Comparison of acoustic NDT for assessment of small stiffness changes during low temperature thermal treatment

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Outline

- Scots pine and Douglas-fir
- Treated at low temperature (110 C) for several weeks
- Monitoring of longitudinal stiffness (E_{dyn}) and shear modulus (G_{dyn}) changes by non-destructive acoustic methods
- Can we measure these small changes?
- Do the ratios stay the same?

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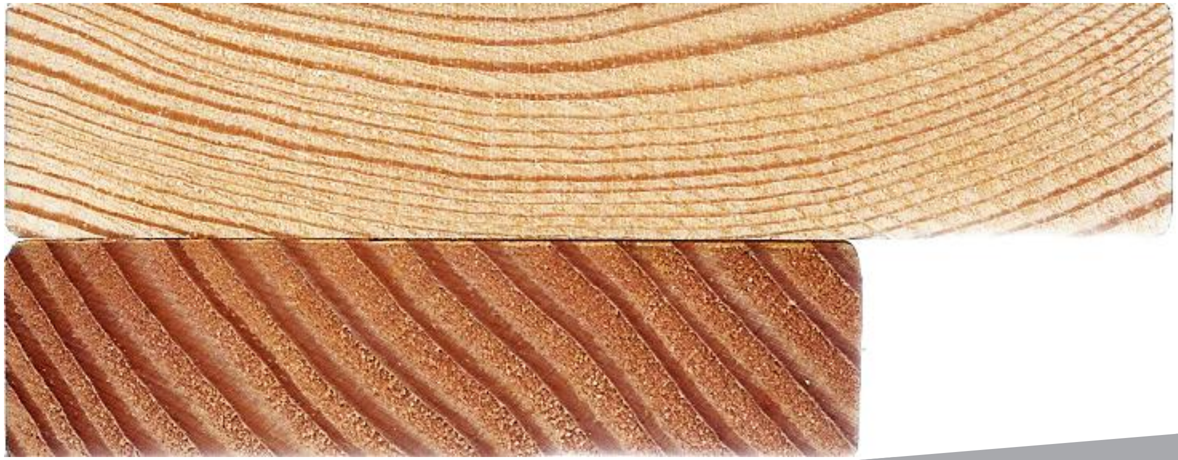
Clear samples of

- Scots pine (*Pinus sylvestris*)
  - 20 x 93 x 300 mm
- Douglas-fir (*Pseudotsuga menziesii*)
  - 18 x 70 x 300 mm



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Samples

4 samples of each species cut from the same plank

Treatment

- Heated in an oven at 110 ±2.5 °C
- On a weekly basis (approximately)
  - Dry weight
  - Dimensions
  - Impulse excitation
  - Ultrasonic time of flight
- Total treatment time of 170 days

  (Time in oven)

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Acoustic techniques

- Well established and commonly used
- But caution!
  - Relationships do vary
    - By technique
    - By moisture condition
    - By growth region
    - Piece to piece
  - Underlying assumptions / simplifications

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SIRT

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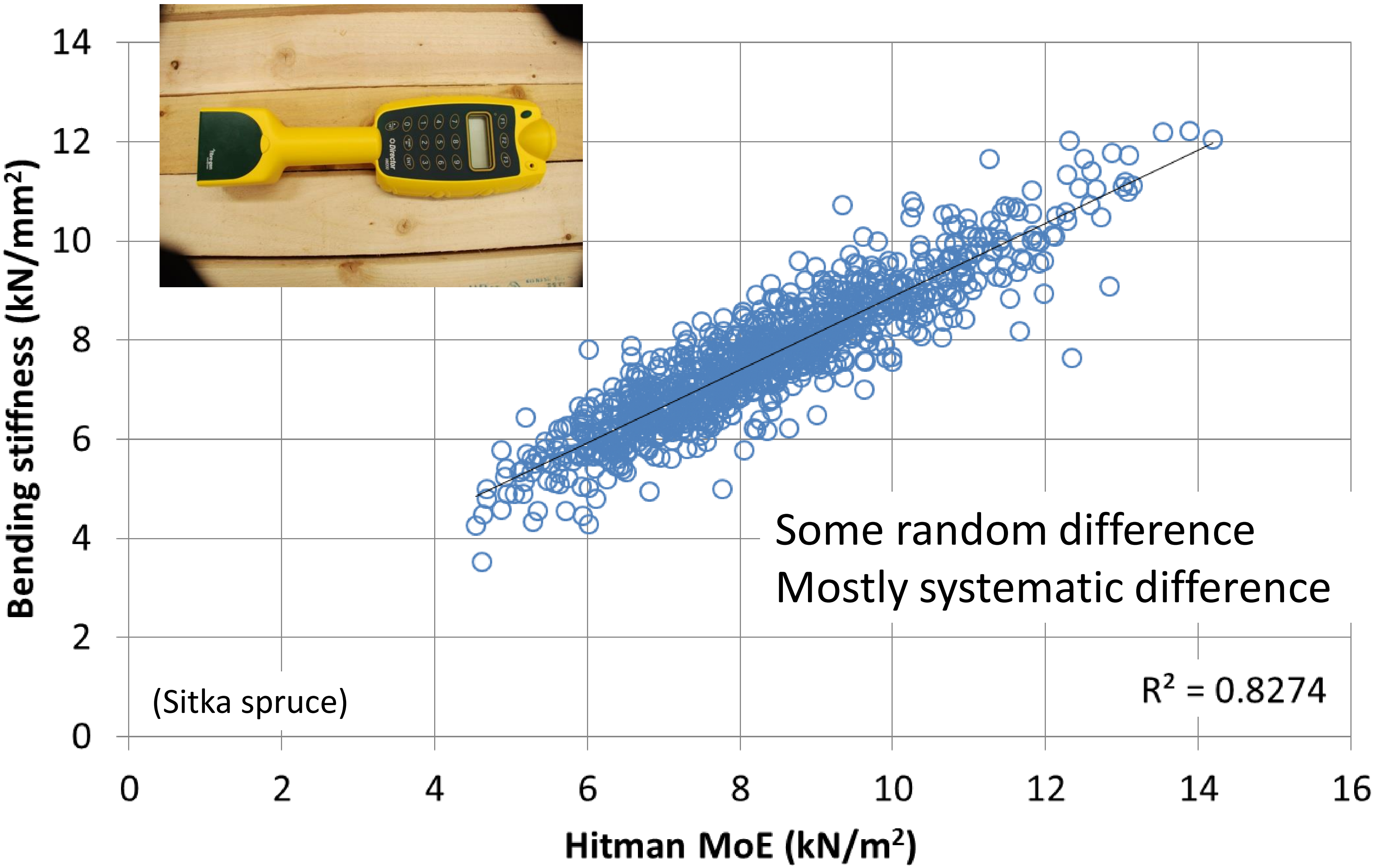
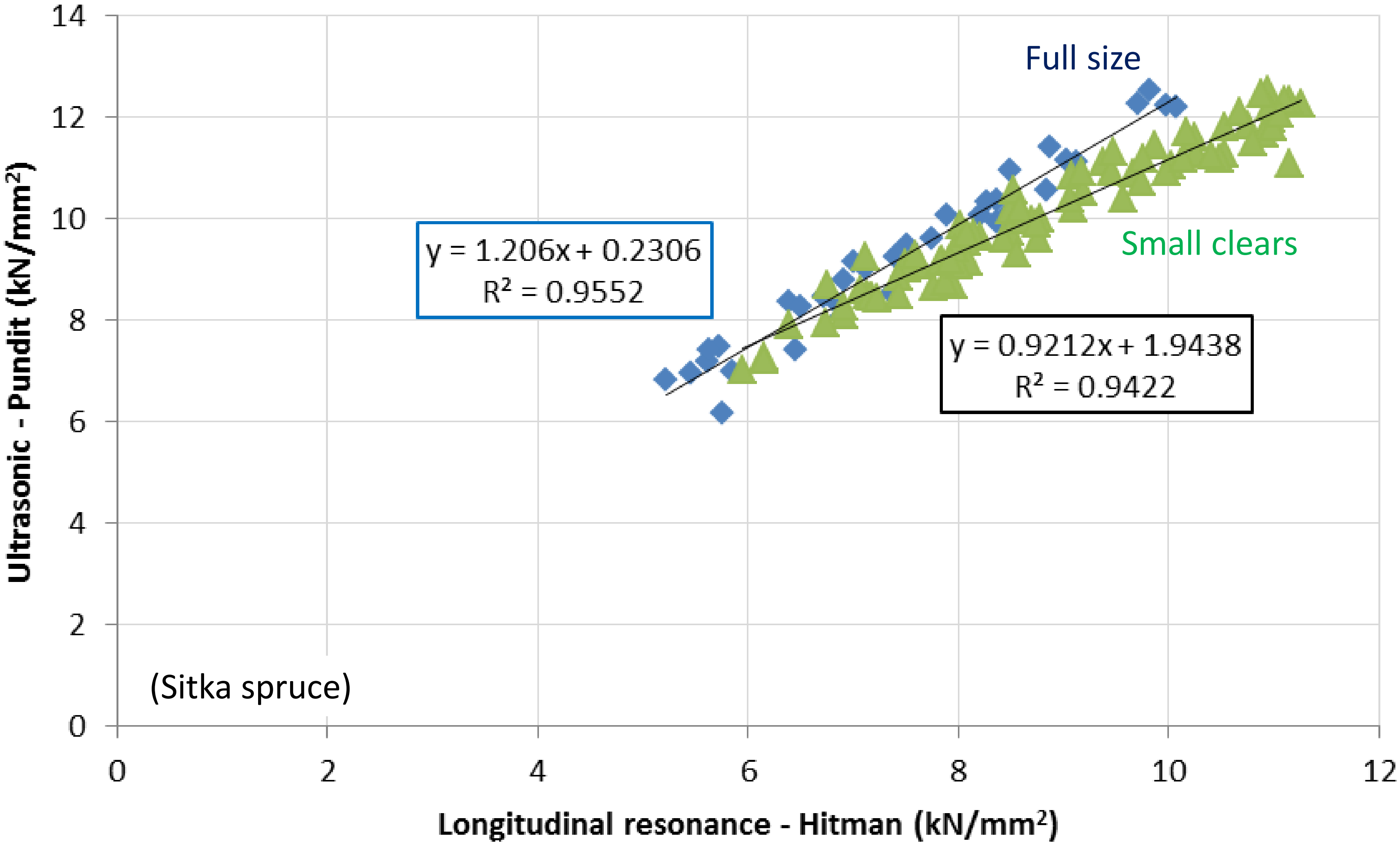
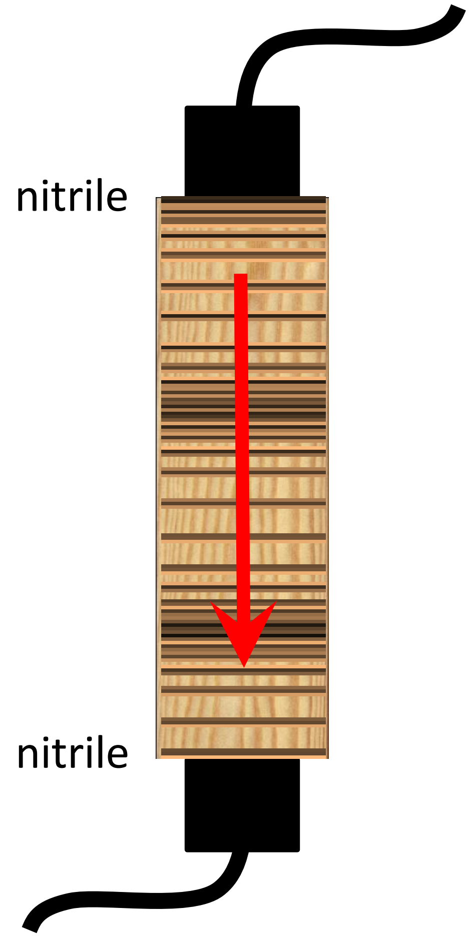




Ultrasonic - Pundit (kN/mm²)
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
Longitudinal resonance - Hitman (kN/mm²)
Full size
Small clears
y = 1.206x + 0.2306
R² = 0.9552
y = 0.9212x + 1.9438
R² = 0.9422
(Sitka spruce)

Ultrasonic time-of-flight

$$E = \rho V^2 = \rho \left(\frac{L}{T}\right)^2$$



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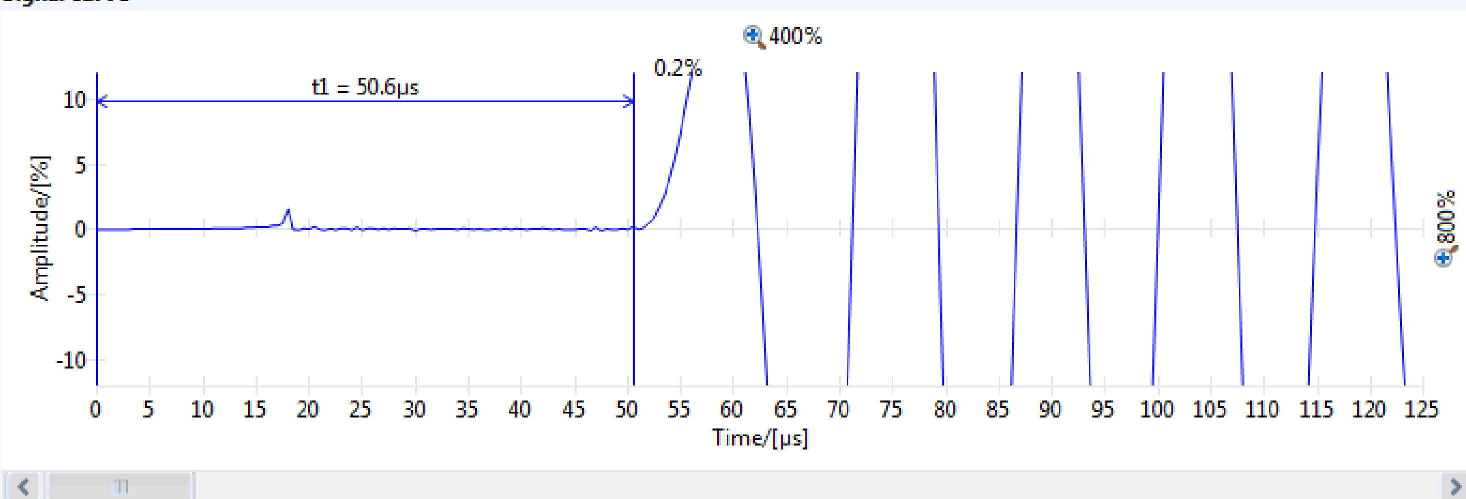
Ultrasonic time-of-flight

$$E = \rho V^2 = \rho \left(\frac{L}{T}\right)^2$$

24 kHz
54 kHz
150 kHz
250 kHz

Name	Date & Time	Measurement Type	Velocity	Time 1	Time 2	Distance	Crack Depth	Correction Factor	Temperature	Compressive Strength	C
	04/03/2012 12:0...	Direct (default)	5909 ...	50.6 μs	0.0 μs	0.299 m	0.000 m	1.00	18.2 °C	--	-

Signal curve



Settings

Pulse length:	9.3 μs
Probe frequency:	54 kHz
Pulse amplitude:	350V
Rx probe gain:	5x
Calib. time offset:	-6.1 μs
Device name:	Pundit Lab+
Serial number:	PL02-001-0038
Software version:	2.0.5
Hardware index:	B0

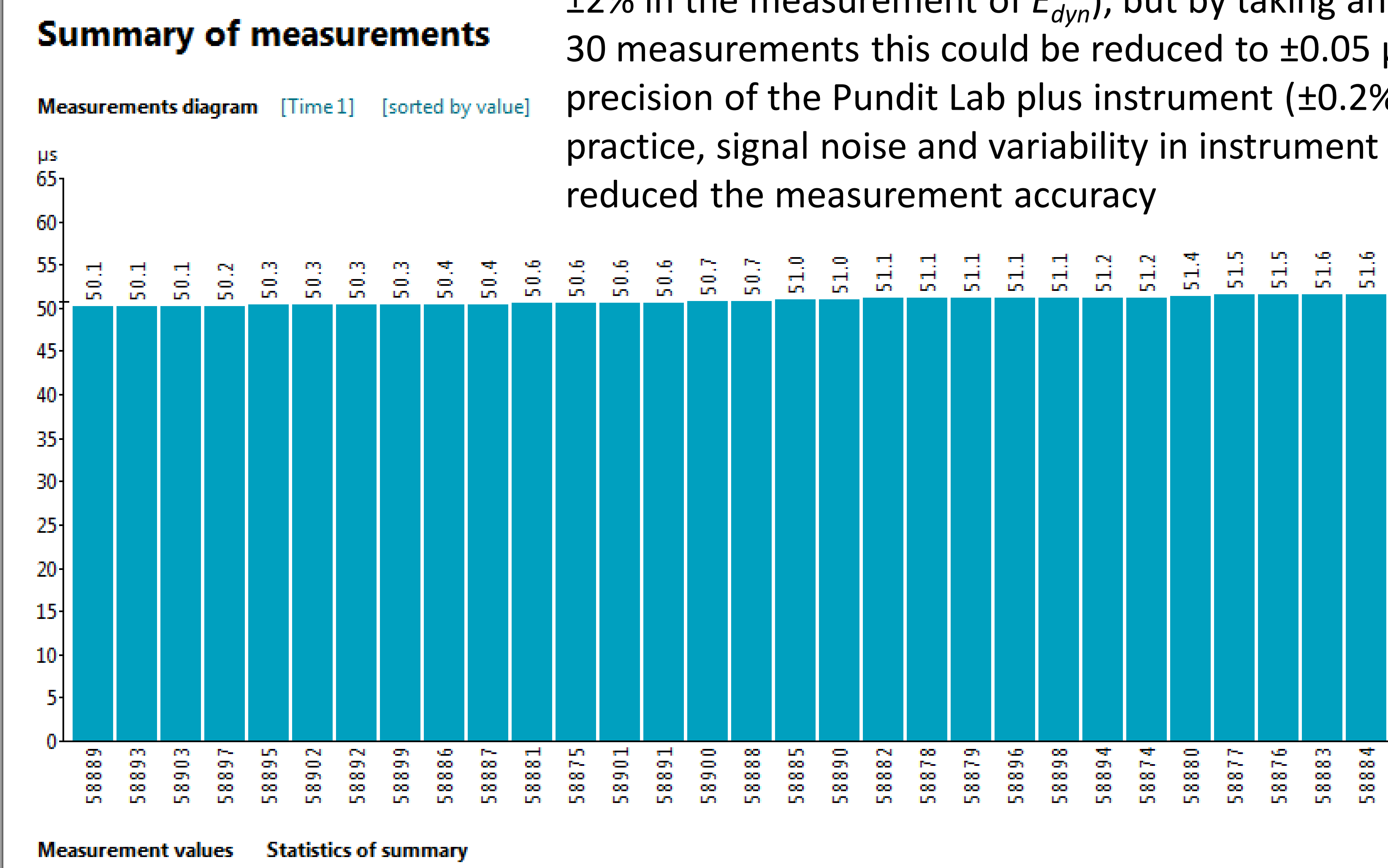
Poisson's Ratio + E-Modulus

Density:	0.0	kg/m3
Velocity 2:	0	m/s
Poisson's Ratio:	0.00	
E-Modulus:	0.00	MPa

Comment

Ultrasonic time-of-flight

Individual measurements typically ranged ±0.5 μs (equating to ±2% in the measurement of E_{dyn}), but by taking an average of 30 measurements this could be reduced to ±0.05 μs, the precision of the Pundit Lab plus instrument (±0.2% of E_{dyn}). In practice, signal noise and variability in instrument calibration reduced the measurement accuracy



Impulse excitation method

- Recording with a 16 bit 48 kHz USB microphone with 50 Hz to 19 kHz range
- Analysis using Sigview32 2.4.0 software which uses the Kiss FFT library
- Repeated strikes analysed together

The frequency accuracy of the equipment is unknown although a comparison was made between simultaneous sound recordings made with the USB microphone, an Apple iPhone 3GS (mpg4 65kbps) and an Olympus LS-20M digital sound recorder (24-bit, 96 KHz wav at 4608kbps) and, while they deferred in frequency range covered, all three gave the same peak frequencies to within the underlying experimental error (equating to ±2% in the measurement of E_{dyn} and G_{dyn})

Aspect ratios

- Scots pine: 20 x 93 x 300 mm
  
  - L/t = 15.0 (<20: !flexural, !longitudinal)
  - L/b = 3.22
  - b/t = 4.65 (>2: !longitudinal)
- Douglas-fir: 18 x 70 x 300 mm
  
  - L/t = 16.7 (<20: !flexural, !longitudinal)
  - L/b = 4.29
  - b/t = 3.89 (>2: !longitudinal)

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Impulse excitation

EN 843-2 *Advanced technical ceramics - Mechanical properties of monolithic ceramics at room temperature - Part 2: Determination of Young's modulus, shear modulus and Poisson's ratio*, CEN, 2006

ASTM E1876 *Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration*, ASTM, 2009

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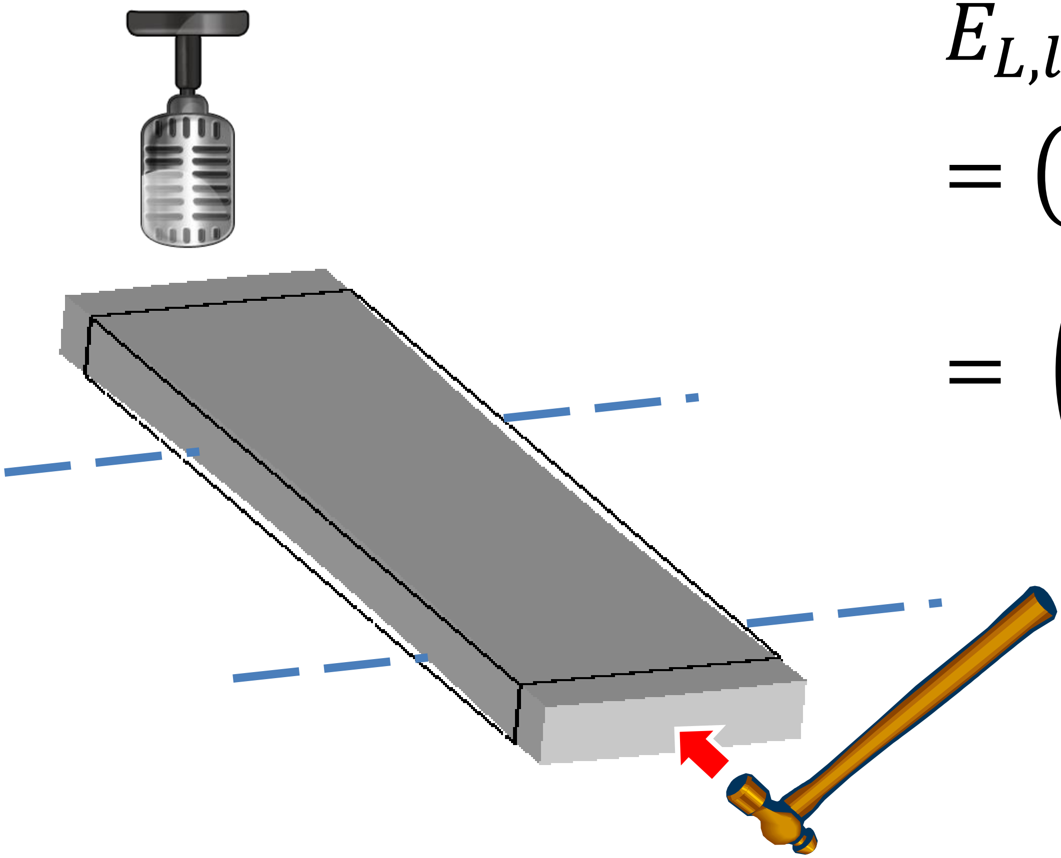
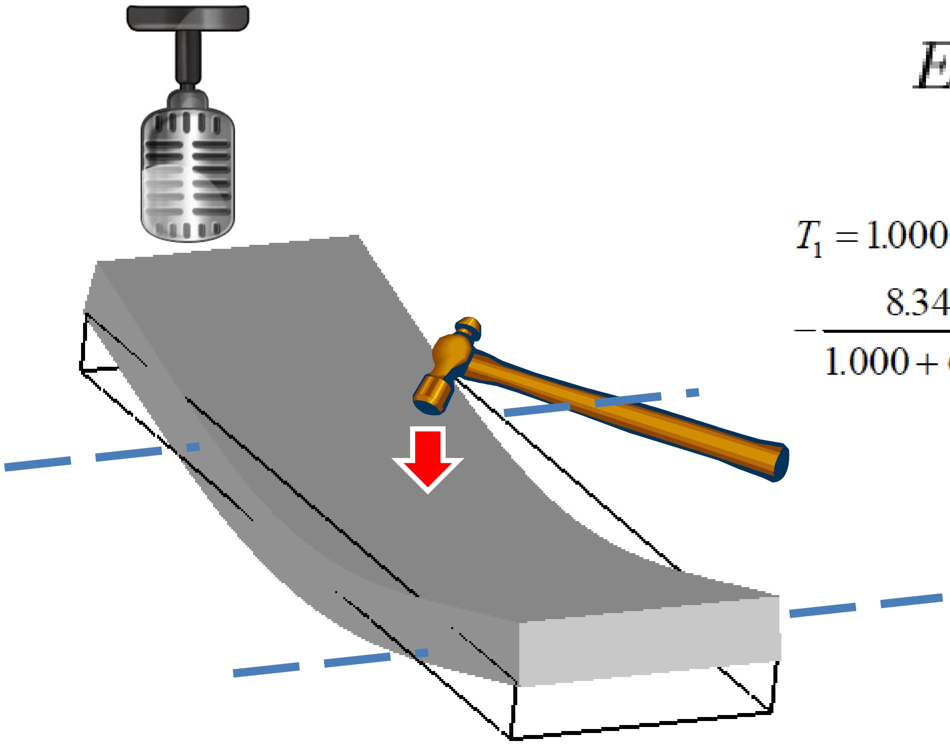
Impulse excitation - longitudinal



$$E_{L,long,n} = \rho V_{long,n}^2$$
$$= \left(f_{long,n} \times \lambda_{long,n}\right)^2$$
$$= \left(f_{long,n} \times \frac{2L}{n}\right)^2$$

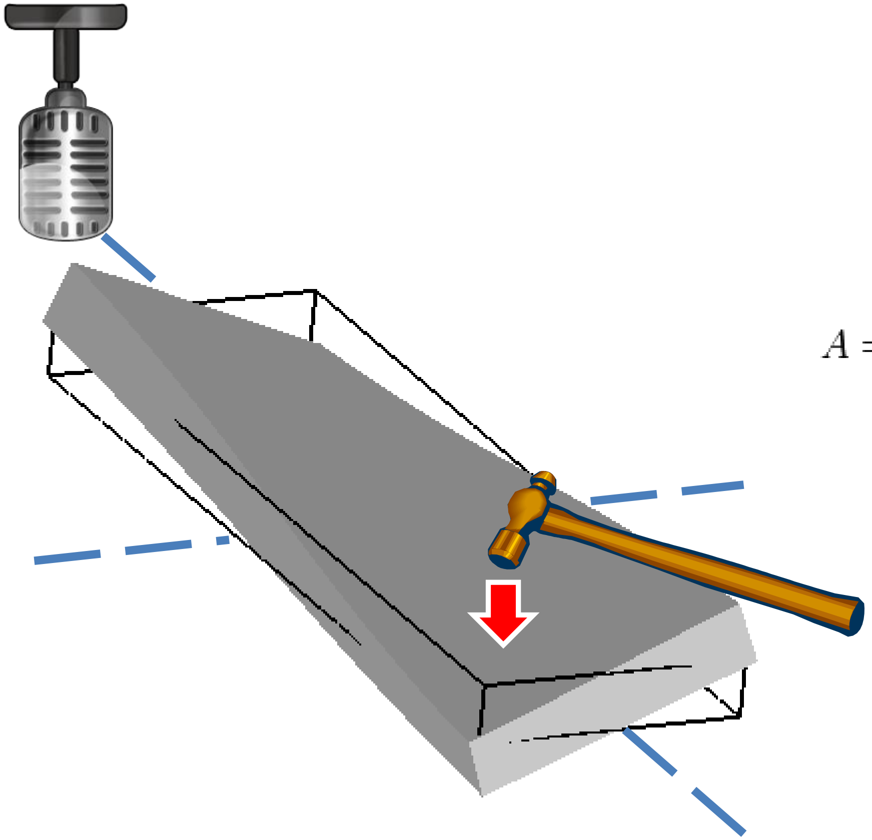
Impulse excitation - flexural



$$E = 0.9465\left(\frac{mf_f^2}{b}\right)\left(\frac{L^3}{t^3}\right)T$$

$$T_1 = 1.000 + 6.585(1 + 0.0752\mu + 0.8109\mu^2)(t/L)^2 - 0.868(t/L)^4 - \frac{8.340(1 + 0.2023\mu + 2.173\mu^2)(t/L)^4}{1.000 + 6.338(1 + 0.1408\mu + 1.536\mu^2)(t/L)^2}$$

Impulse excitation - torsional



$$G = \frac{4Lmf_t^2}{bt}\left(\frac{B}{1+A}\right)$$

$$A = \left(\frac{0.5062 - 0.8776\,(b/t) + 0.3504\,(b/t)^2 - 0.0078\,(b/t)^3}{12.03\,(b/t) + 9.892\,(b/t)^2}\right)$$

$$B = \left(\frac{b/t + t/b}{4\,(t/b) - 2.52\,(t/b)^2 + 0.21\,(t/b)^6}\right)$$

Finite element modelling

- CalculiX for Windows 2.5
- 1600 quadratic solid elements
- (C3D20)
- Confirmation of frequencies for modes and calculation of mechanical properties

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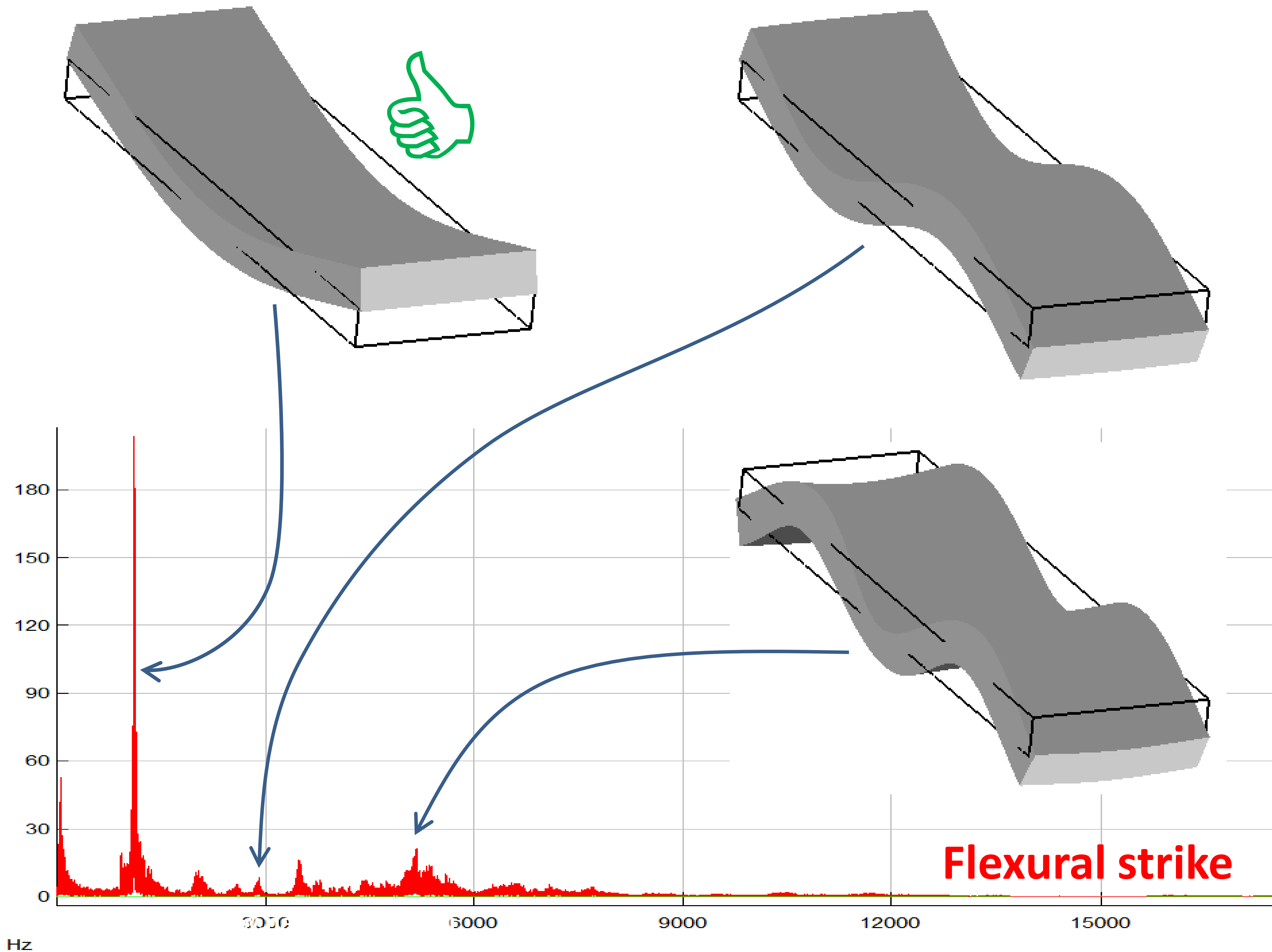
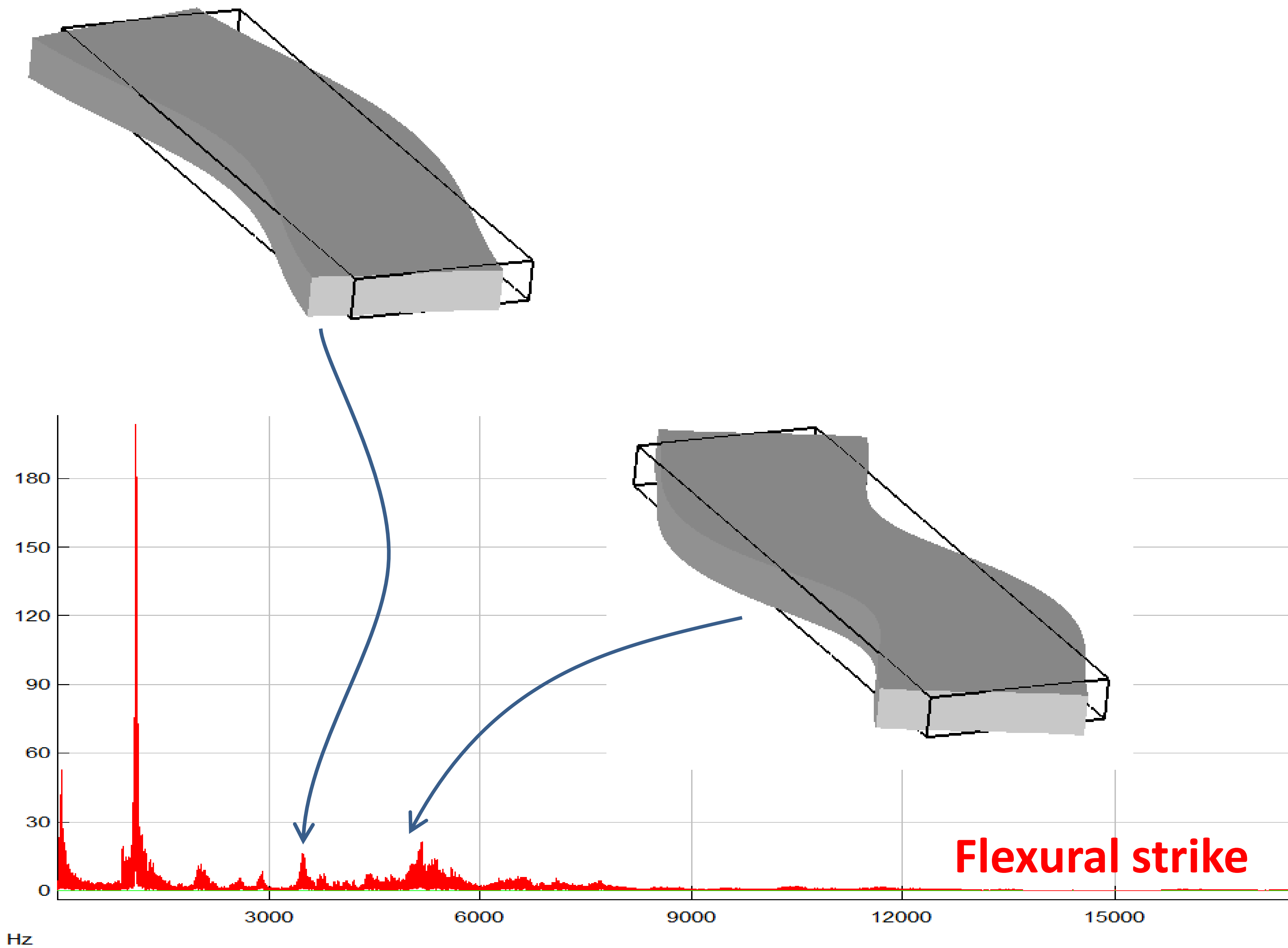
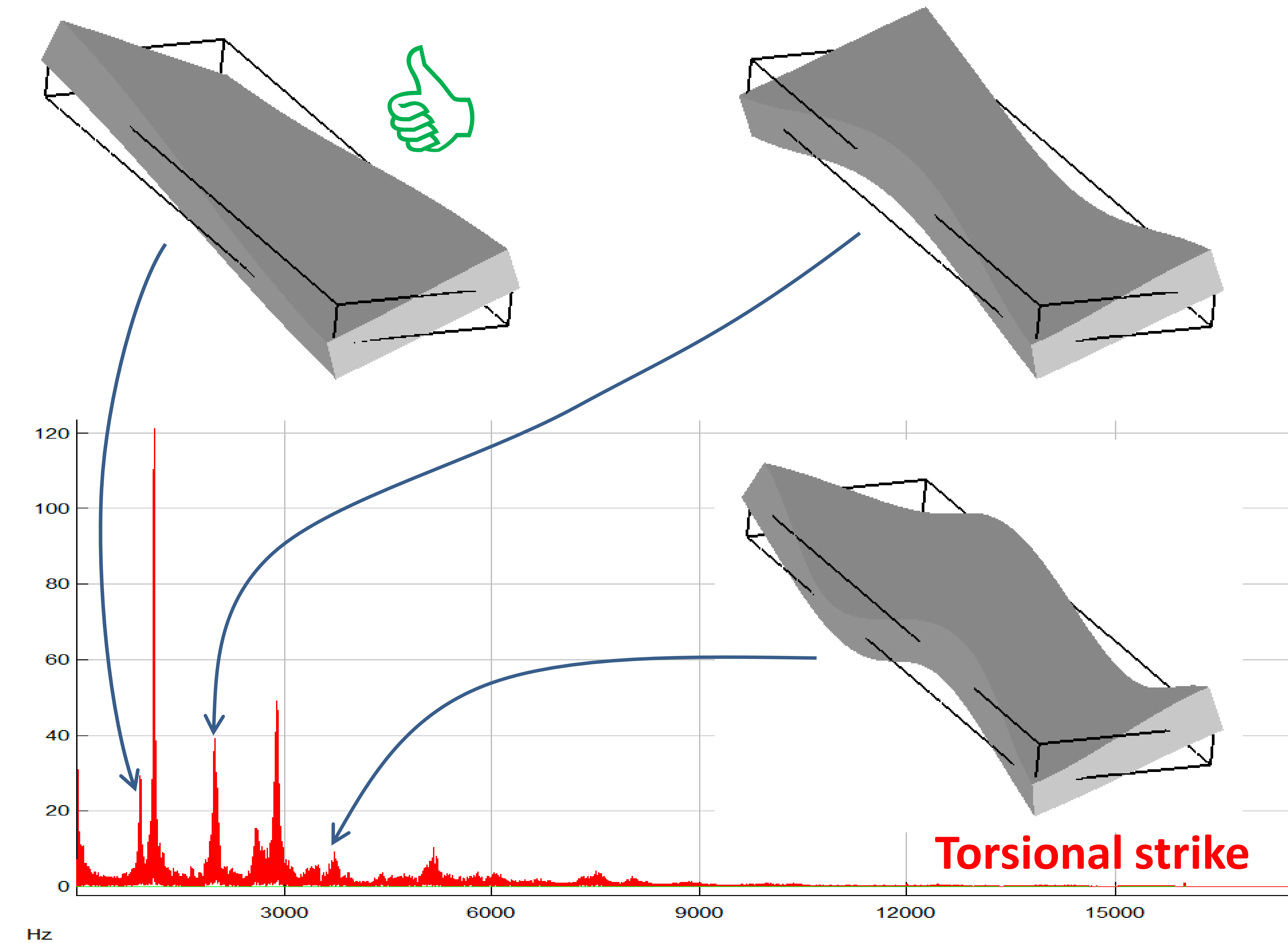
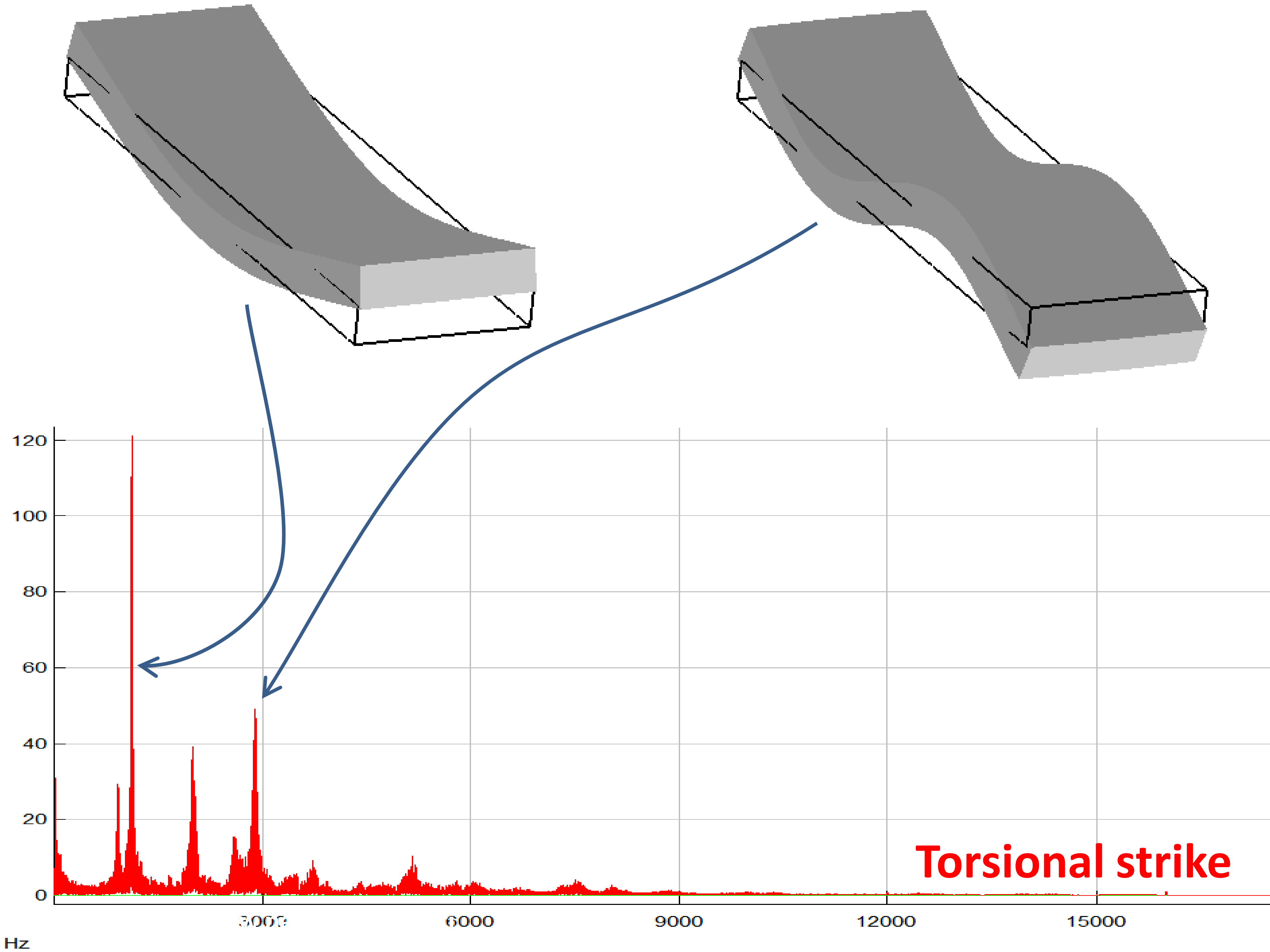

180
150
120
90
60
30
0
3000
6000
9000
12000
15000
Hz
Flexural strike

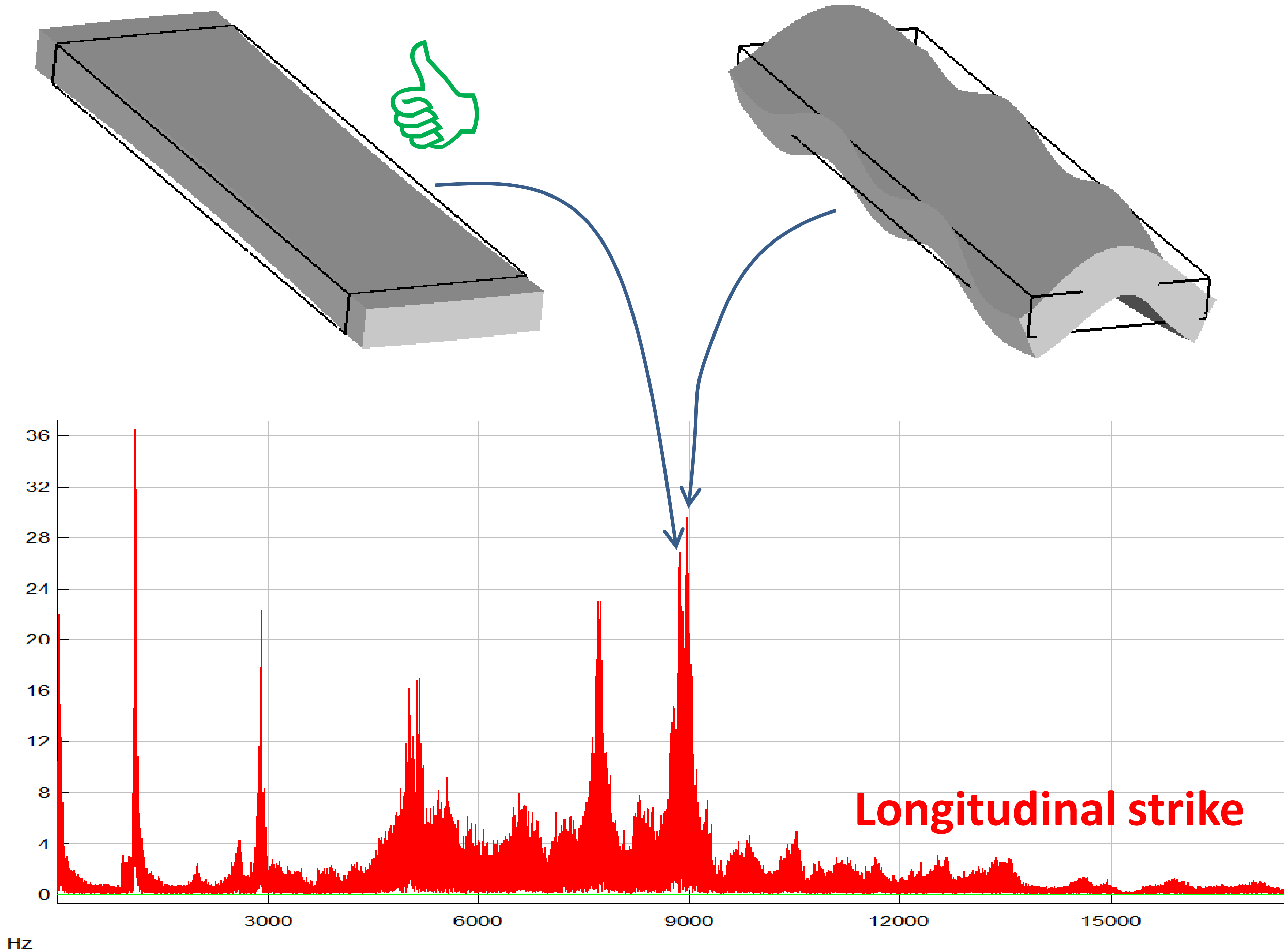


180
150
120
90
60
30
0
3000
6000
9000
12000
15000
Hz
Flexural strike

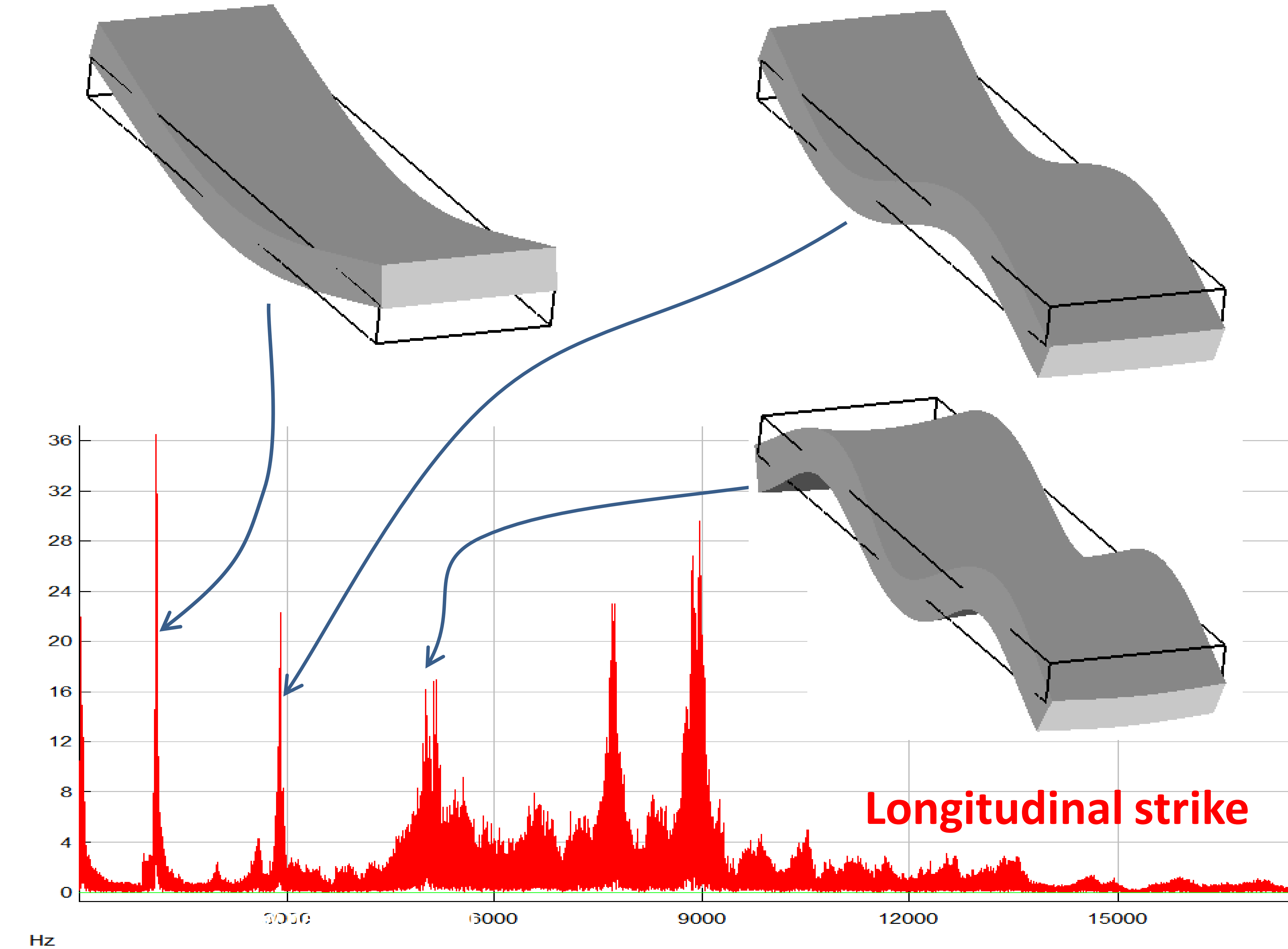


120
100
80
60
40
20
0
3000
6000
9000
12000
15000
Hz
Torsional strike

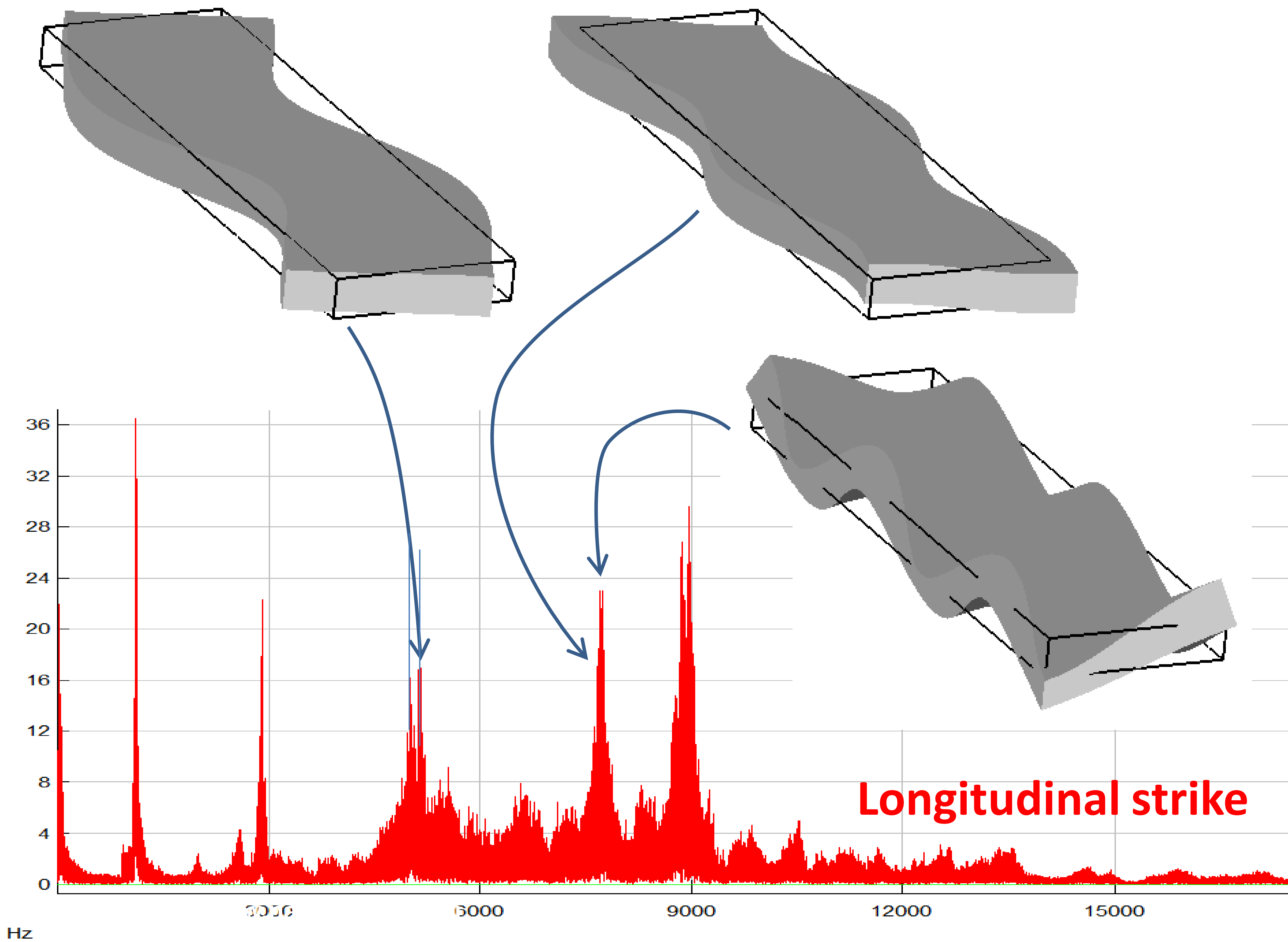

120
100
80
60
40
20
0
6000
9000
12000
15000
Hz
Torsional strike



36
32
28
24
20
16
12
8
4
0
3000
6000
9000
12000
15000
Hz
Longitudinal strike

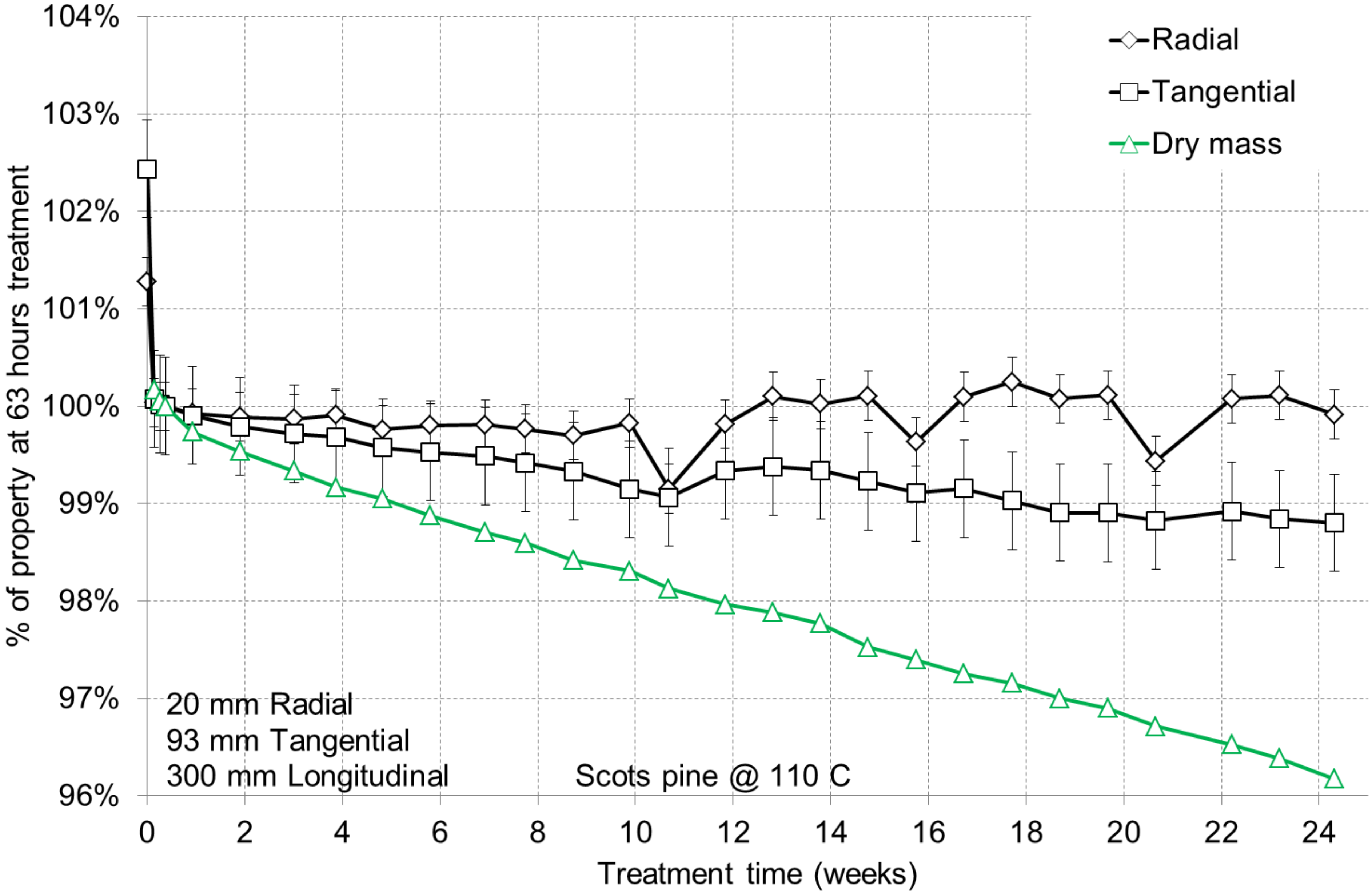


Longitudinal strike
36
32
28
24
20
16
12
8
4
0
6000
9000
12000
15000
Hz



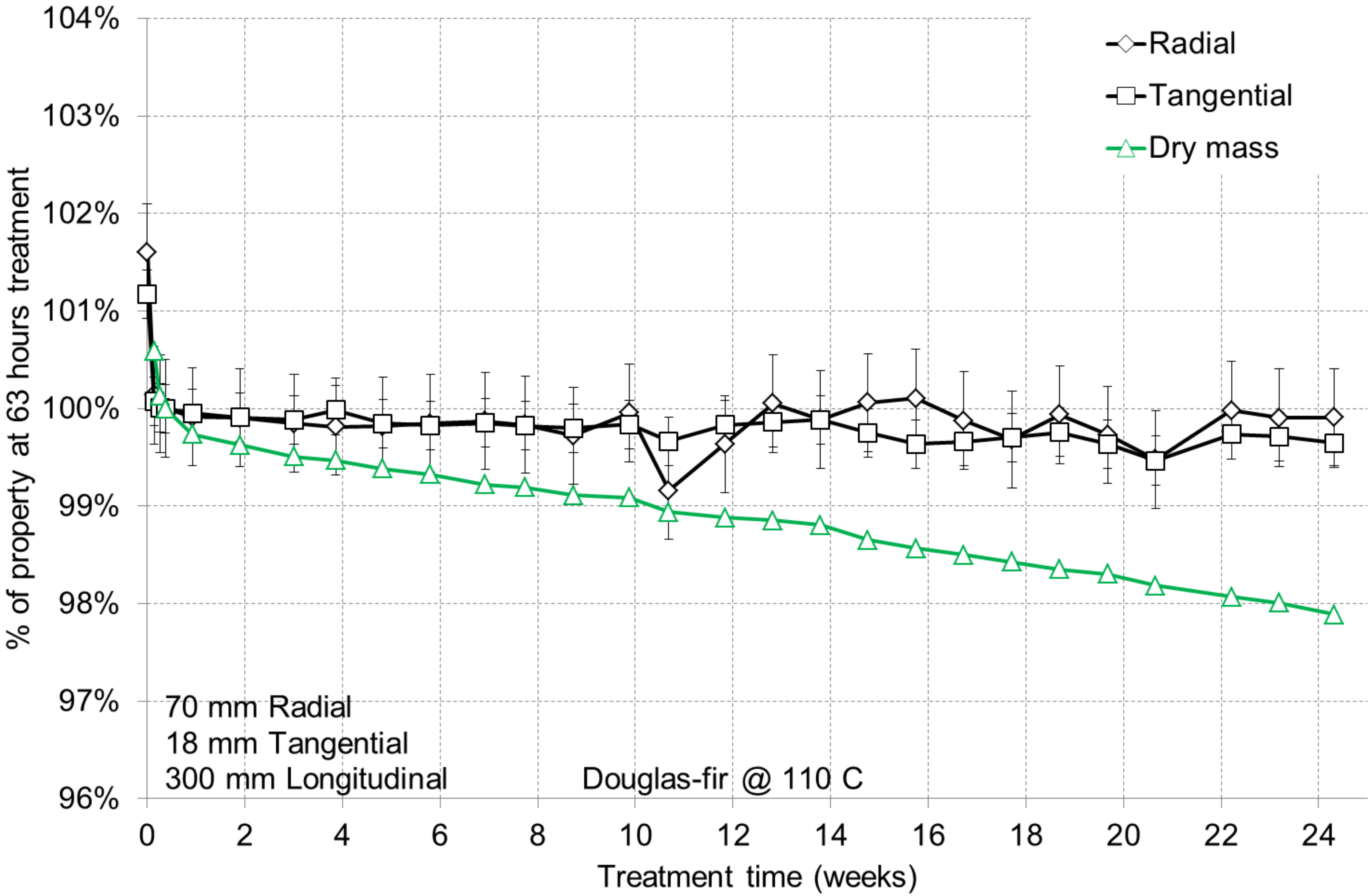
36
32
28
24
20
16
12
8
4
0
3000
6000
9000
12000
15000
Hz
Longitudinal strike

Scots pine



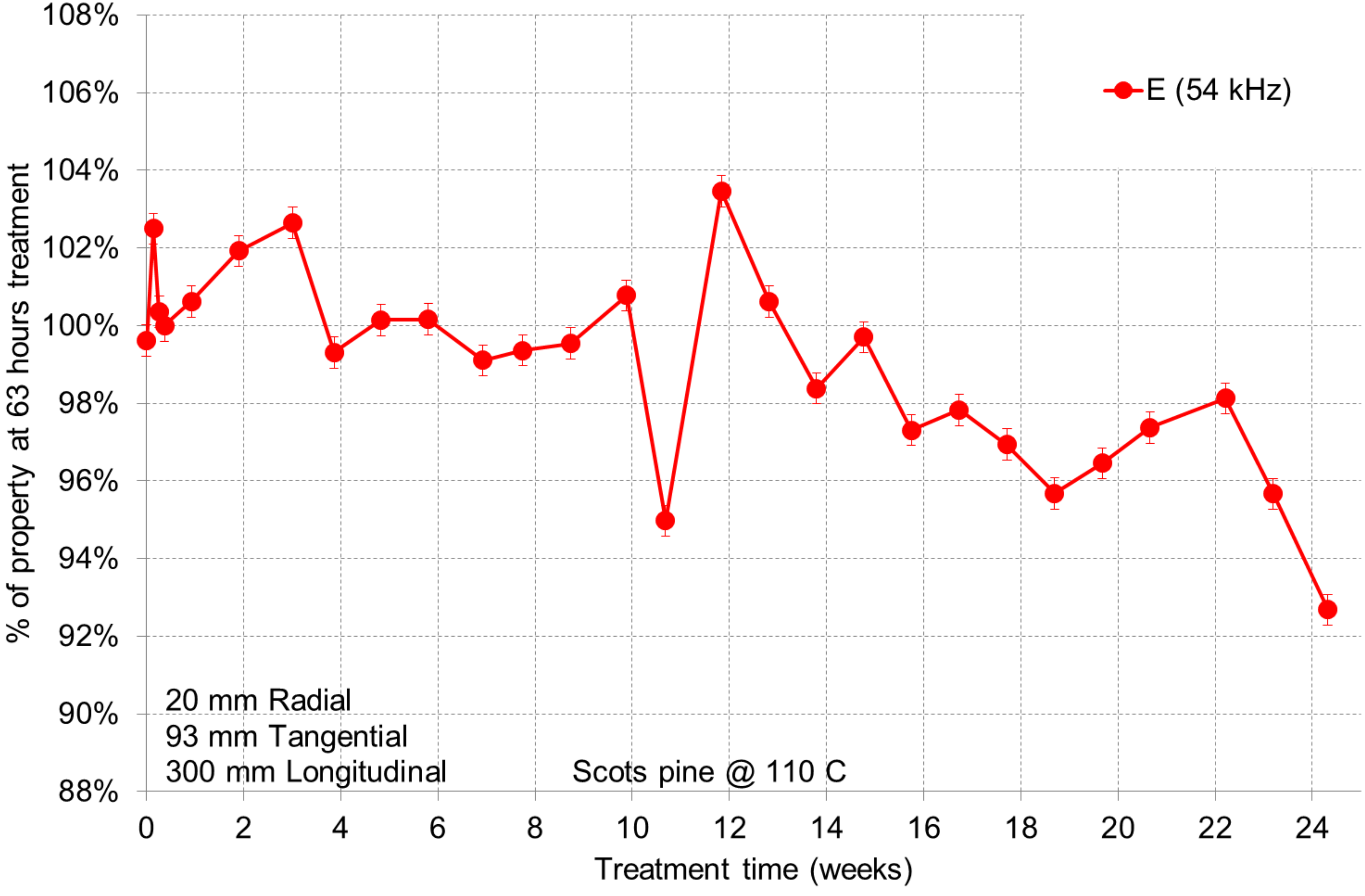
104%
103%
102%
101%
100%
99%
98%
97%
96%
% of property at 63 hours treatment
0
2
4
6
8
10
12
14
16
18
20
22
24
Treatment time (weeks)
Radial
Tangential
Dry mass
20 mm Radial
93 mm Tangential
300 mm Longitudinal
Scots pine @ 110 C

Douglas-fir



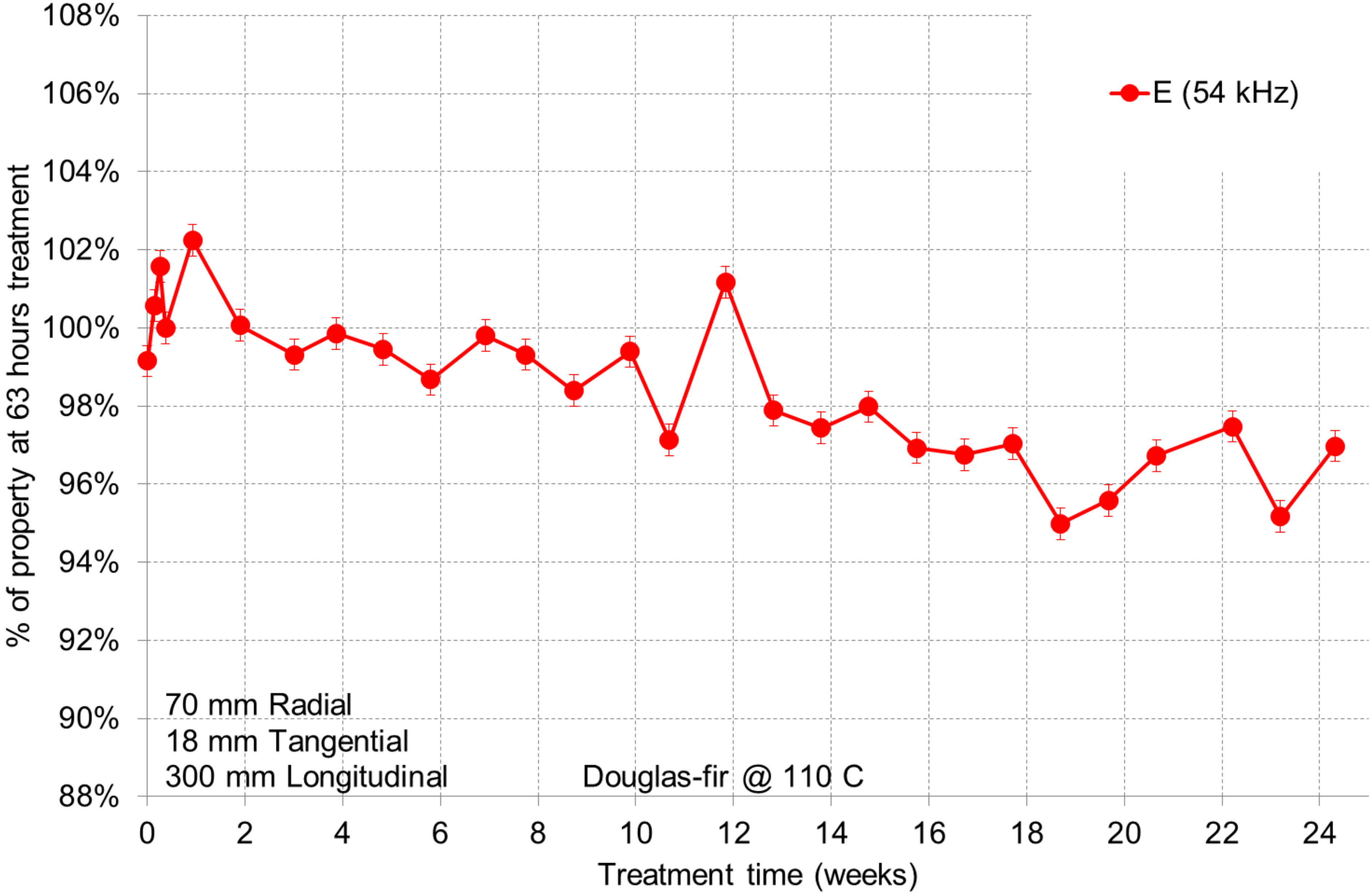
104%
103%
102%
101%
100%
99%
98%
97%
96%
% of property at 63 hours treatment
0
2
4
6
8
10
12
14
16
18
20
22
24
Treatment time (weeks)
Radial
Tangential
Dry mass
70 mm Radial
18 mm Tangential
300 mm Longitudinal
Douglas-fir @ 110 C

Scots pine



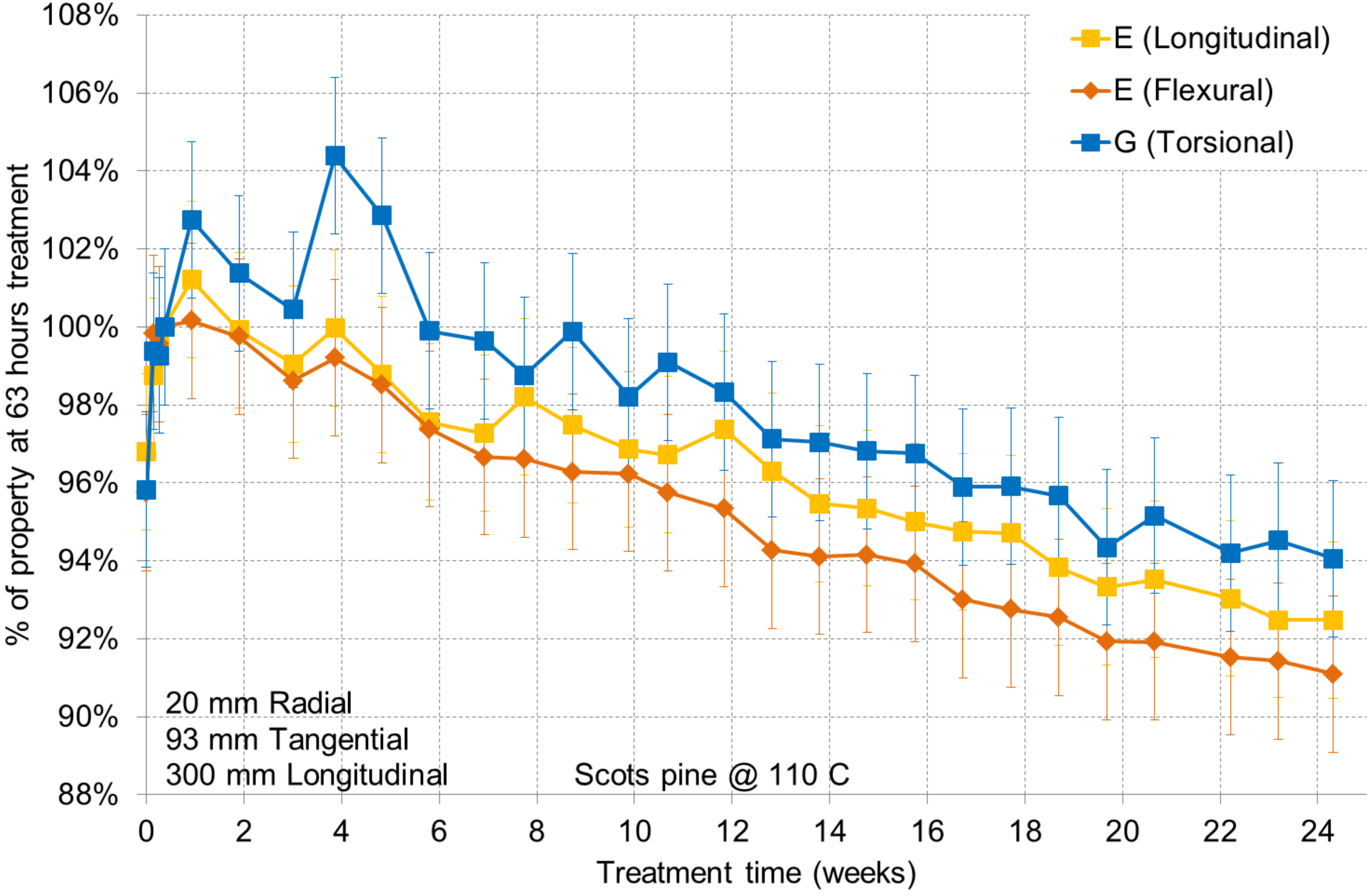
E (54 kHz)
% of property at 63 hours treatment
108%
106%
104%
102%
100%
98%
96%
94%
92%
90%
88%
0
2
4
6
8
10
12
14
16
18
20
22
24
Treatment time (weeks)
20 mm Radial
93 mm Tangential
300 mm Longitudinal
Scots pine @ 110 C

Douglas-fir



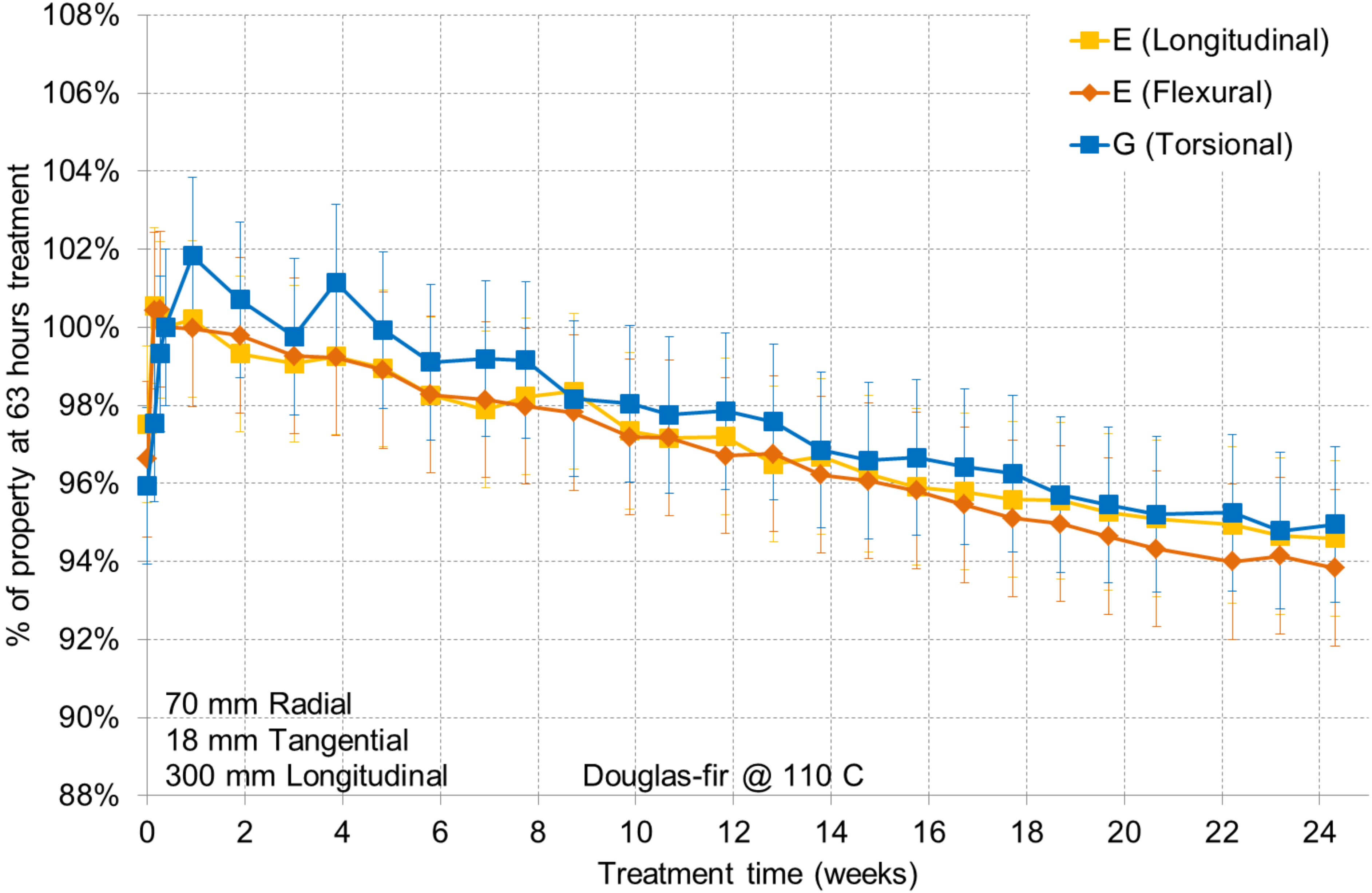
108%
106%
104%
102%
100%
98%
96%
94%
92%
90%
88%
% of property at 63 hours treatment
E (54 kHz)
70 mm Radial
18 mm Tangential
300 mm Longitudinal
Douglas-fir @ 110 C
0
2
4
6
8
10
12
14
16
18
20
22
24
Treatment time (weeks)

Scots pine



E (Longitudinal)
E (Flexural)
G (Torsional)
% of property at 63 hours treatment
108%
106%
104%
102%
100%
98%
96%
94%
92%
90%
88%
0
2
4
6
8
10
12
14
16
18
20
22
24
Treatment time (weeks)
20 mm Radial
93 mm Tangential
300 mm Longitudinal
Scots pine @ 110 C

Douglas-fir


108%
106%
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102%
100%
98%
96%
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92%
90%
88%
% of property at 63 hours treatment
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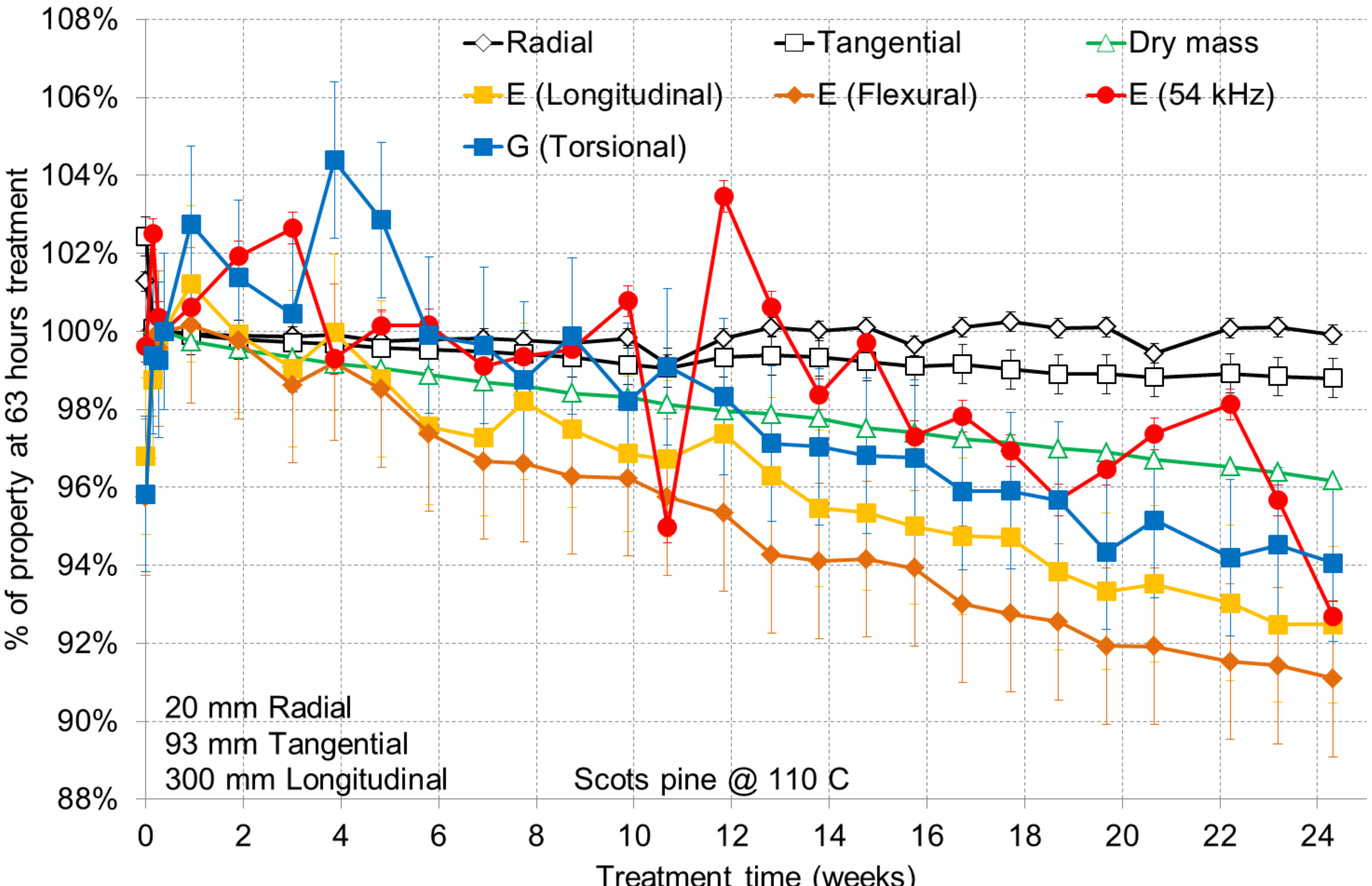
24
Treatment time (weeks)
E (Longitudinal)
E (Flexural)
G (Torsional)
70 mm Radial
18 mm Tangential
300 mm Longitudinal
Douglas-fir @ 110 C

Scots pine



Radial
Tangential
Dry mass
E (Longitudinal)
E (Flexural)
E (54 kHz)
G (Torsional)
108%
106%
104%
102%
100%
98%
96%
94%
92%
90%
88%
% of property at 63 hours treatment
0
2
4
6
8
10
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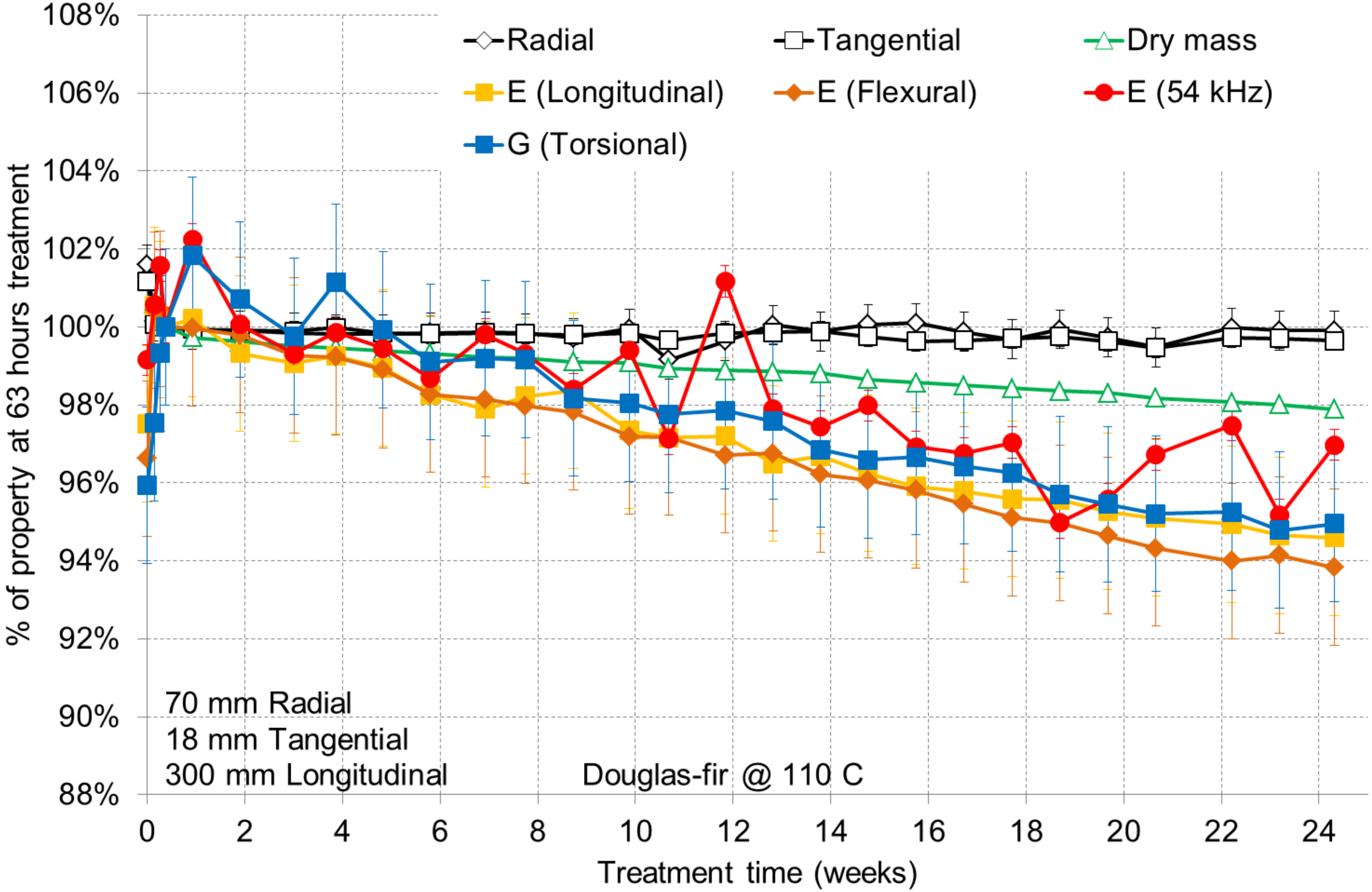
24
Treatment time (weeks)
20 mm Radial
93 mm Tangential
300 mm Longitudinal
Scots pine @ 110 C

Douglas-fir



Radial
Tangential
Dry mass
E (Longitudinal)
E (Flexural)
E (54 kHz)
G (Torsional)
% of property at 63 hours treatment
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104%
102%
100%
98%
96%
94%
92%
90%
88%
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2
4
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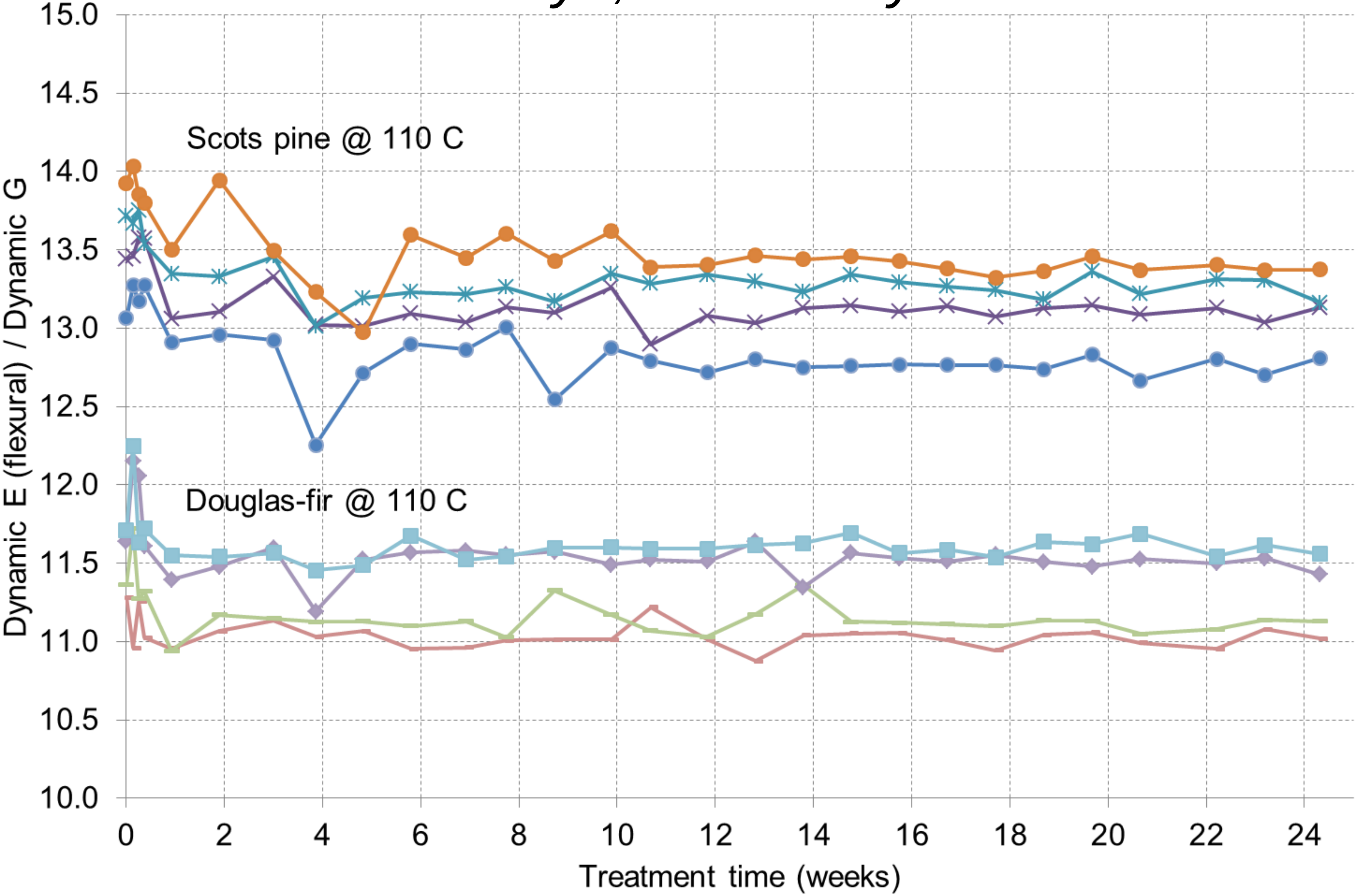
8
10
12
14
16
18
20
22
24
Treatment time (weeks)
70 mm Radial
18 mm Tangential
300 mm Longitudinal
Douglas-fir @ 110 C

$E_{dyn,flex}$ / G_{dyn}



Summary

- Even at this relatively low temperature, the wood underwent thermal modification
- Losing mass (~0.02%/day for Scots pine and ~0.01%/day for Douglas-fir)
- And stiffness (~0.05%/day for Scots pine and ~0.04%/day for Douglas-fir).
- The change in E_{dyn} was similar to the change in G_{dyn}.

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Summary

- The impulse excitation method is an effective and inexpensive way to track even small stiffness changes
- If the samples are the right size & shape
- But spectra can be hard to interpret
  - Repeated measurements
  - Finite element modelling
- Dimensions are the biggest source of error

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