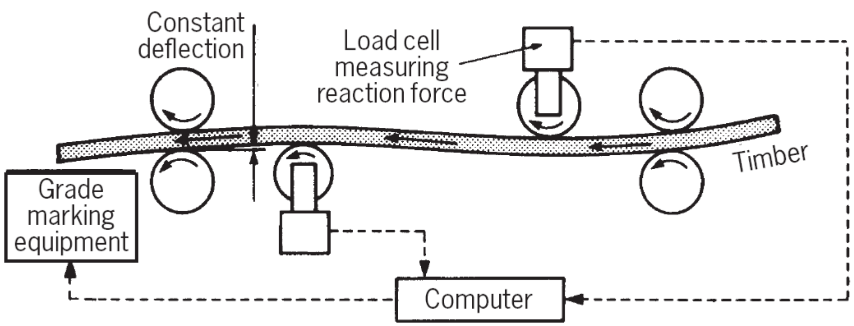
Cook-Bolinder



Computermatic



Timgrader



Figures from BRE Digest 476 “Guide to machine strength grading of timber”

Acoustic graders

- Measure acoustic velocity
  - Through axial or transverse vibration
  - Or time of flight (including ultrasonic)
  - May or may not include density ($MoE_{dyn} = \rho v^2$)
- Fast
- Can be hand-held
- Measure the whole piece
- …but all at once

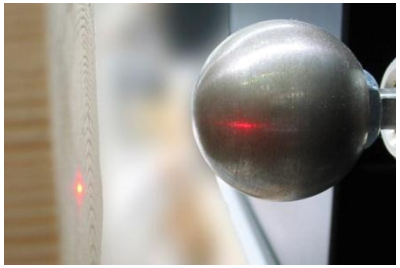
EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

SIRT

Forest Products Research Institute

Acoustic graders

ViSCAN (MiCROTEC)



MTG (Brookhuis)

Precigrader (Dynalyse AB)

Triomatic (CBS-CBT)

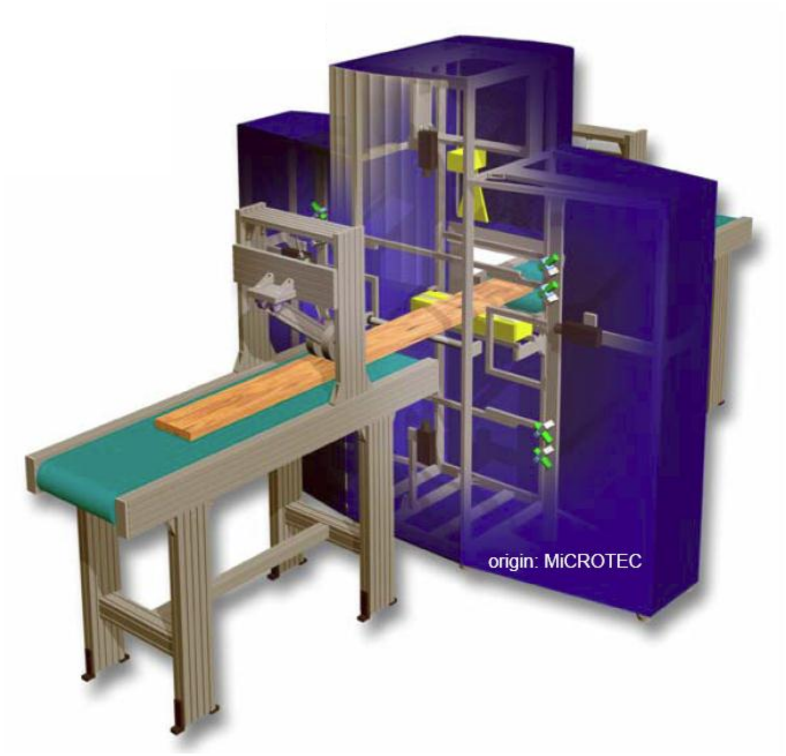
X-ray graders

- Measure
  - Clear wood and average density
  - Knot size and location
- Very fast (and permit board splitting)
- …but big and expensive
- Measure the whole piece
- …and all parts of it individually
- But not great at predicting stiffness

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

X-ray graders

GOLDENEYE 702 (MiCROTEC)

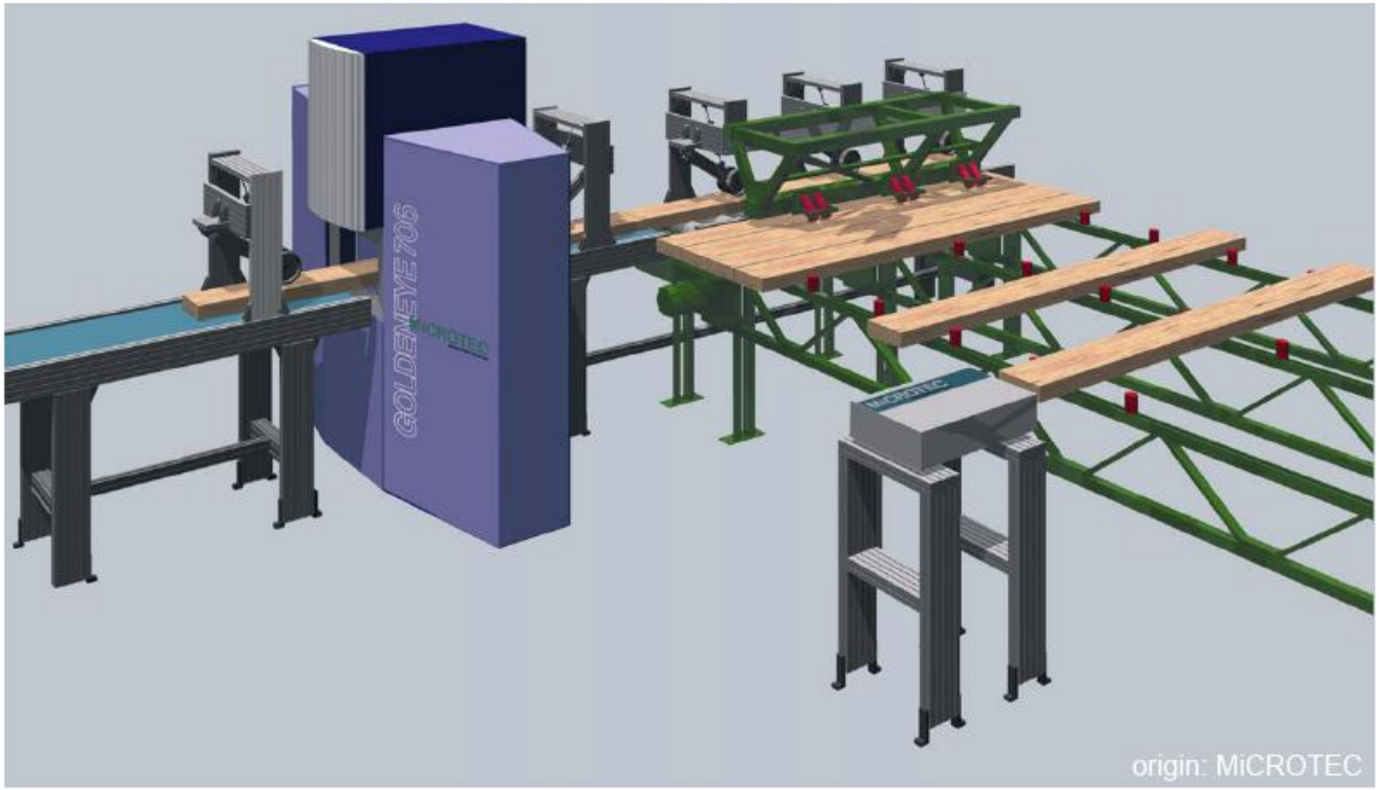


EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

Edinburgh Napier UNIVERSITY

Combination graders

GOLDENEYE 706 (MiCROTEC)



EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

But that's not everything yet

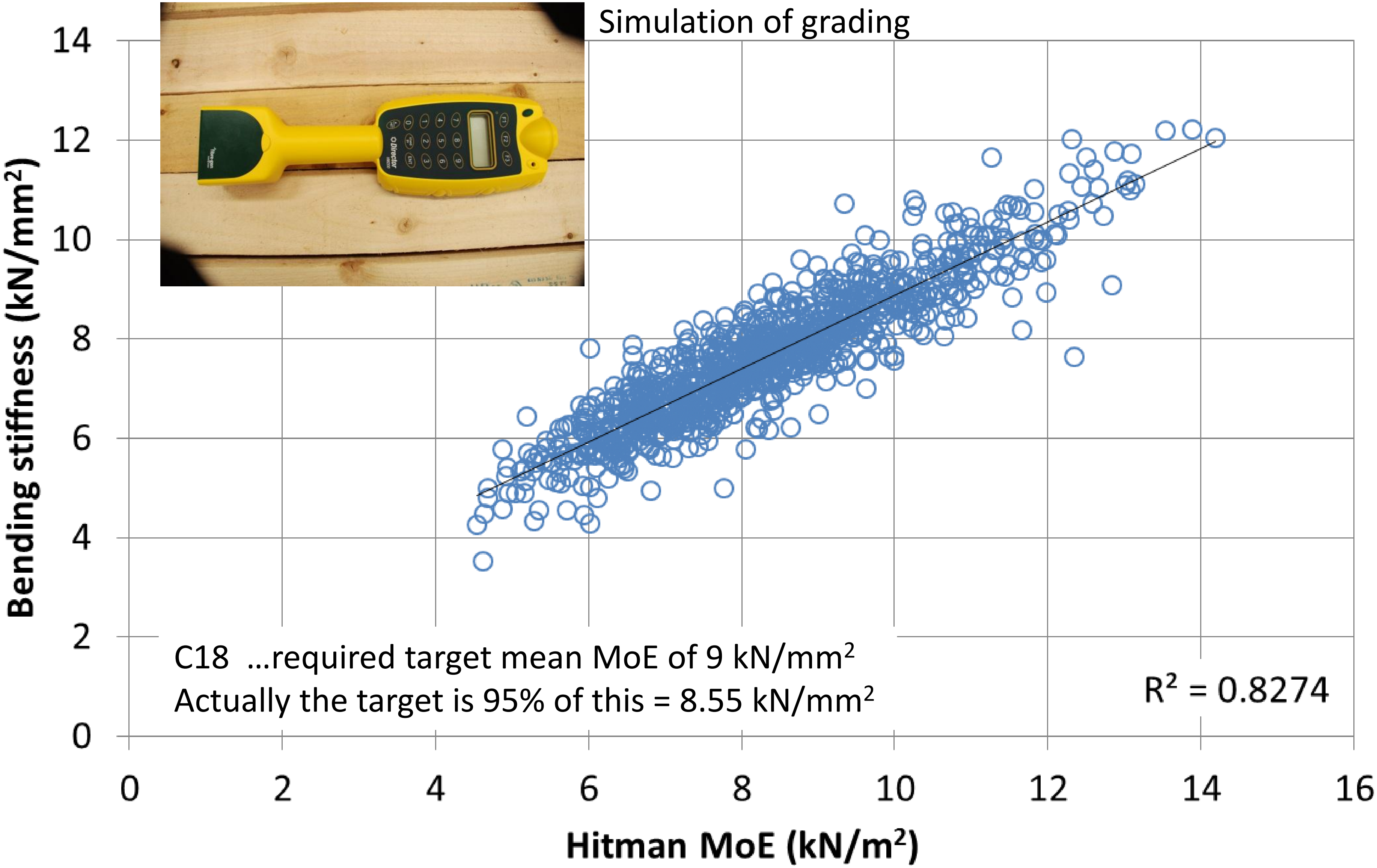
- "Visual" override
  - Distortion (might be by machine)
  - Fissures (cannot be detected by machine)
  - Wane
  - Soft rot and insect damage
  - Knots and slope of grain on any portion that cannot be machine graded (i.e. the ends of the timber for bending type machines)
  - Anything else that causes concern

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

SIRT

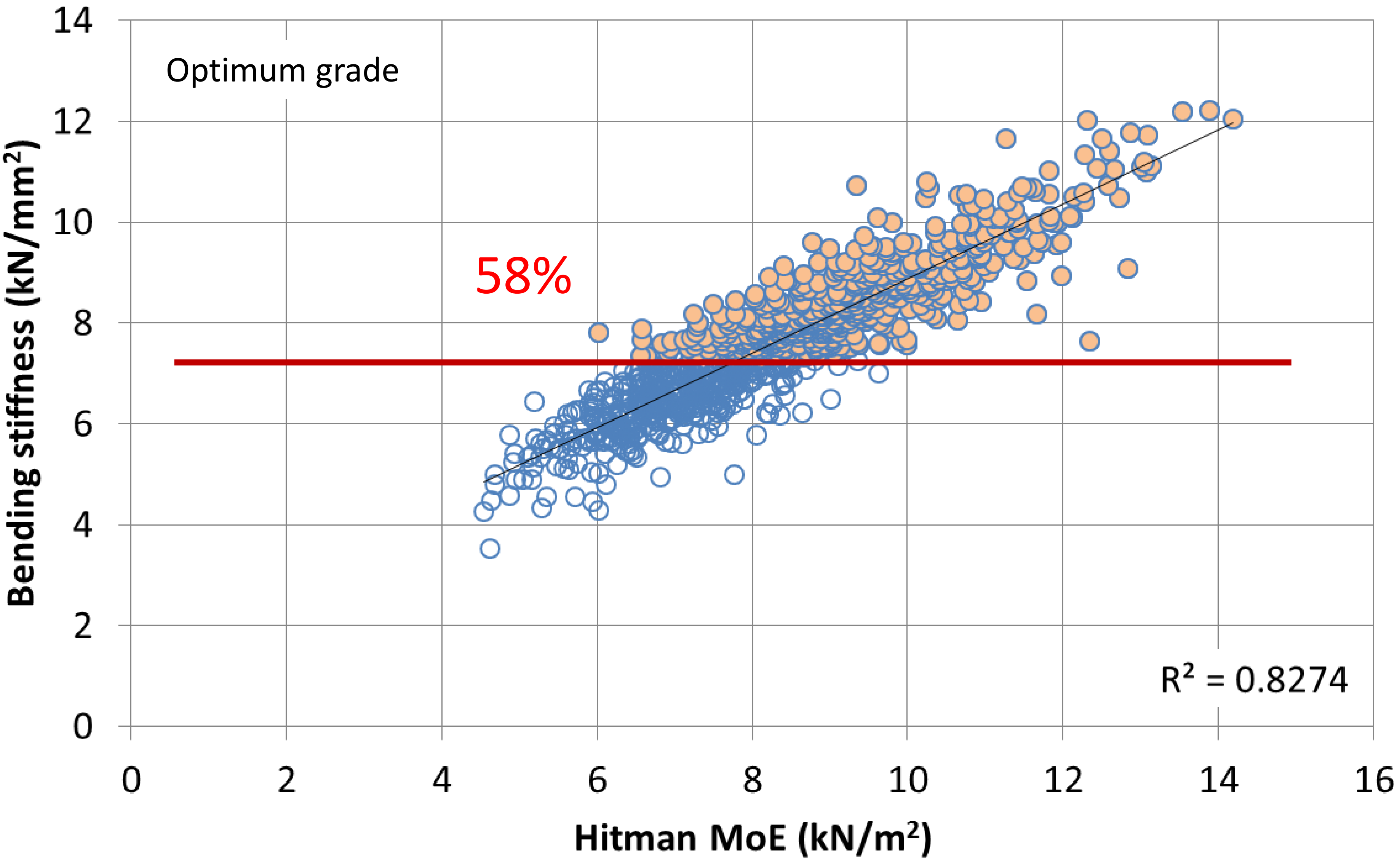
Forest Products Research Institute

Simulation of grading



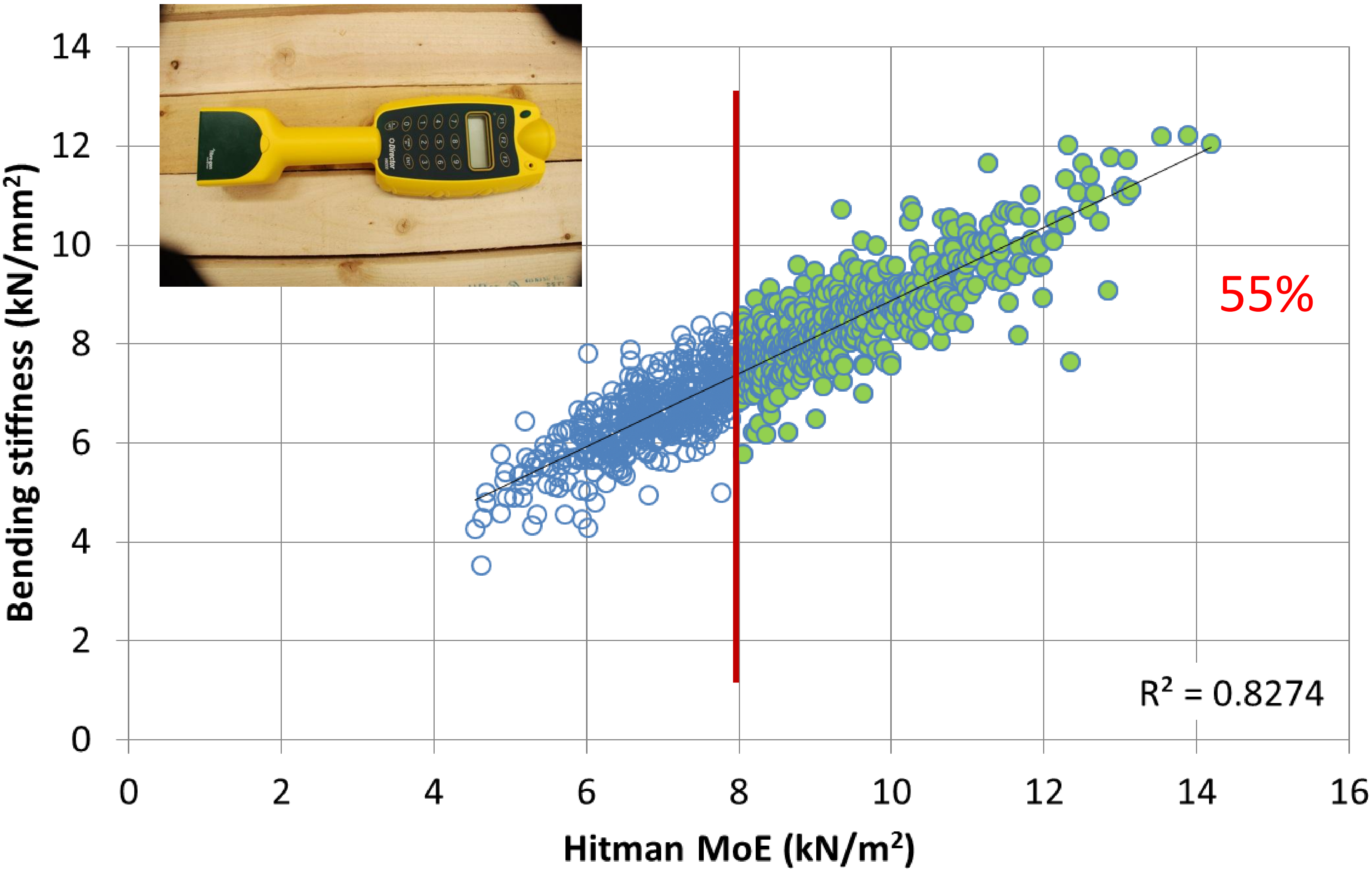
C18 …required target mean MoE of 9 kN/mm^2

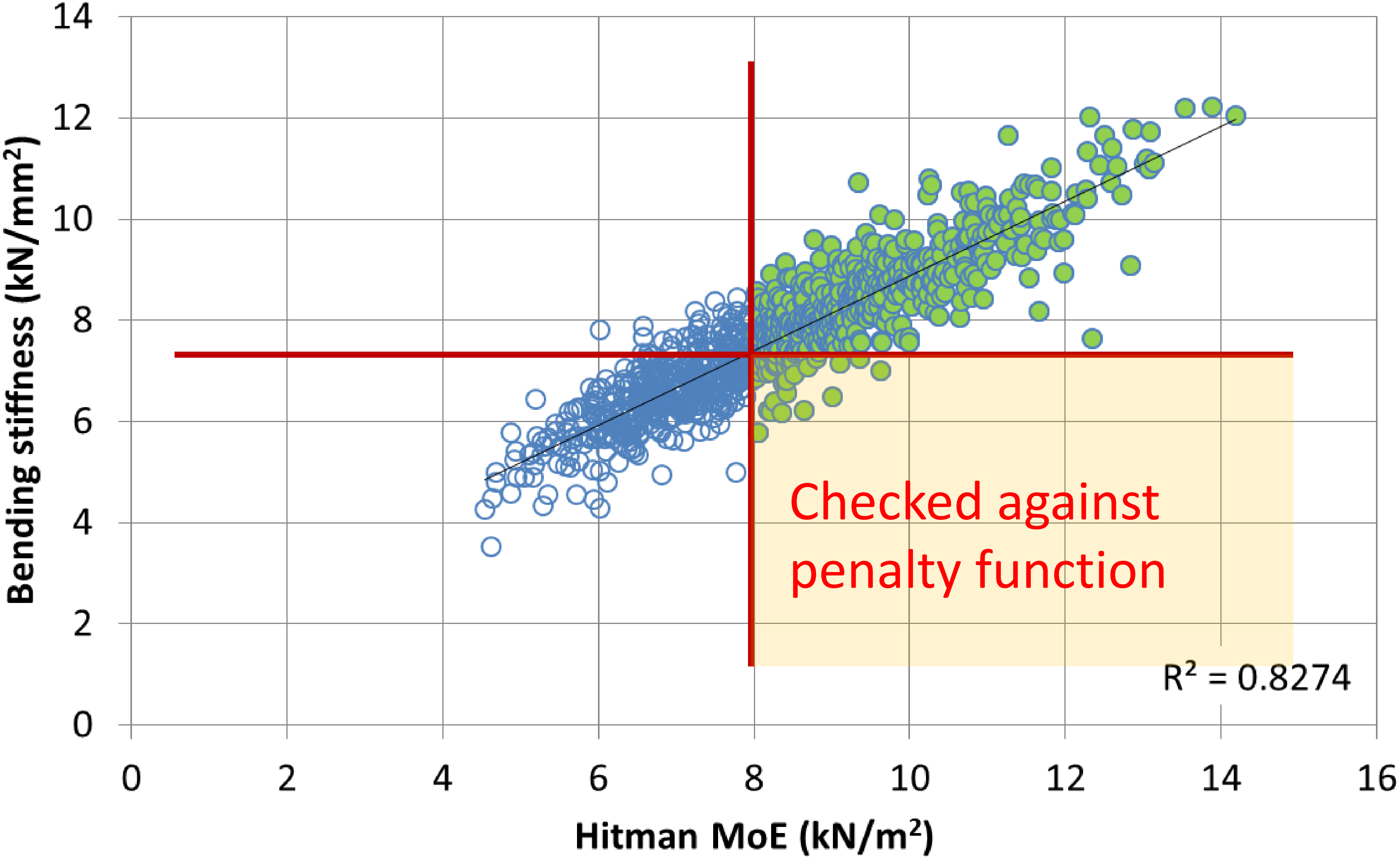
Actually the target is 95% of this = 8.55 kN/mm^2


Optimum grade
58%
R² = 0.8274
Bending stiffness (kN/mm²)
Hitman MoE (kN/m²)
0
2
4
6
8
10
12
14
16

SIRT

Forest Products Research Institute

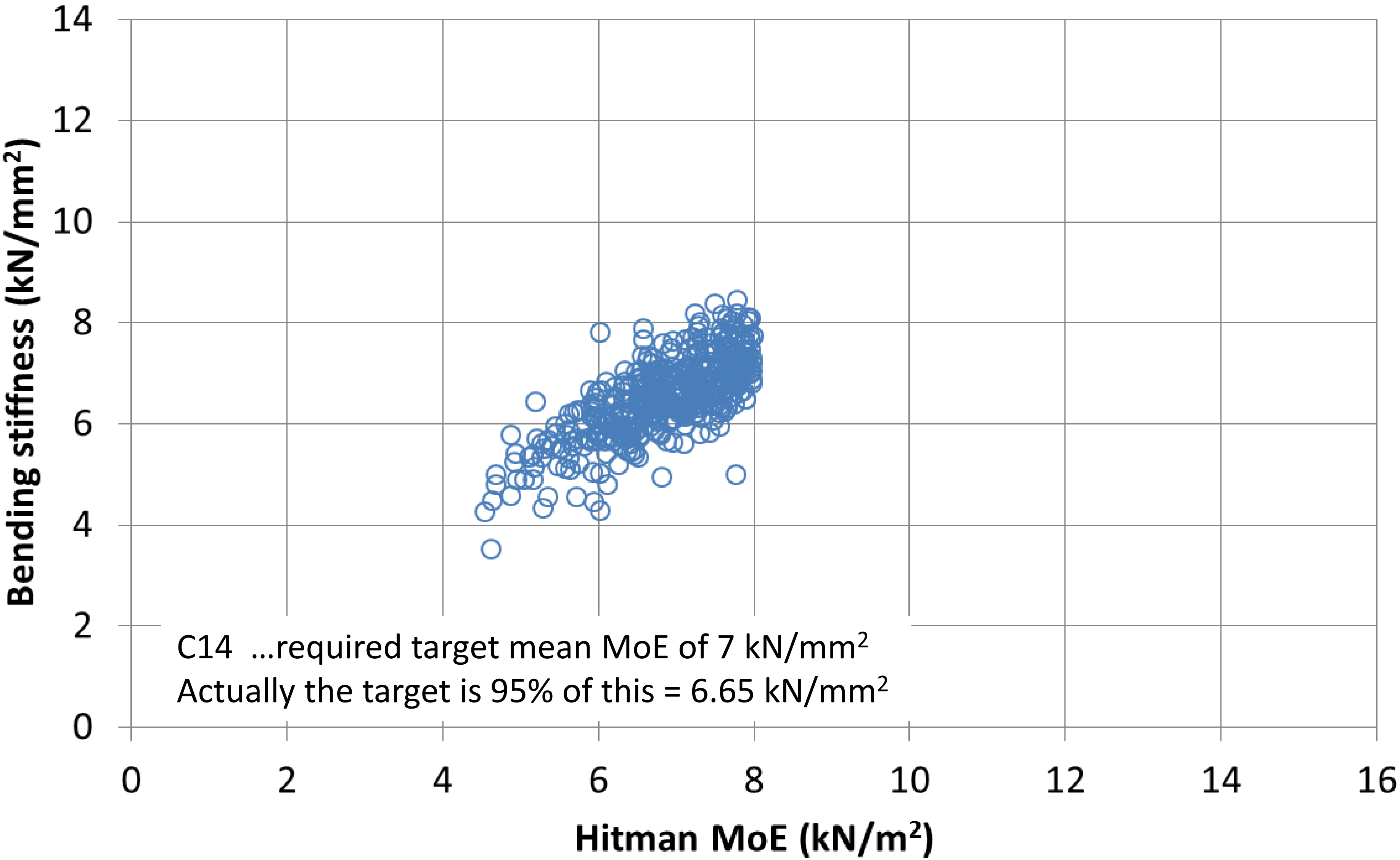


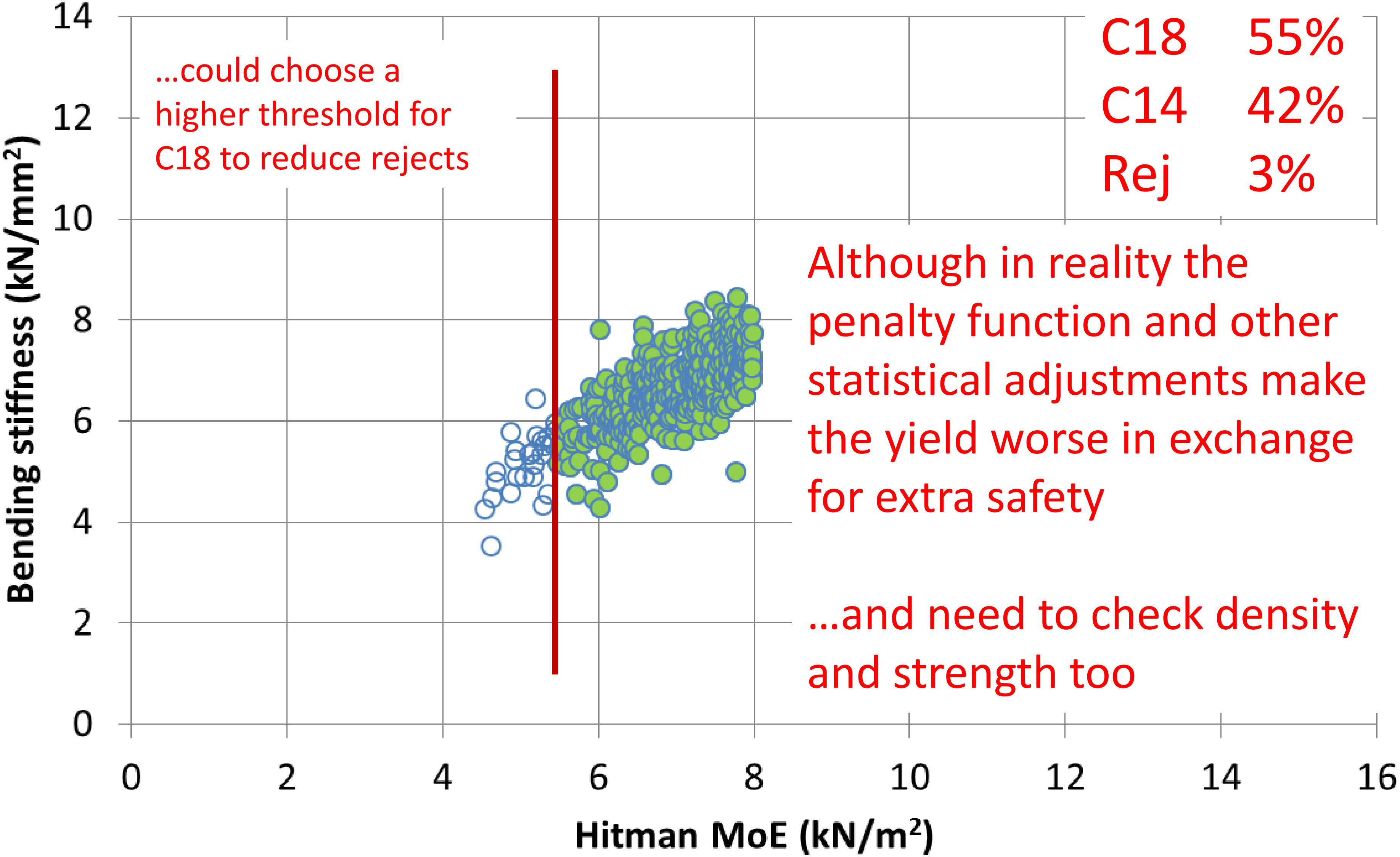


Bending stiffness (kN/mm²)
Hitman MoE (kN/m²)
Checked against penalty function
R² = 0.8274
0
2
4
6
8
10
12
14
16

SIRT

Forest Products Research Institute





…could choose a higher threshold for C18 to reduce rejects

C18	55%
C14	42%
Rej	3%

Although in reality the penalty function and other statistical adjustments make the yield worse in exchange for extra safety

…and need to check density and strength too

What about British timber?

British spruce: Sitka spruce and Norway spruce combined from UK and Ireland

SIRT benchmarking validation, 957 pieces

British spruce			C14	**C16**	C18	C20	C22
Strength	20.9	N/mm^2	14	16	18	20	22
Stiffness	8.2	kN/mm^2	7	8	9	9.5	10
Density	338	kg/m^3	290	310	320	330	340

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

Other species

SIRT benchmarking validation, 957 pieces

British spruce		C14	**C16**	C18	C20	C22	C24	C27	C30	C35	C40
Strength	20.9 N/mm^2	14	16	18	20	22	24	27	30	35	40
Stiffness	8.2 kN/mm^2	7	8	9	9.5	10	11	11.5	12	13	14
Density	338 kg/m^3	290	310	320	330	340	350	370	380	400	420

James Ramsay PhD, 166 pieces

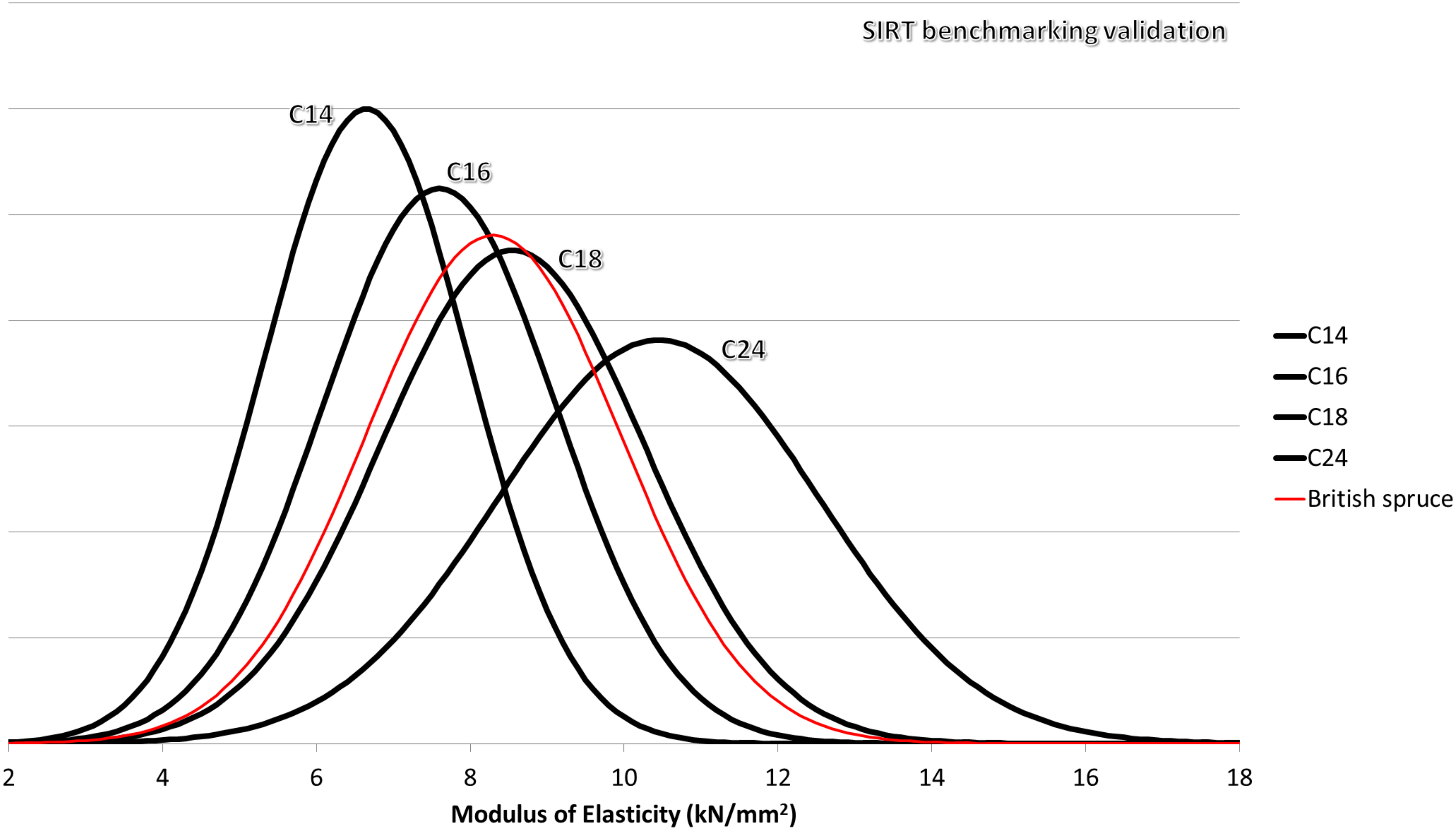
Scottish larch		C14	C16	**C18**	C20	C22	C24	C27	C30	C35	C40
Strength	23.8 N/mm^2	14	16	18	20	22	24	27	30	35	40
Stiffness	9.4 kN/mm^2	7	8	9	9.5	10	11	11.5	12	13	14
Density	407 kg/m^3	290	310	320	330	340	350	370	380	400	420

Tom Drewett PhD, 188 pieces

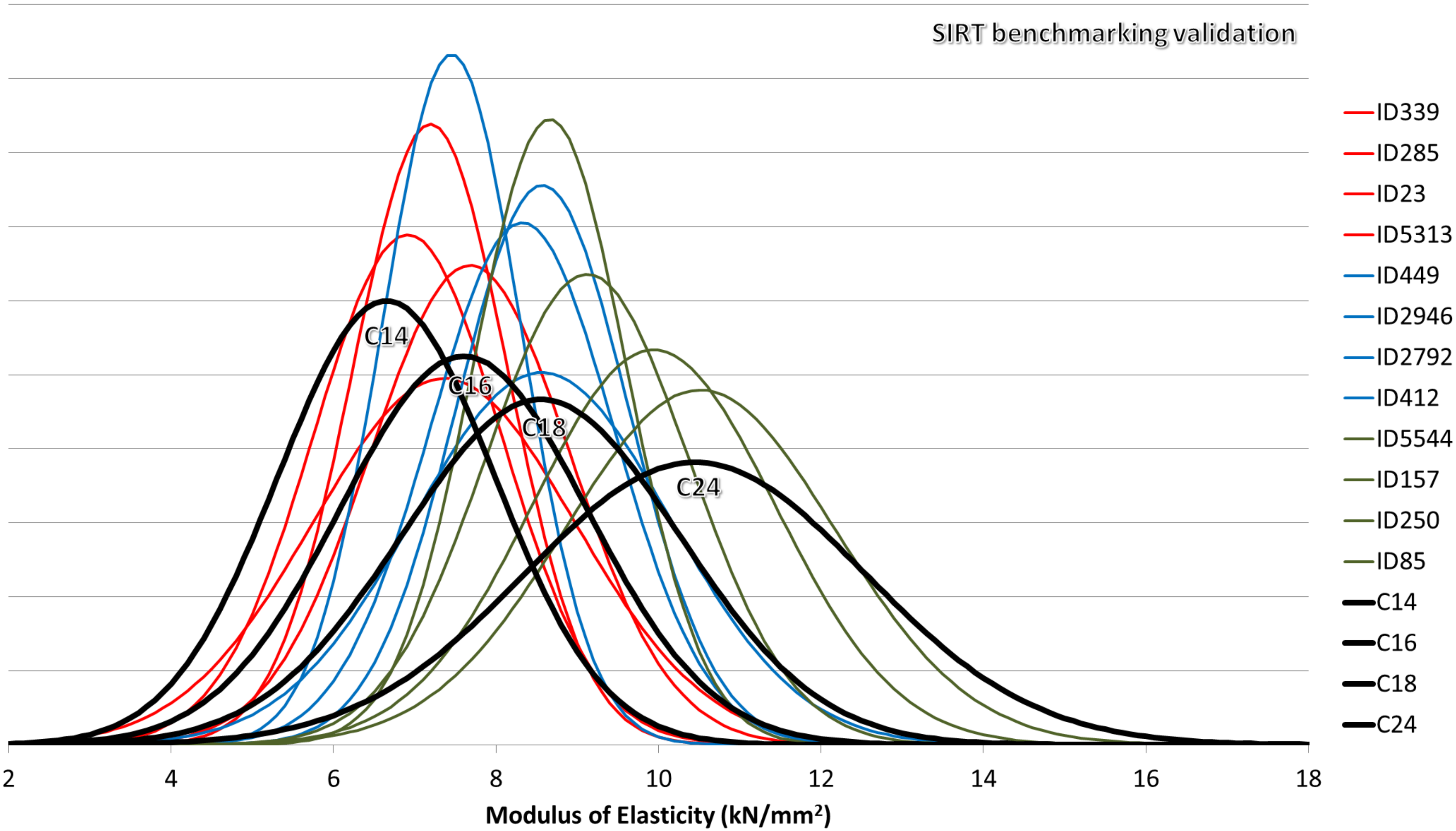
Scottish&Welsh Douglas-fir		C14	C16	**C18**	C20	C22	C24	C27	C30	C35	C40
Strength	18.8 N/mm^2	14	16	18	20	22	24	27	30	35	40
Stiffness	9.2 kN/mm^2	7	8	9	9.5	10	11	11.5	12	13	14
Density	398 kg/m^3	290	310	320	330	340	350	370	380	400	420

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future

Variation in the resource



Variation in the resource



Sources of the variation

Source	Density	Strength	Stiffness
Between sites	23%	18%	26%
Between trees on a site	51%	25%	36%
Between logs in a tree	2%	5%	2%
Within log	25%	52%	35%

Moore, J. R., Lyon, A. J., Searles, G. J., Lehneke, S. A., Ridley-Ellis, D. J. Within- and between-stand variation in selected properties of Sitka spruce sawn timber in the United Kingdom: implications for segregation and grade recovery. Annals of Forest Science (in press)

Summary

- Grading is not proof testing
- Rate of growth ≠ quality for construction
  (at least not as simply as usually thought)
- British timber is fine for construction
- C16 is a structural grade!
- There are higher grades too
- And the resource can be improved
- Scope for more efficient use of resource

EUROPE & SCOTLAND
European Regional Development Fund
Investing in your Future