

Strength and stiffness assessment of secondary timber and cross-laminated secondary timber (CLST)

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Circular economy in a built environment context

**Global material use
in the construction
industry: 26 Gtpa**

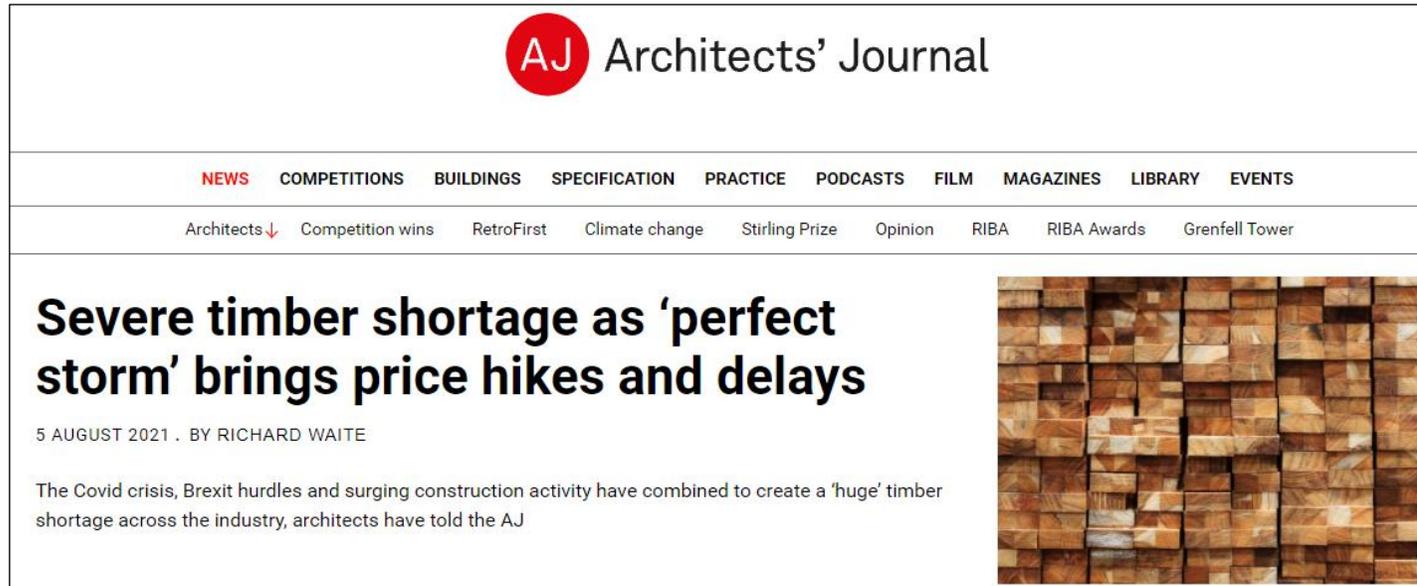
(Haas et al., 2015)

**Global waste generation
in the construction
industry: 9 Gtpa**

(Haas et al., 2015)



Economic rationale: Timber shortages; volatile and rising prices



The screenshot shows the homepage of Architects' Journal (AJ). The logo is a red circle with 'AJ' in white, followed by 'Architects' Journal' in black. Below the logo is a navigation menu with categories: NEWS, COMPETITIONS, BUILDINGS, SPECIFICATION, PRACTICE, PODCASTS, FILM, MAGAZINES, LIBRARY, and EVENTS. Underneath is a secondary menu with links: Architects (with a dropdown arrow), Competition wins, RetroFirst, Climate change, Stirling Prize, Opinion, RIBA, RIBA Awards, and Grenfell Tower. The main article features the headline 'Severe timber shortage as 'perfect storm' brings price hikes and delays' in bold black text. Below the headline, it says '5 AUGUST 2021 . BY RICHARD WAITE'. A sub-headline reads: 'The Covid crisis, Brexit hurdles and surging construction activity have combined to create a 'huge' timber shortage across the industry, architects have told the AJ'. To the right of the text is a photograph of a large stack of cut timber logs.



The screenshot shows a BBC News article. The top navigation bar includes the BBC logo, a user profile 'Colin', and links for Home, News, Sport, Weather, and iPlayer. A red banner with the word 'NEWS' in white is prominent. Below this is a secondary navigation bar with links: Home, Coronavirus, Climate, UK, World, Business, Politics, Tech, Science, Health, and Family & Education. The article is categorized under 'Science & Environment'. The headline is 'Timber shortage due to 'unprecedented' post-lockdown demand' in large, bold black font. Below the headline, it says 'By Claire Marshall' and 'BBC Environment & Rural Affairs Correspondent'. There is a timestamp '4 August' and a 'Comments' link. At the bottom left, there is a red share icon and a 'Climate change' tag.

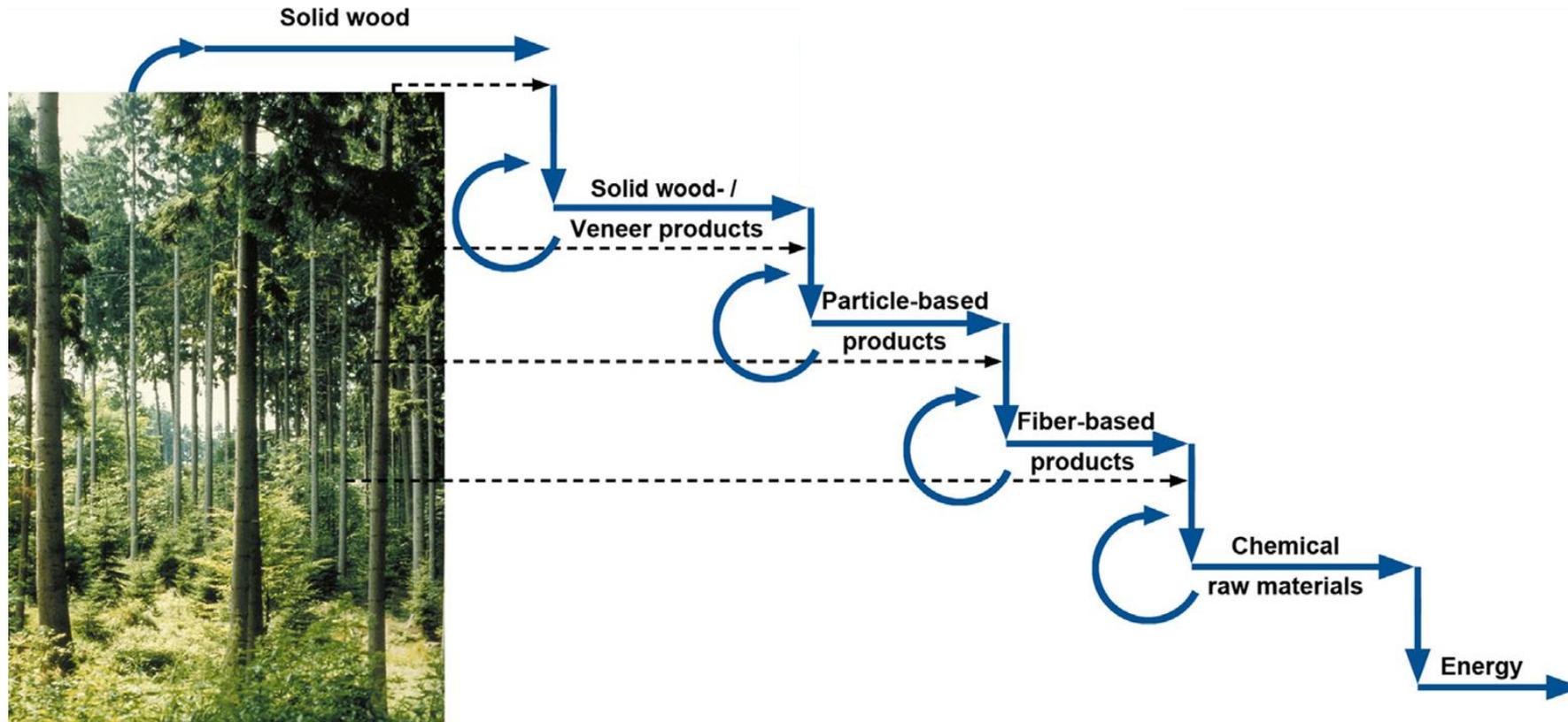
News articles from August 2021; Greener Growth through Good Wood (The World Bank, 2020)

Economic rationale: Disposal continues unabated



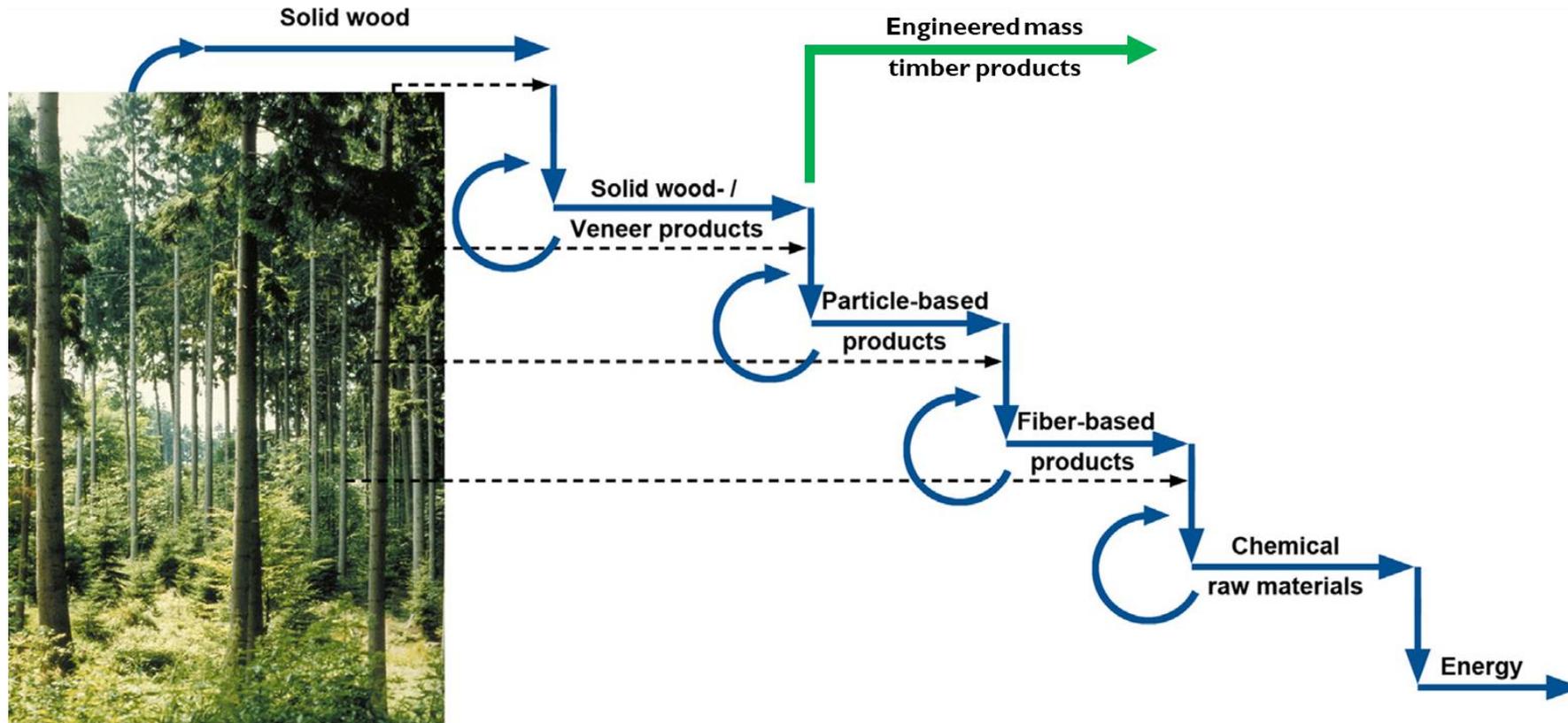
Skip full of timber, spotted while cycling (photo by Colin Rose, 2021)

Environmental rationale: Typical cascading lifecycle of wood



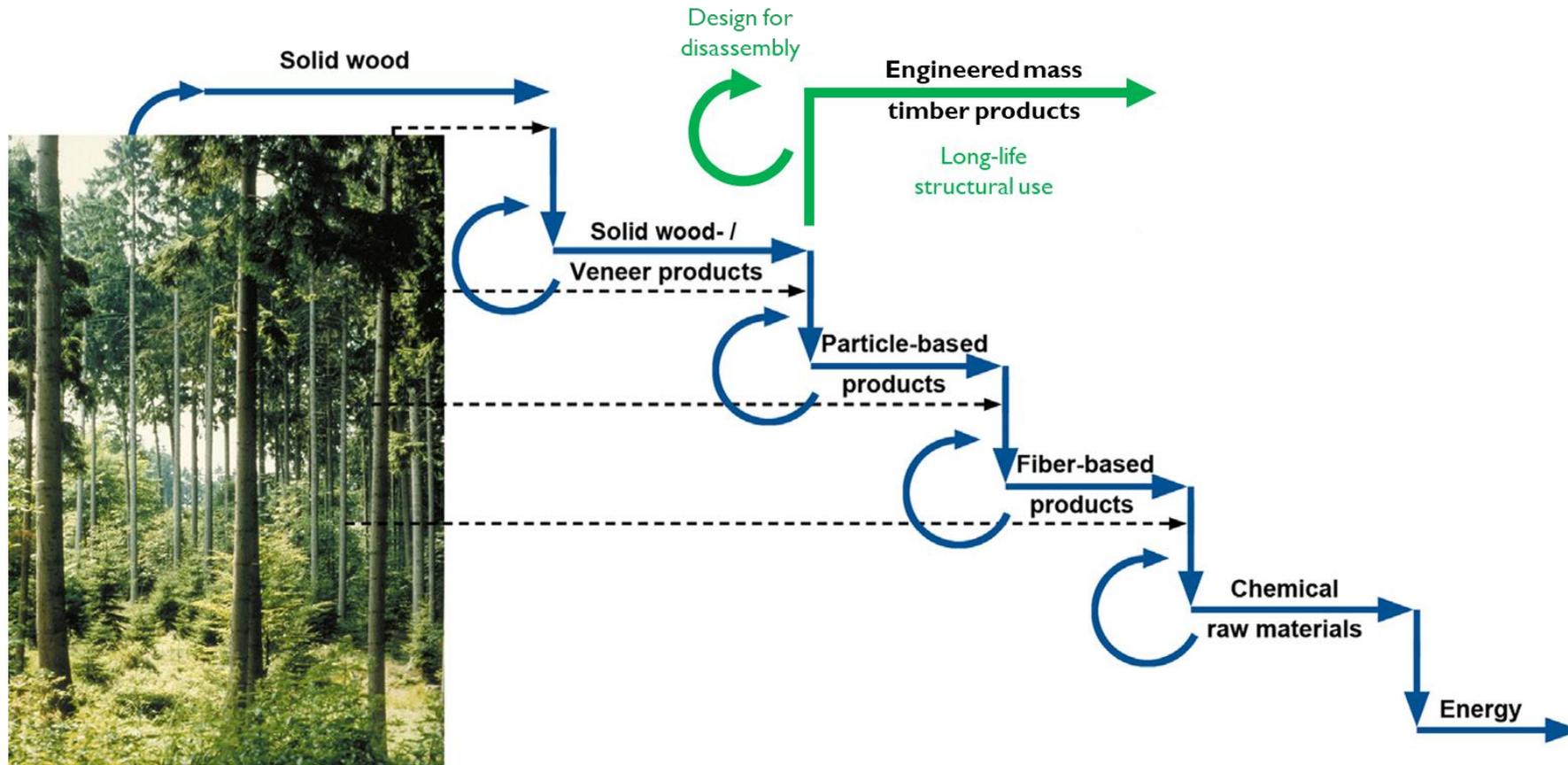
Cascading uses of timber: downcycling (Höglmeier et al, 2013)

Environmental rationale: Maintain quality and prolong lifespan



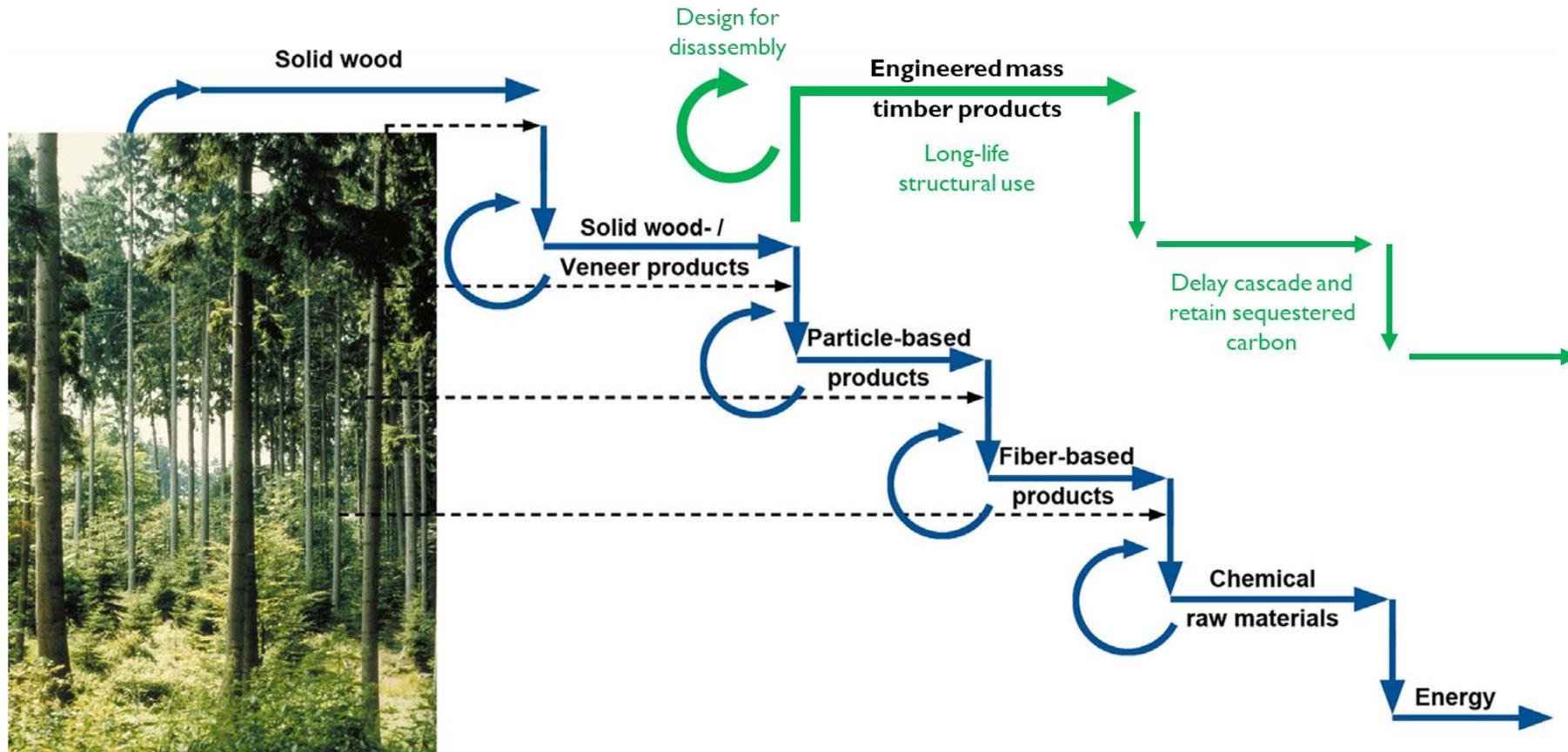
Upcycle to disrupt cascade: Rose et al, 2018 (additions to figure from Höglmeier et al, 2013)

Environmental rationale: Maintain quality and prolong lifespan



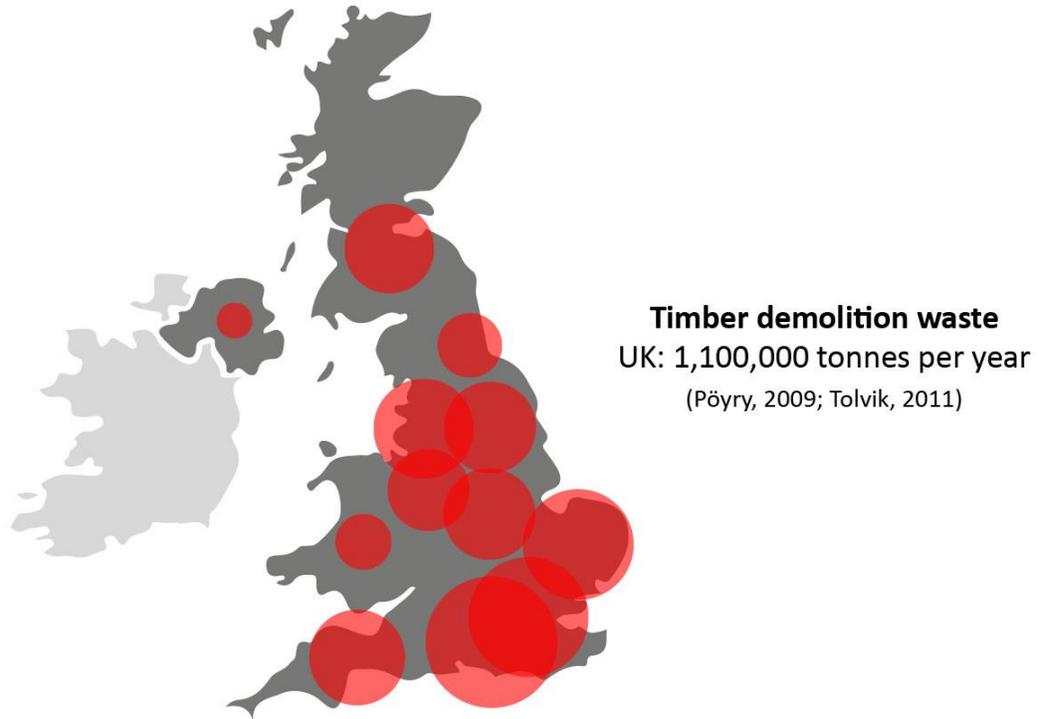
Upcycle to disrupt cascade: Rose et al, 2018 (additions to figure from Höglmeier et al, 2013)

Environmental rationale: Maintain quality and prolong lifespan

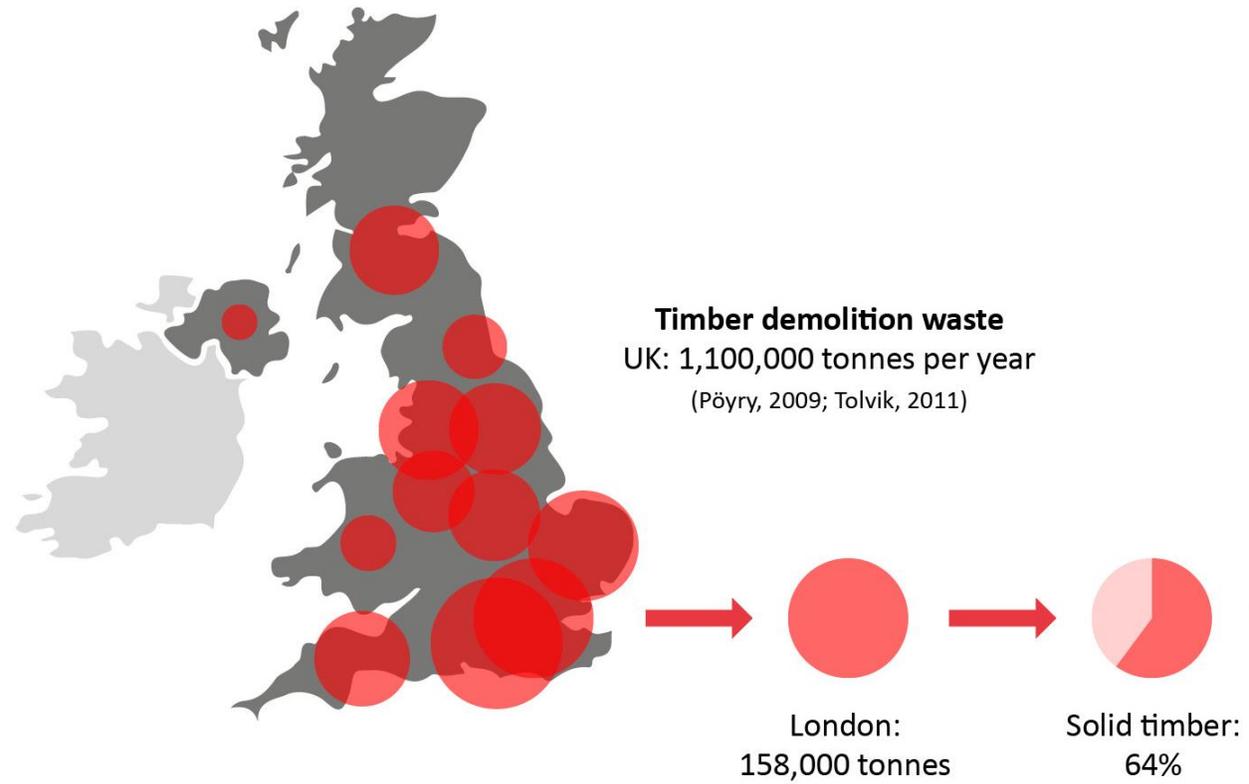


Upcycle to disrupt cascade: Rose et al, 2018 (additions to figure from Höglmeier et al, 2013)

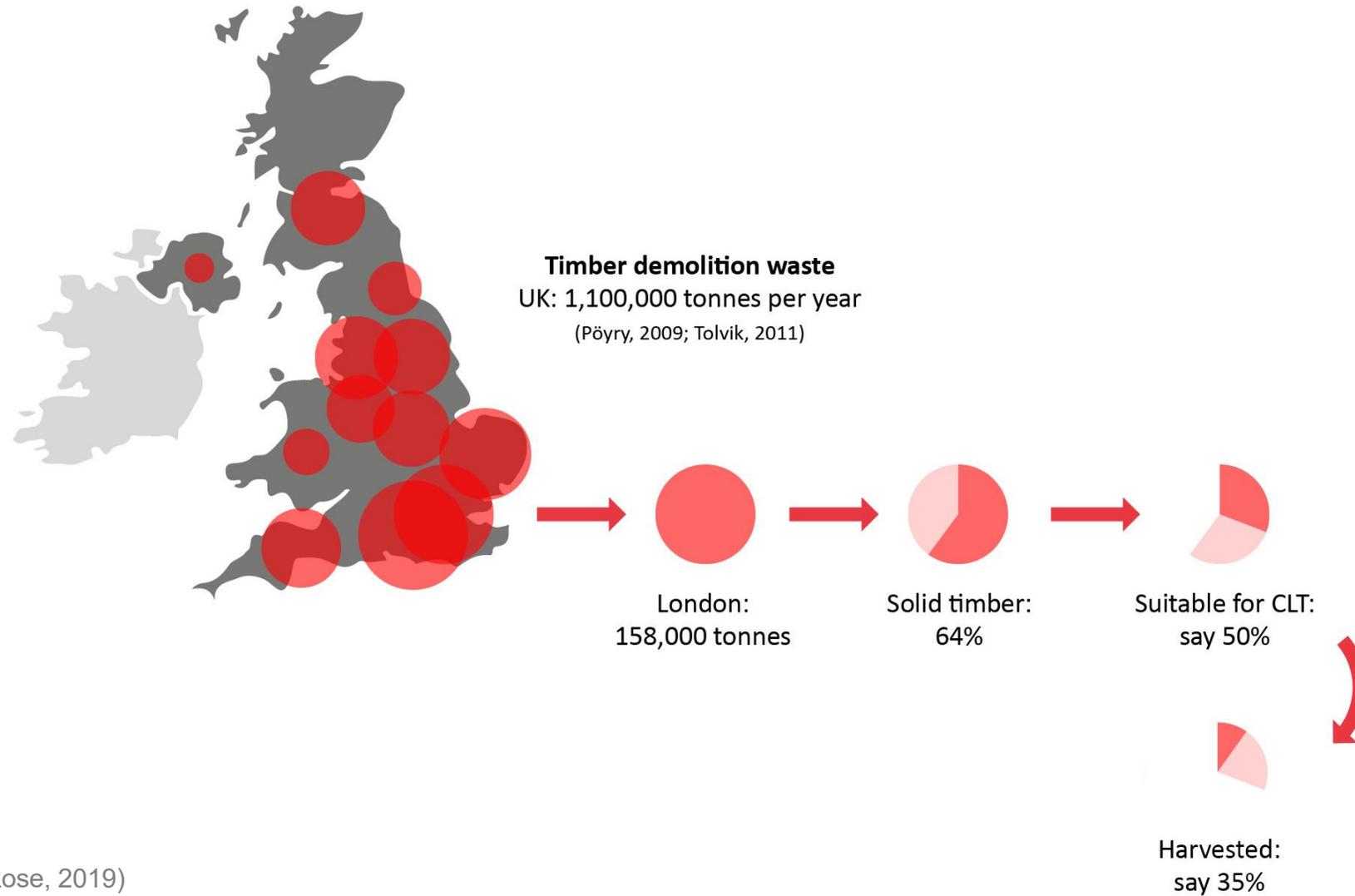
Business rationale: Scale of the opportunity



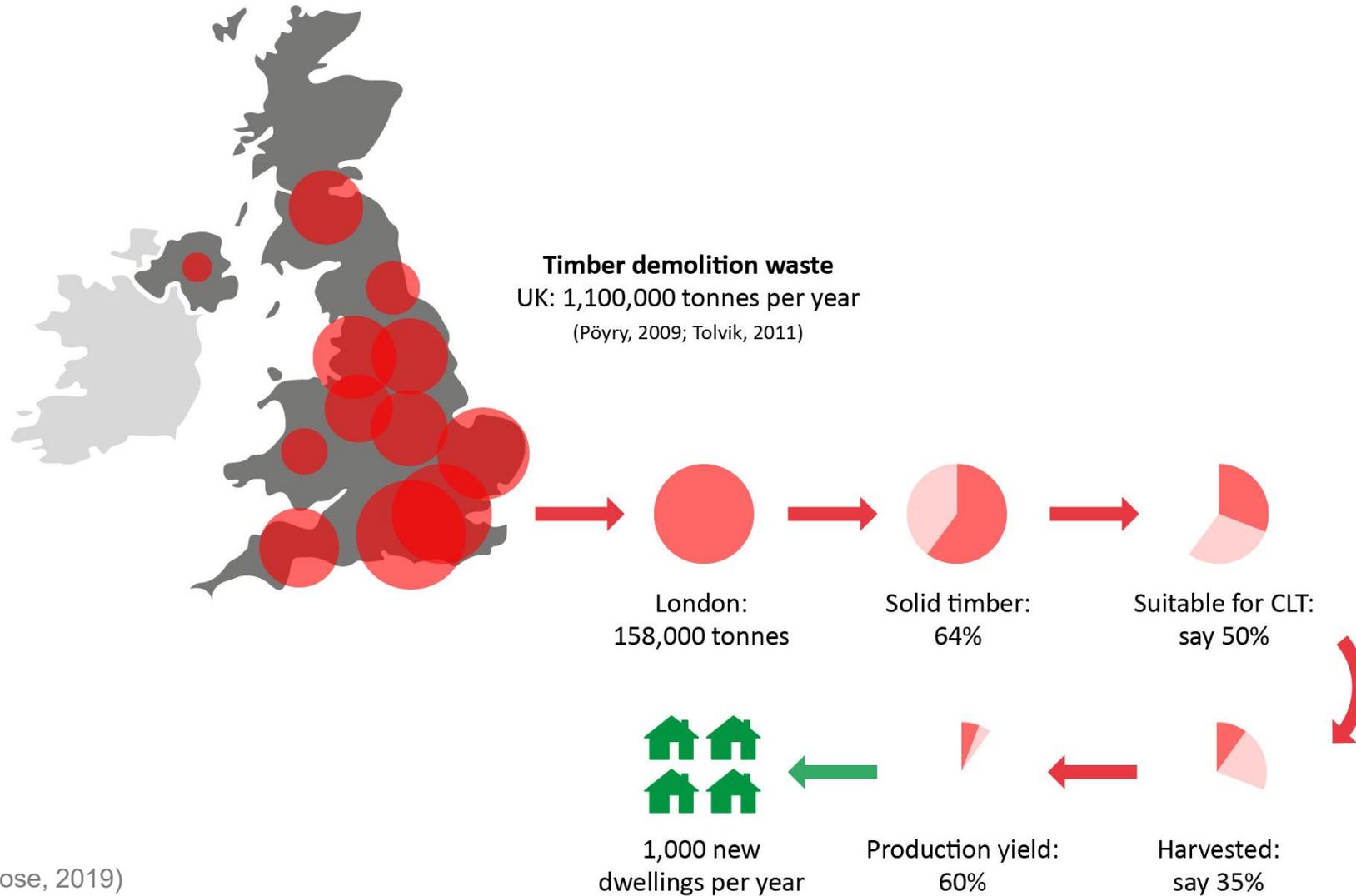
Business rationale: Scale of the opportunity



Business rationale: Scale of the opportunity



Business rationale: Scale of the opportunity



Scale of the opportunity (Rose, 2019)

Property rationale: dense but short and twisting



Table 1 — Values for tolerance class 1

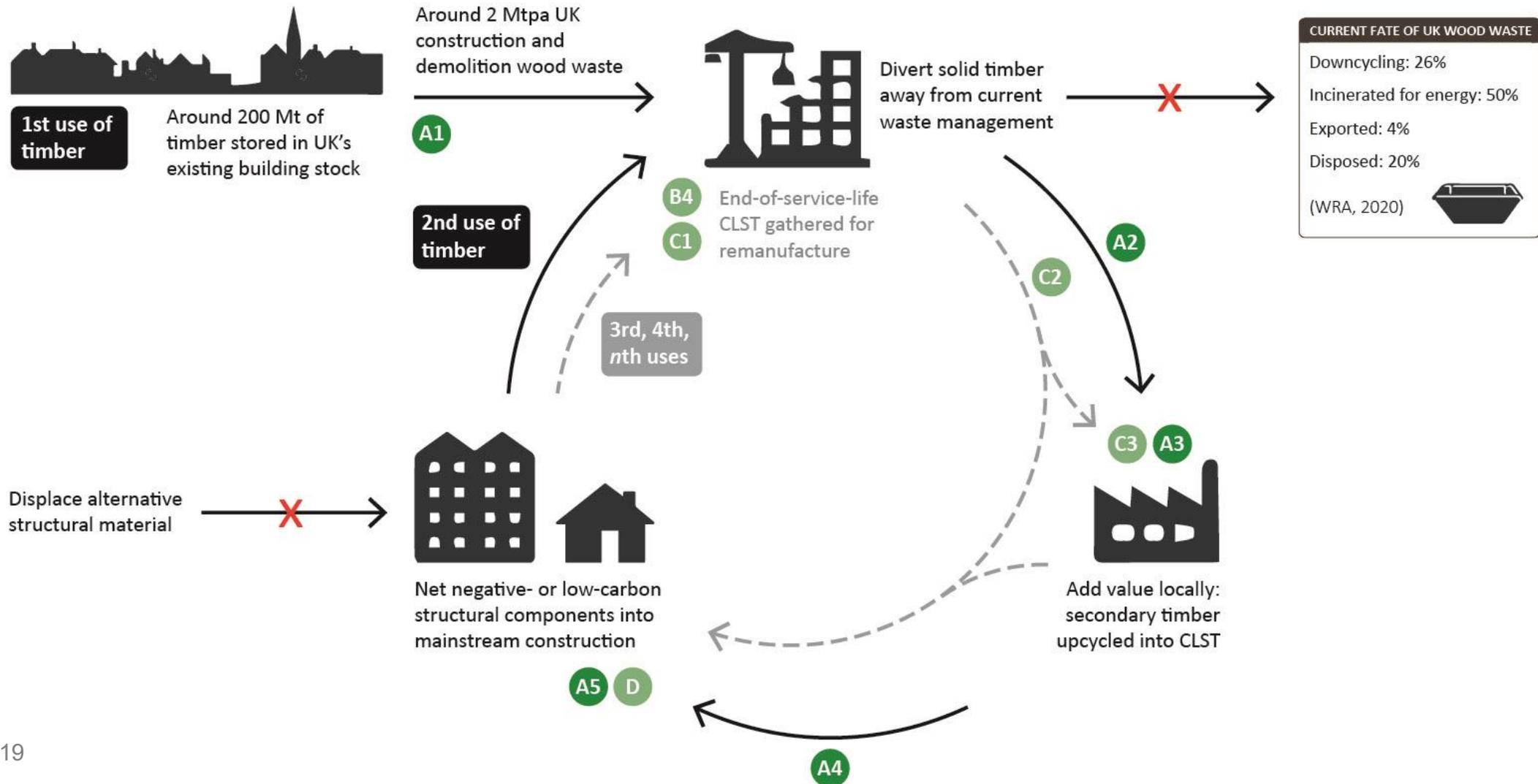
For thicknesses and widths ≤ 100 mm:	(-1 +3) mm
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Tolerance requirement in EN 336



Short pieces after cutting

CLST lifecycle schematic



Difficulties: Carbon accounting and structural performance assessment

Three parts to carbon accounting for secondary timber product

1. Carbon capture

Firm carbon saving based on sequestered carbon remaining locked in timber over the long term

2. Displacement

Potential carbon saving based on reducing the demand for alternative, more carbon intensive materials

3. Production

Carbon cost of carrying out the process of gathering, processing and delivering the product to site

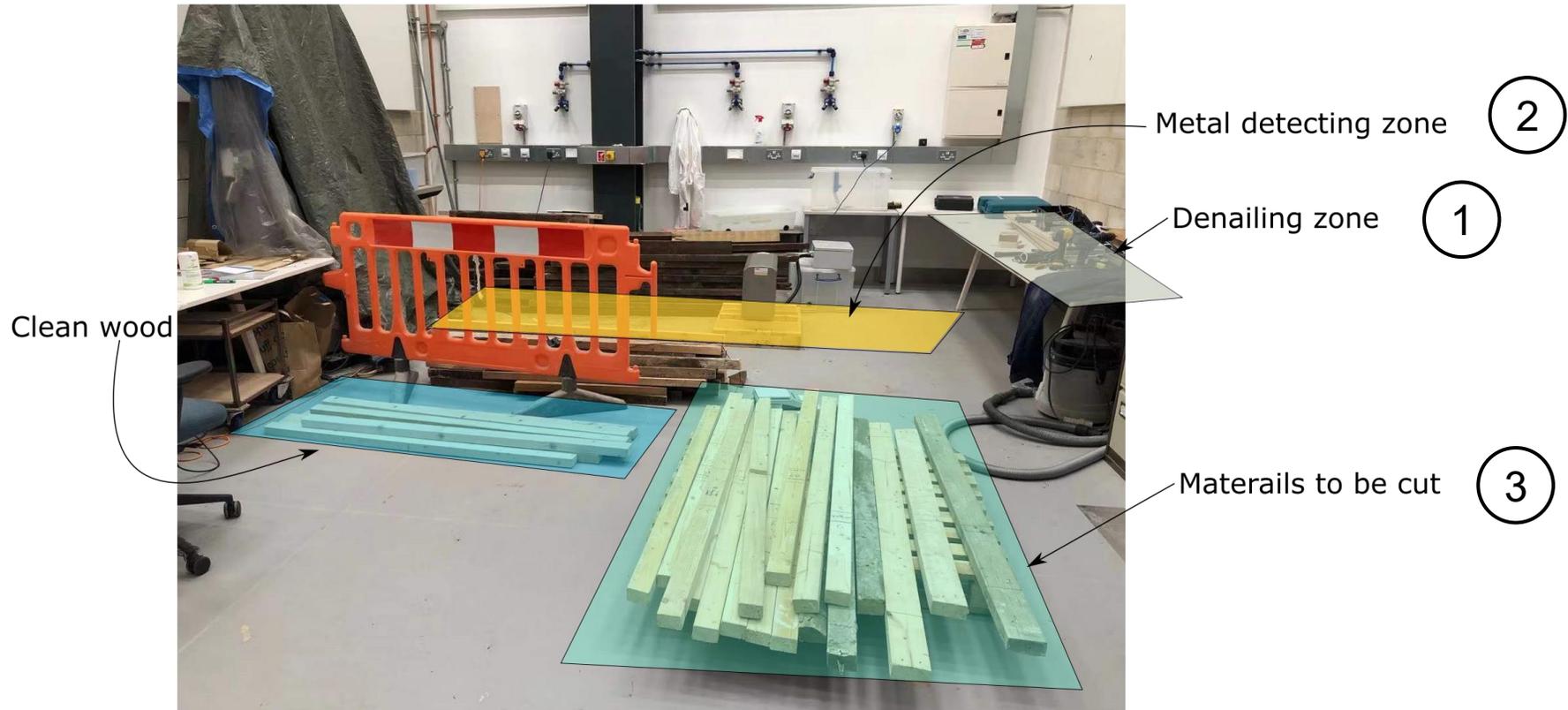
Processing feedstock

- Wood collection from different construction sites



Processing feedstock

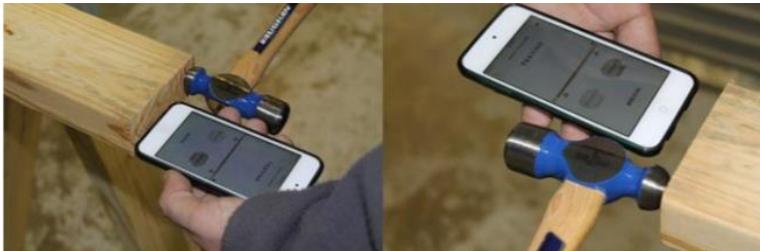
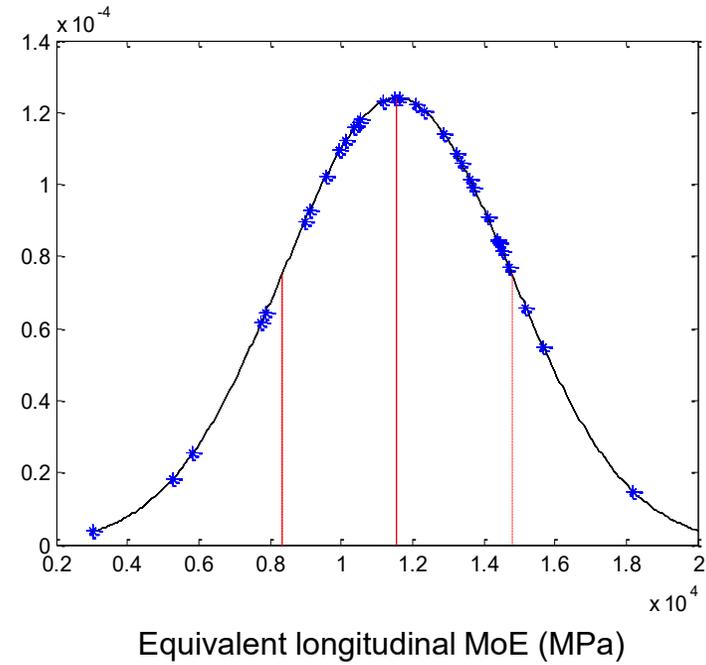
- Denailing and metal detecting



Wood preparation before machining

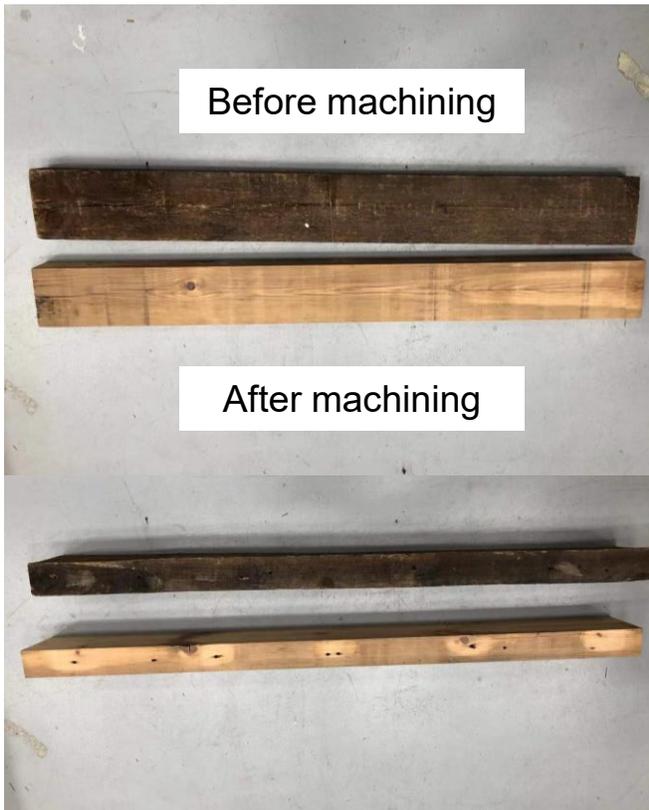
Processing feedstock

- Acoustic performance assessment

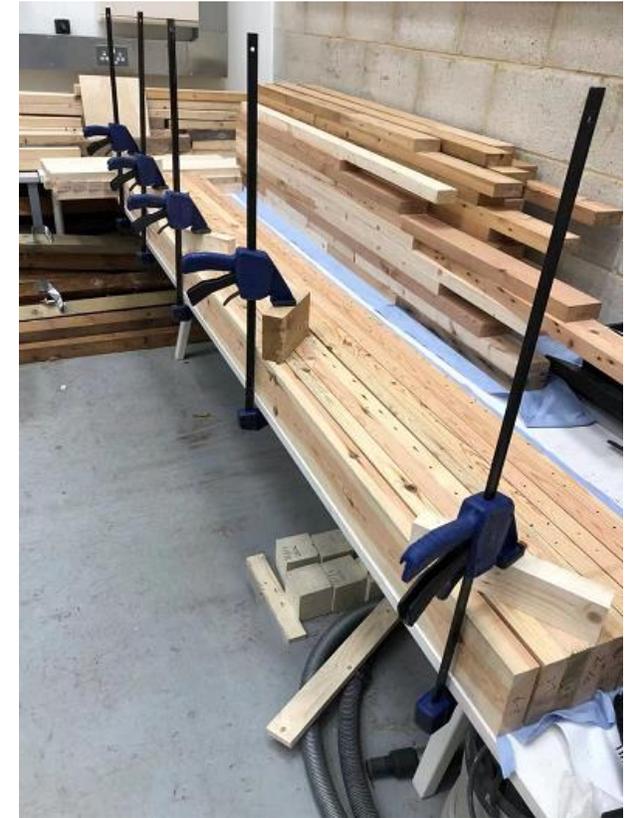


Processing feedstock

- Machining



Short pieces for inner layers



Long pieces for outer layers

Processing feedstock

- Panel lamination



Adhesive application



Panel layup



Vacuum pressing

Processing feedstock

- Final specimens



Full-size panels for bending tests



Secondary timber from demolition site



Cross laminated secondary timber (CLST) panels

Questions:

1. Is there a way to predict the structural properties of secondary timber?

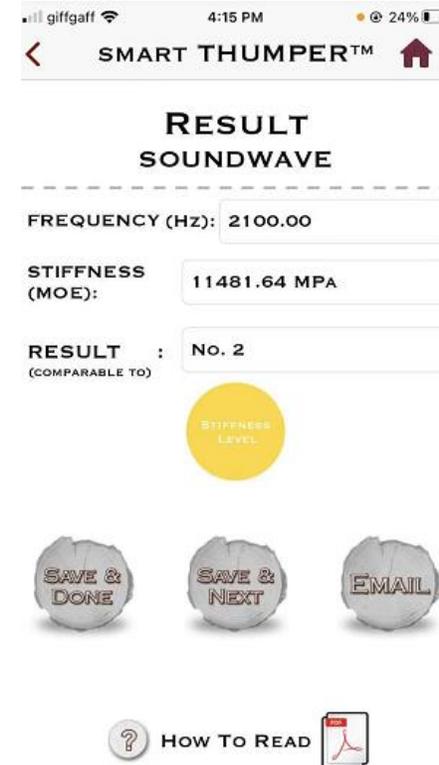
Test preparation

- Acoustic assessment



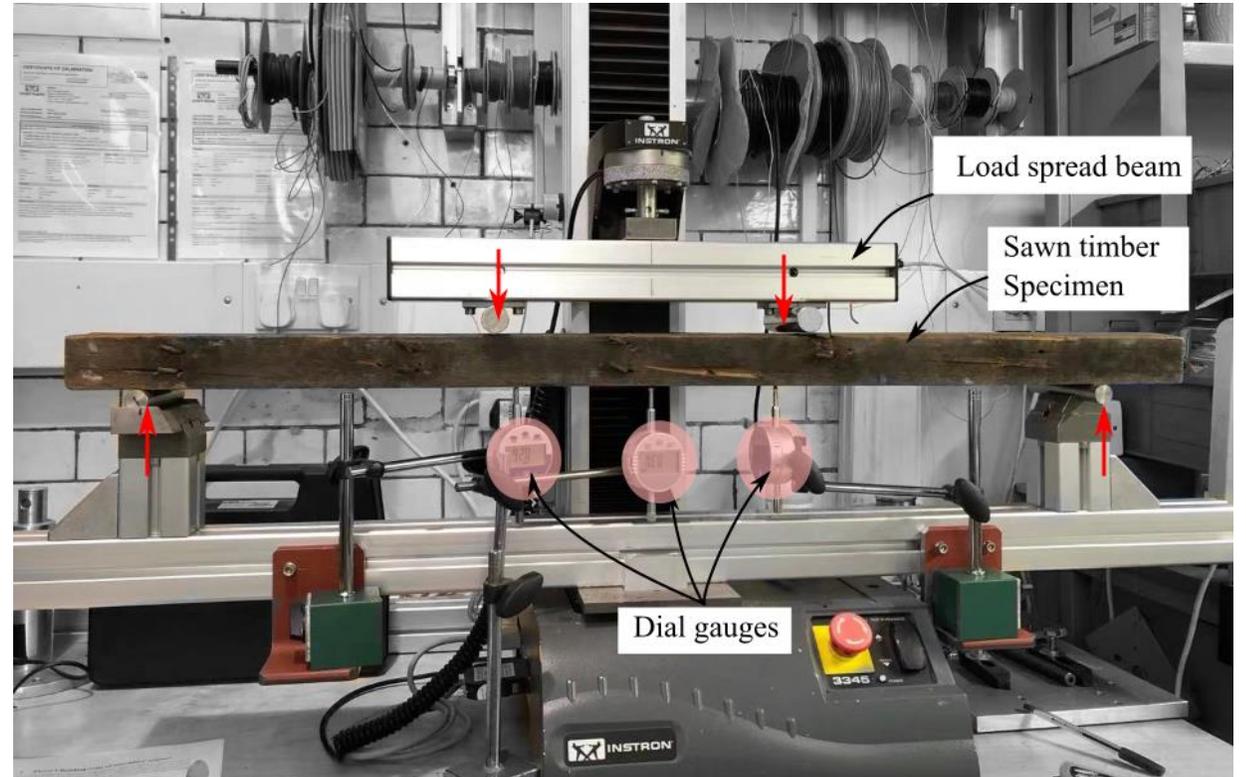
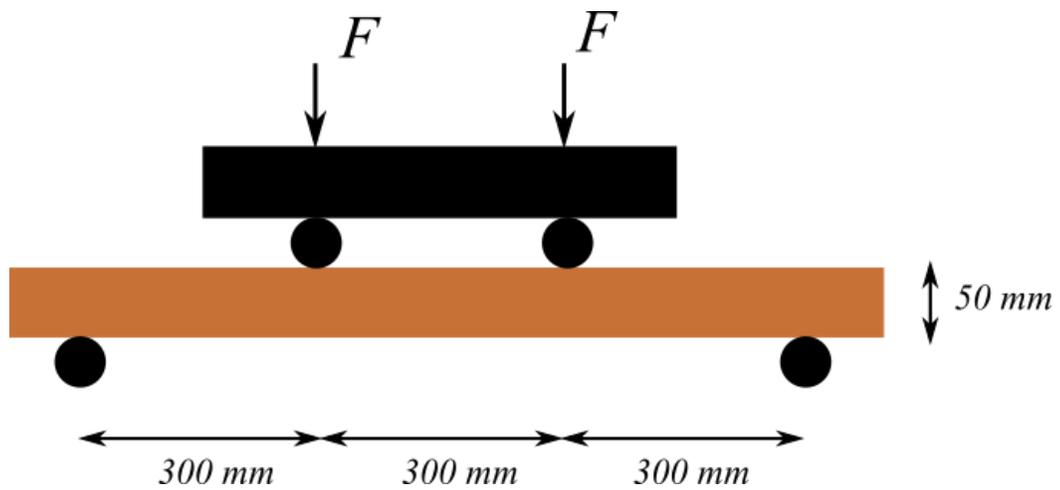
$$E_{Longitudinal} = \rho V^2$$

Timber longitudinal vibration measurements



Test preparation

- Testing verification



Bending test setup according to EN 408

Test samples

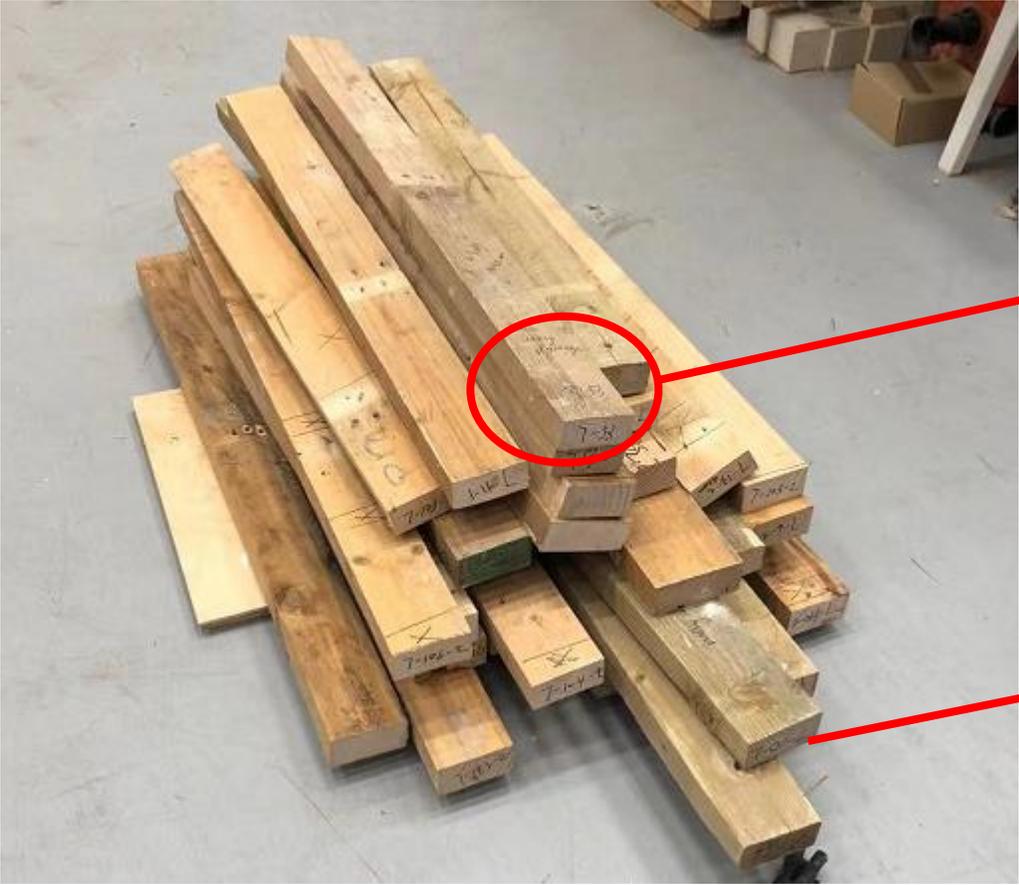


80 x 50 cross section

100 x 50 cross section

Secondary sawn timber

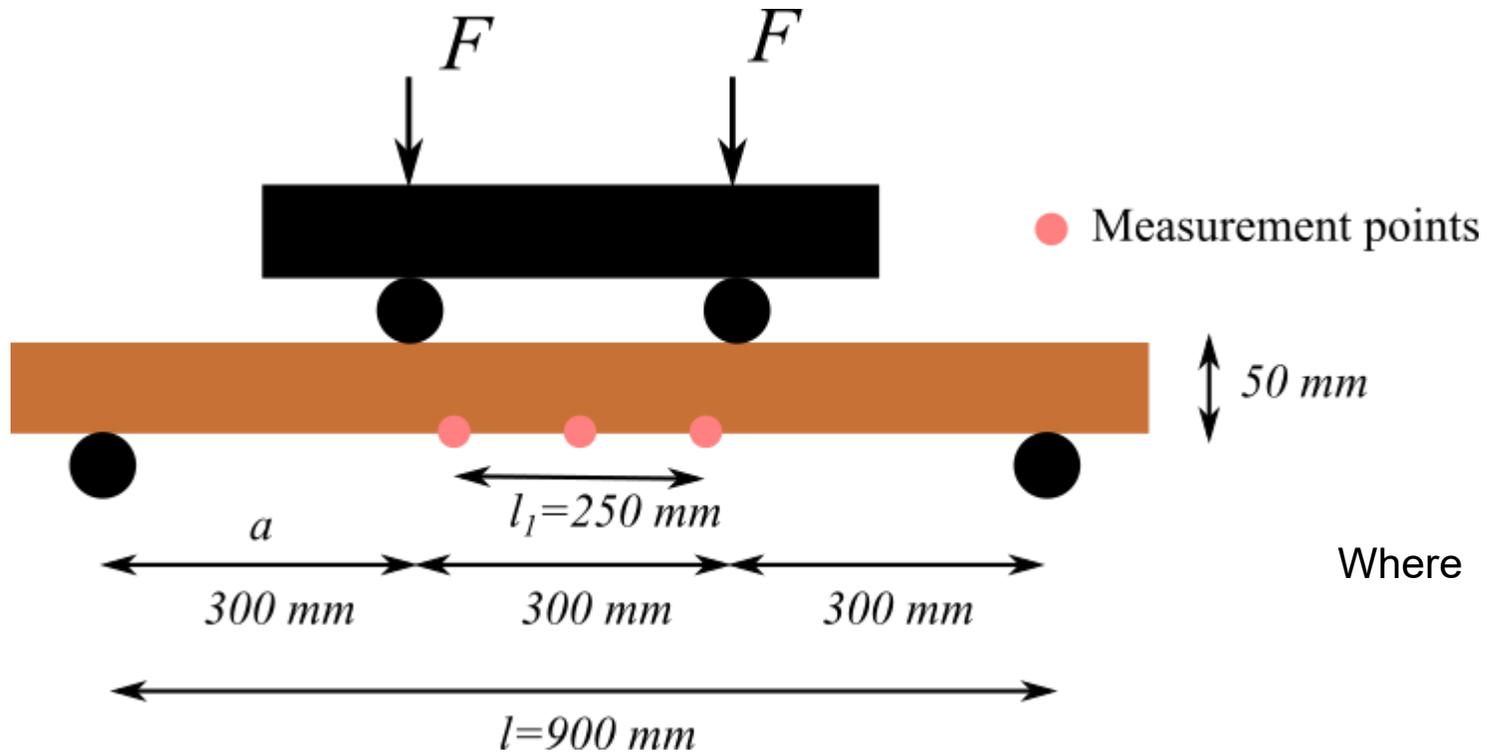
Test samples



100 x 50 cross section

Secondary sawn timber

Test calculations



$$E_{Local} = \frac{al_1^2(F_2 - F_1)}{16I(\omega_2 - \omega_1)}$$

$$E_{Global} = \frac{3al^2 - 4a^3}{2bh^3 \left(2 \frac{\omega_2 - \omega_1}{F_2 - F_1} - \frac{6a}{5Gb h} \right)}$$

Where

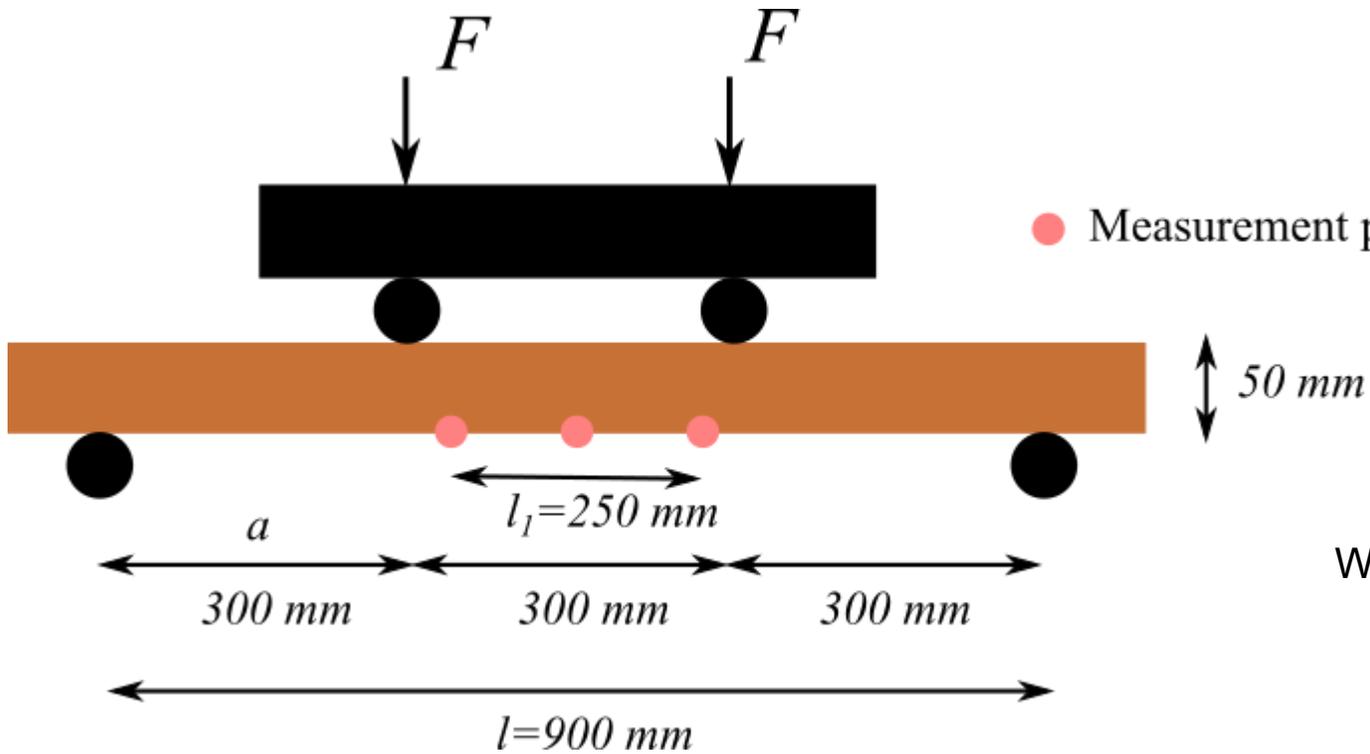
b is the cross section width

h is the cross section height

F is the total force from the load spread beam

G is shear modulus (infinite here) from EN 408

Test calculations



● Measurement points

$$f_b = \frac{3aF}{bh^2}$$

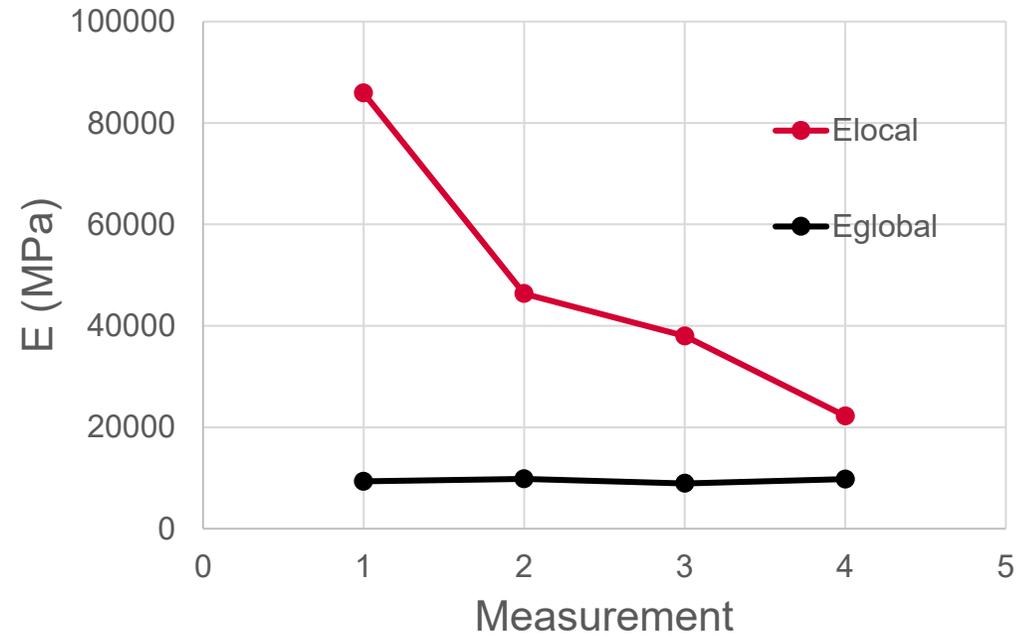
Where

b is the cross section width

h is the cross section height

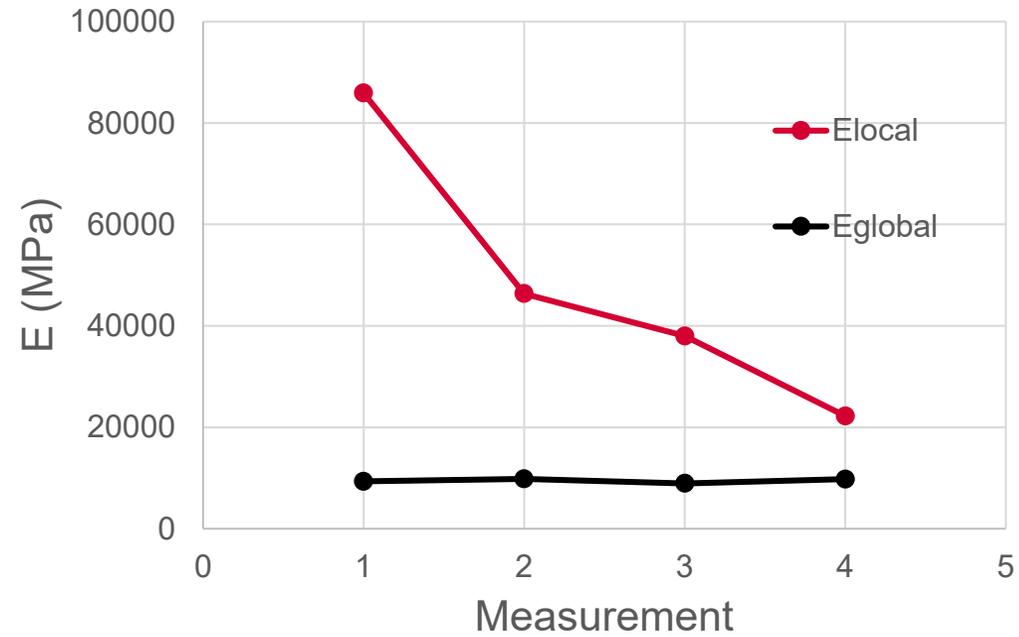
F is the total force from the load spread beam

Test results



Mmeasurements for one specimen

Test results

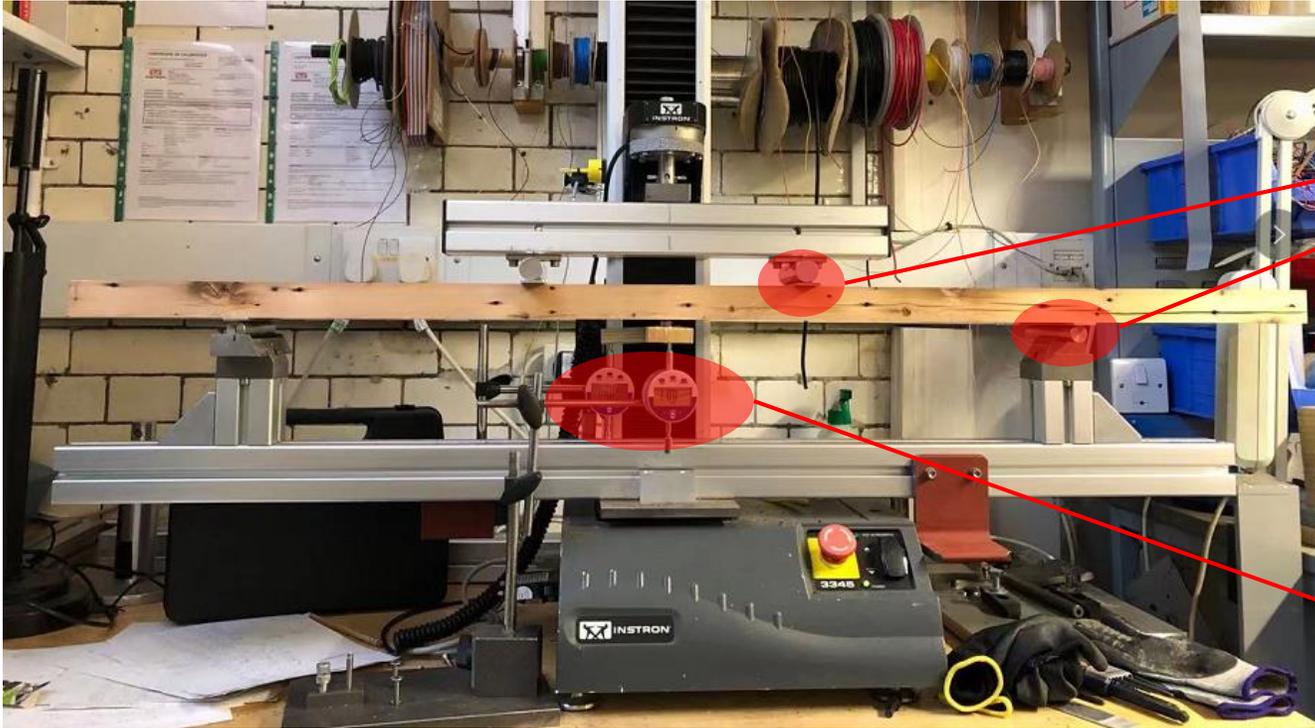


Measurement for one specimen

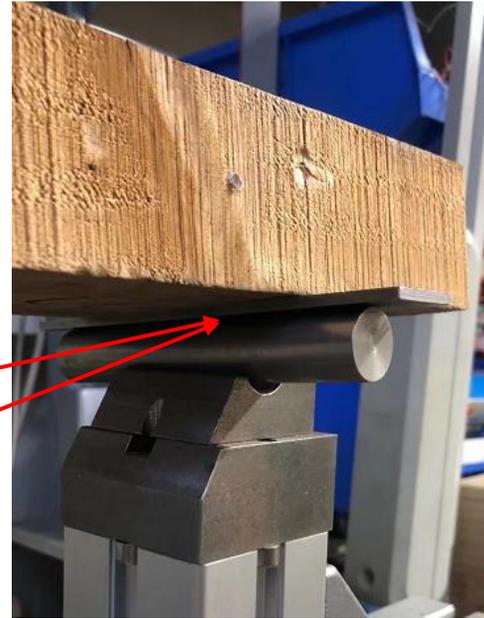


Gap at the support due to twist

Further improvement



Test setup improvement



Steel plates to spread the load



Measurement at both edge and middle



Cupped secondary timber

Test observations

- Failure mode



Bending failure on tension side

Test observations

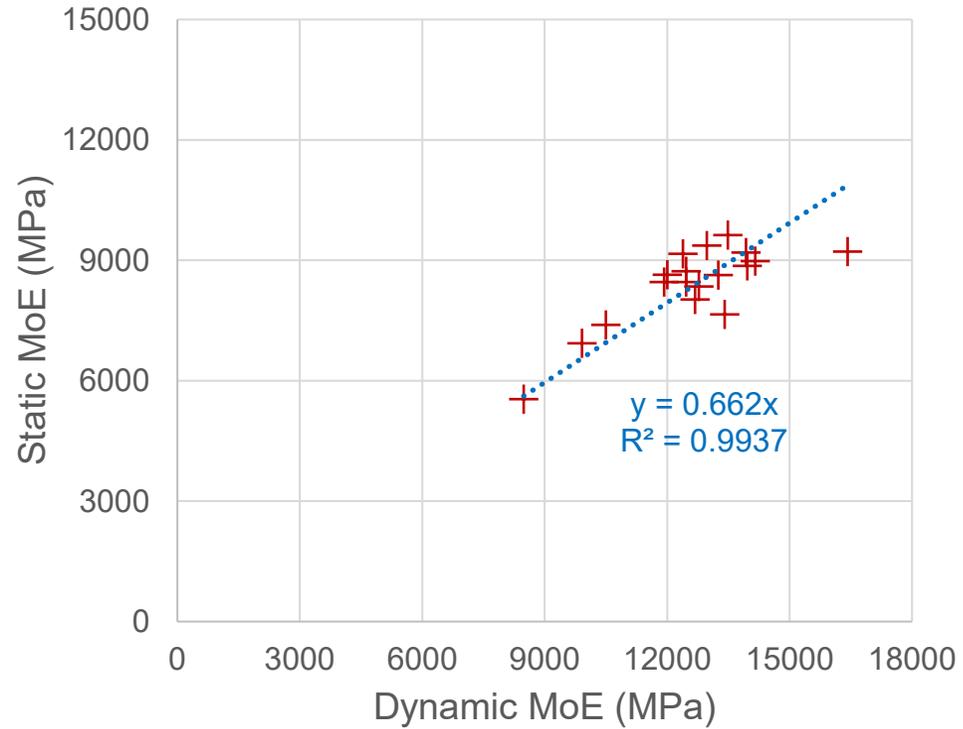
- Failure mode



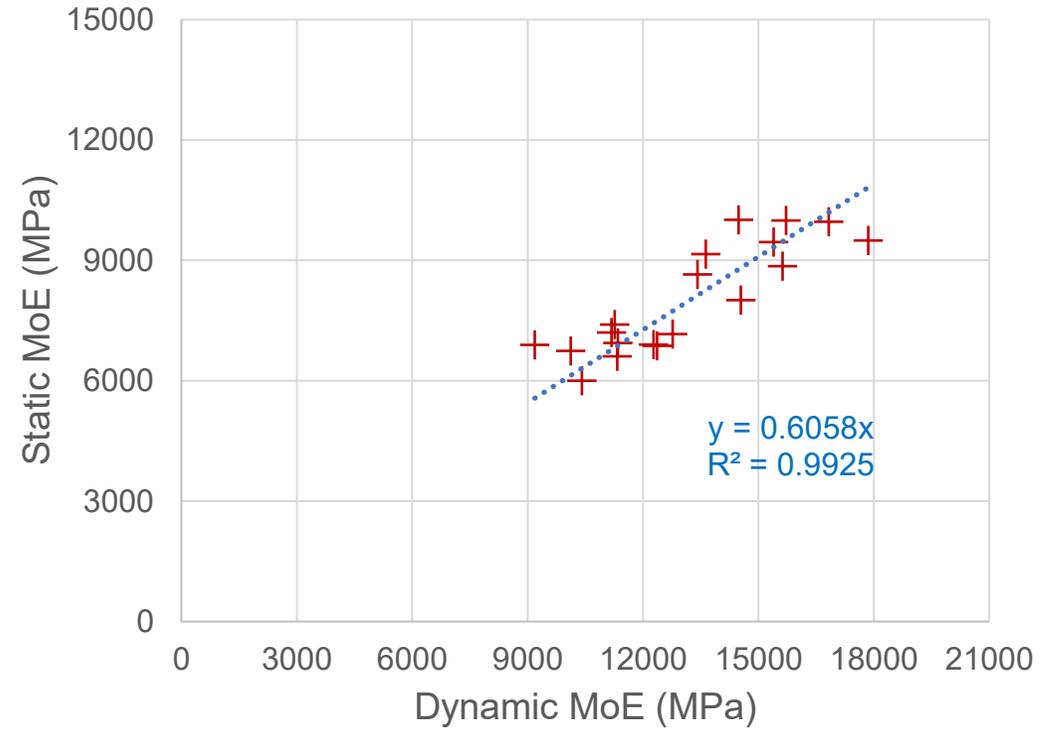
Bending failure on tension side



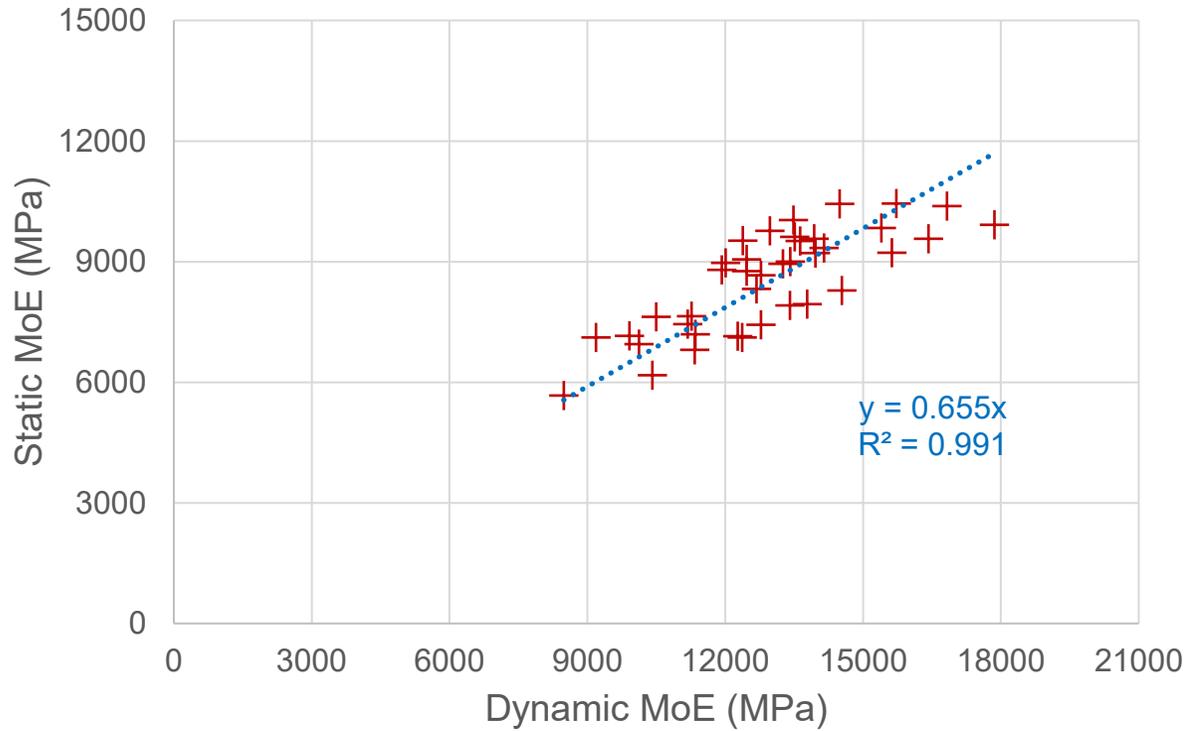
Bending failure on compression side



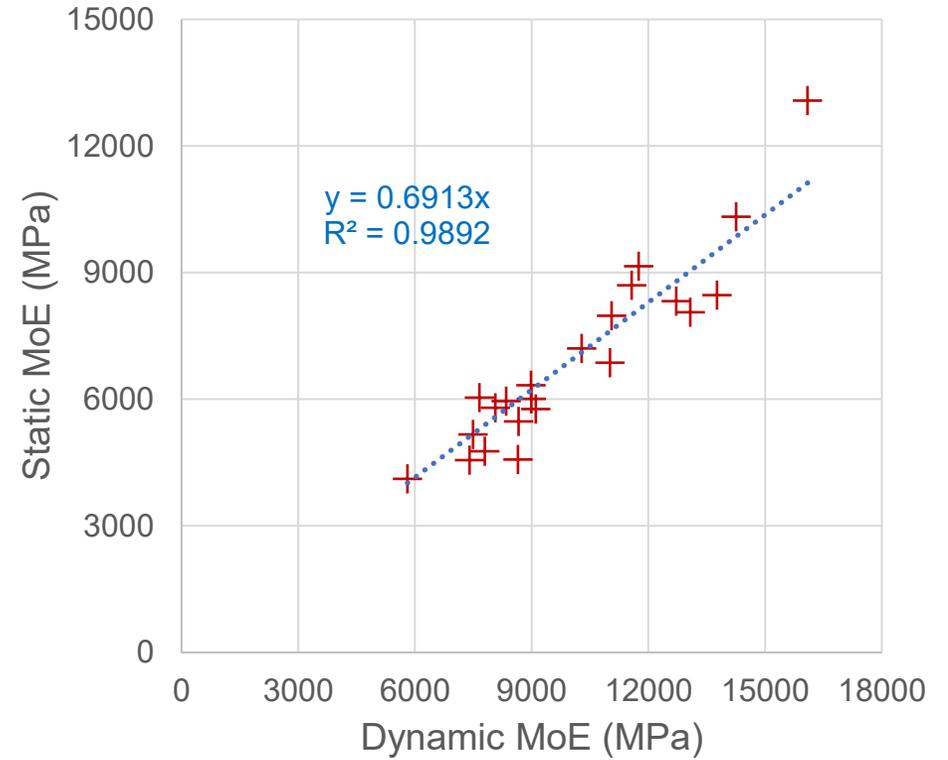
Batch 1 result (80 x 50)
18 specimens



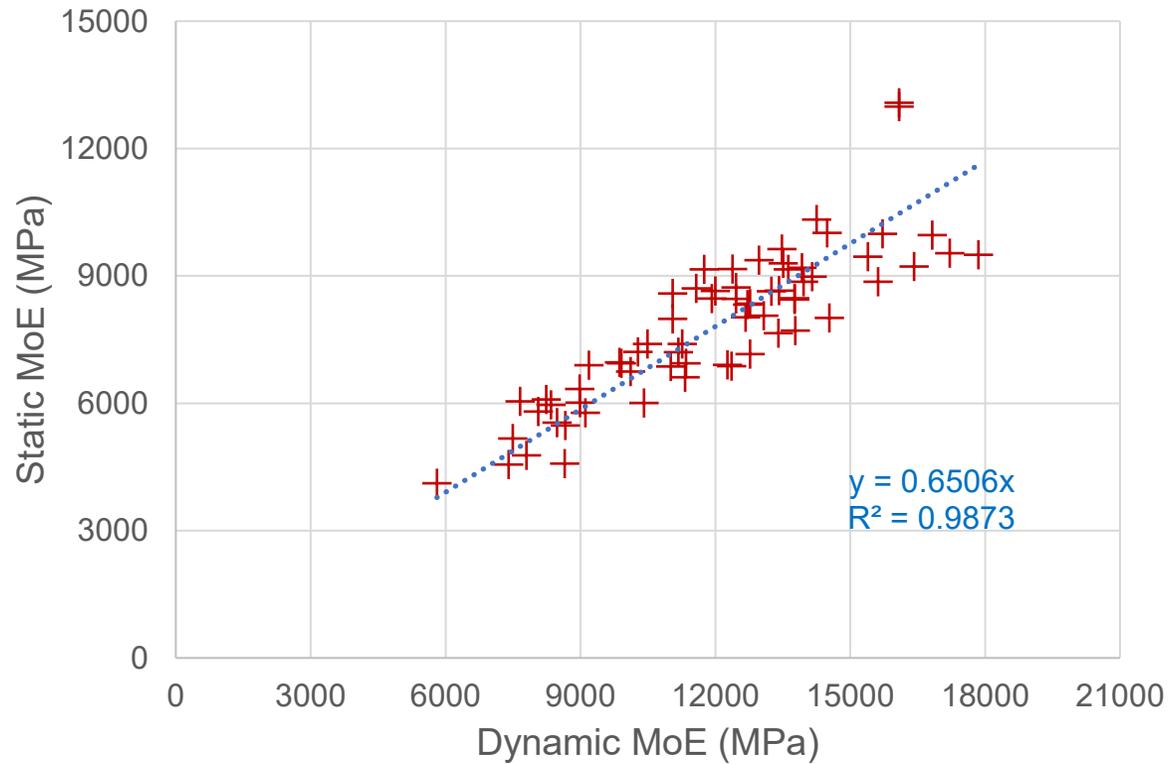
Batch 2 result (100 x 50)
19 specimens



Combined batch 1 and batch 2
result (1800s)



Batch 3 result (in 1990s)

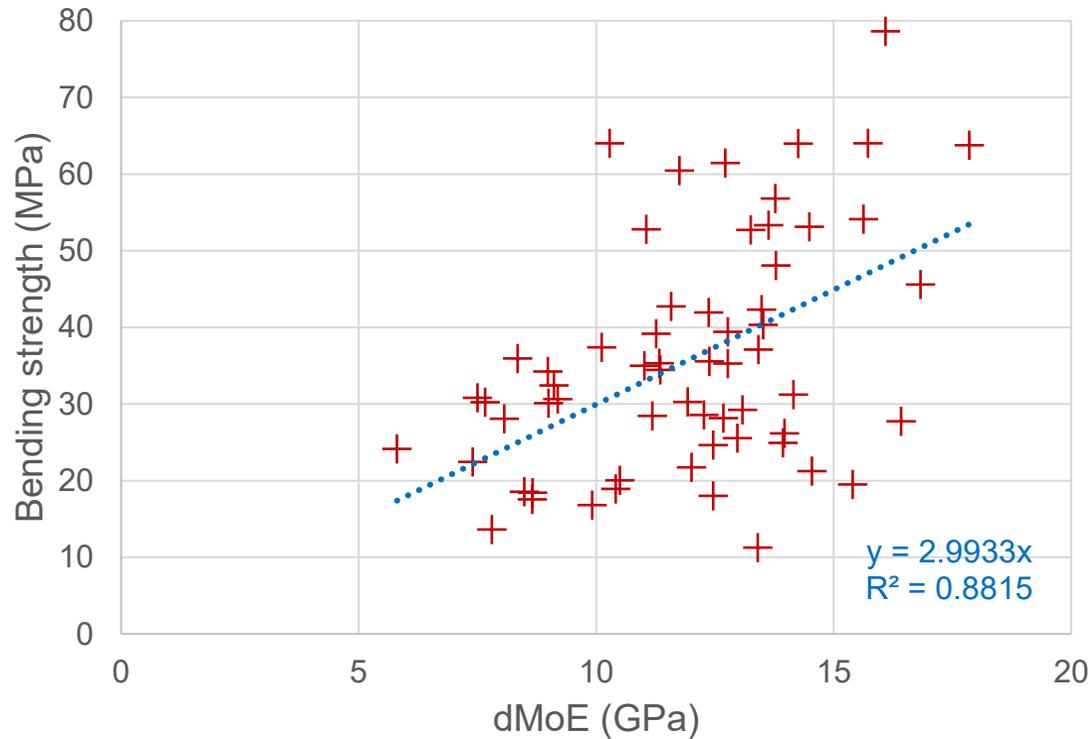


All batch combined results

Characteristic mean static MoE value: **7607** MPa
(0.65dMoE)
Equivalent to C14

	Class	C14	C16	C18
Stiffness properties in kN/mm²				
Mean modulus of elasticity parallel bending	$E_{m,0,mean}$	7,0	8,0	9,0

Strength grade in EN 338-2016



All combined results

Characteristic strength value: **15.1 MPa**
 Equivalent to C14 according to EN 338-2016

	Class	C14	C16	C18
Strength properties in N/mm²				
Bending	$f_{m,k}$	14	16	18

5 percentile density value: **373 kg/m³**
 Mean density: 475 kg/m³
 Equivalent to C27 or higher

		C27	C30	C35	C40
Density in kg/m³					
5 percentile density	ρ_k	360	380	390	400
Mean density	ρ_{mean}	430	460	470	480



Secondary timber from demolition site

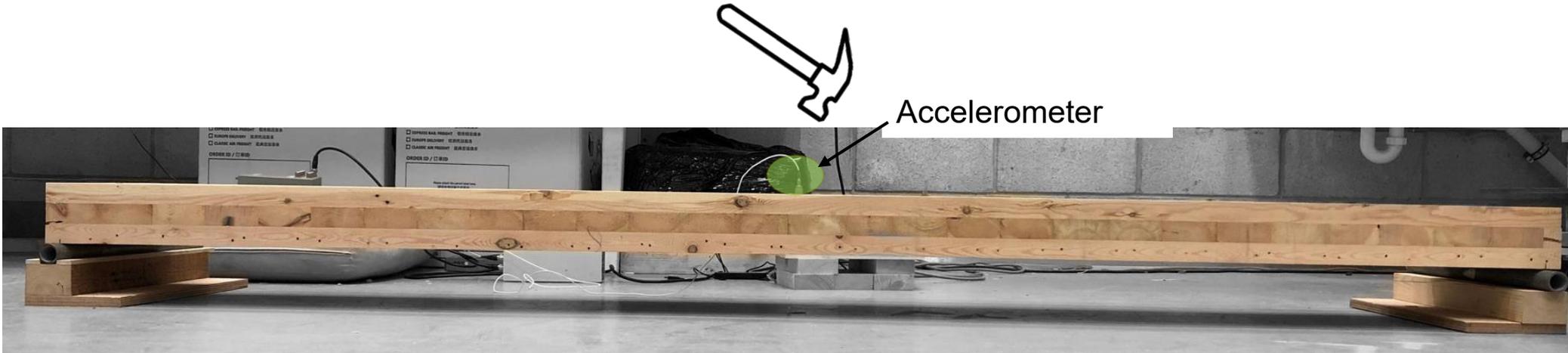


Cross laminated secondary timber (CLST) panels

Questions:

2. Can acoustic method work for the structural assessment of CLST?

Acoustic assessment for CLST panels



Flexural vibration measurements of CLST according to ASTM D6874

$$(EI)_{tv} = \frac{f^2 w \ell^3}{Kg \left(\frac{\ell_t}{\ell} \right)}$$

- w = total specimen weight, lbf (N),
- f = fundamental vibration mode frequency, Hz (s^{-1}),
- I = specimen moment of inertia, in^4 (mm^4); e.g., $bh^3/12$,
for a rectangular cross-section,
- b = horizontal breadth (width), in. (mm),
- d = vertical depth, in. (mm),
- g = acceleration due to gravity, $386 in./s^2$ ($9807 mm/s^2$),
and
- K = constant for free vibration of a beam (see Ref. (4))
= 2.47, if simply supported,

Full-scale panel tests



Four-point bending tests

Test observations

- Failure model



Bending failure



Delamination

Test results

$$(EI)_{CL,local,net} = E_{local} \cdot I_{CL,net} = \frac{l_2 \cdot l_1^2}{16} \cdot \frac{F_2 - F_1}{w_2 - w_1}$$

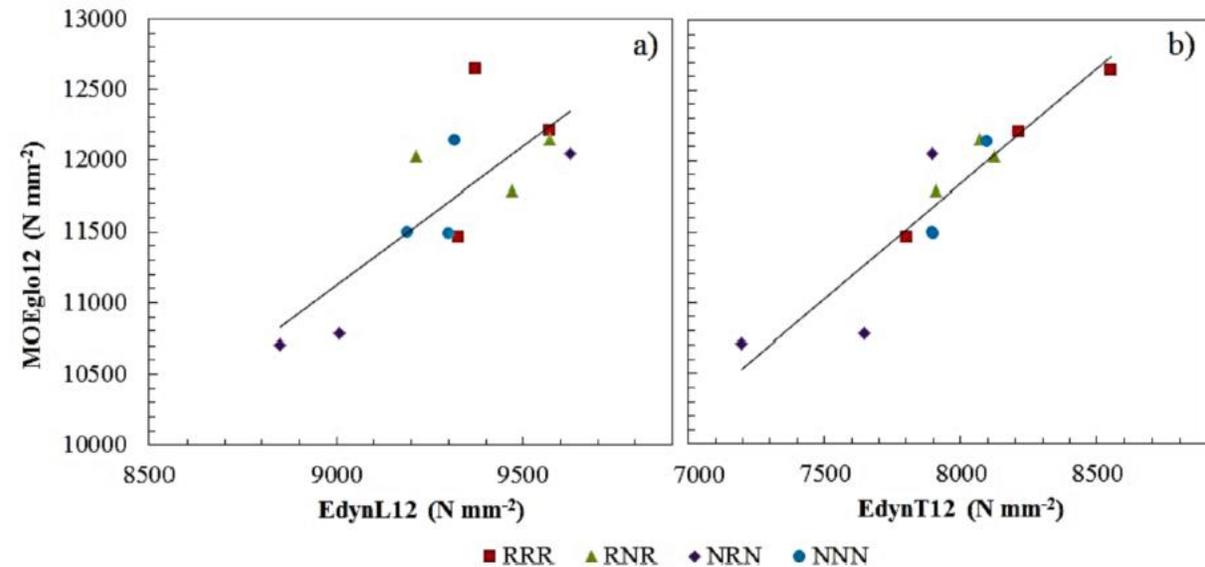
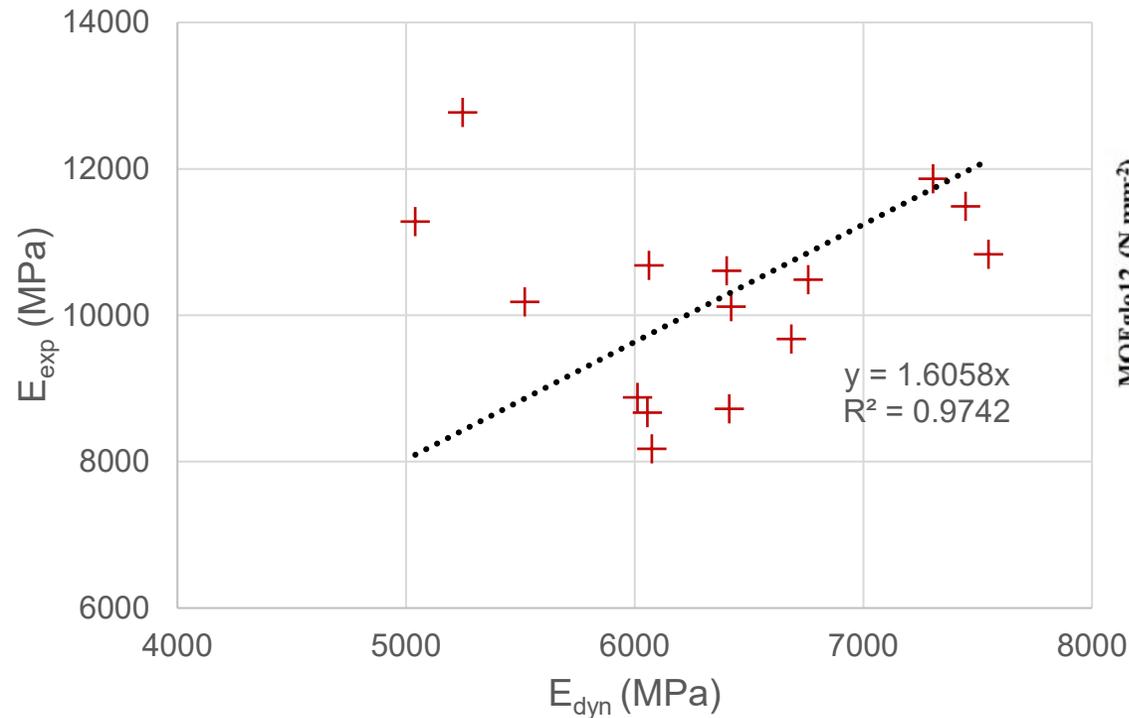
l_1

gauge length for measuring wlocal

l_2

distance between loading position and the nearest support

Local stiffness calculation according to EN 16351



$$MOE_{glo12} = 1.6346 E_{dynT12} - 1235.4 \quad R^2 = 0.85 \quad StE = 234 Nmm^{-2}$$

Results from Llana et al. 2022

Test results

$$E_{\text{mean}} = 10295 \text{ MPa}$$

$$f_{b,\text{mean}} = 31.75 \text{ MPa}$$

$$E_{\text{char}} = 10053 \text{ MPa}$$

$$f_{b,\text{char}} = 21.88 \text{ MPa}$$

Characteristic value according to EN 14358

CLT Grade	Laminations I	
	f_b (MPa)	$E^{(d)}$ (MPa)
E1	28.2	11,700
E2	23.9	10,300
E3	17.4	8,300
E5	23.9	10,300
V1(N)	10.0	11,000
V2	11.8	9,500
V5	11.0	11,000
S1	28.7	10,300
S2	24.2	8,900
S3	22.3	8,900

Grade information from PRG 320-2019

Test results

$$E_{\text{mean}} = 10295 \text{ MPa}$$

$$F_{\text{b,mean}} = 31.75 \text{ MPa}$$

$$E_{\text{char}} = 10053 \text{ MPa}$$

$$F_{\text{b,char}} = 21.88 \text{ MPa}$$

Characteristic value according to EN 14358

Table 1: CLT strength classes; characteristic values of CLT out-of-plane.

Base material T14; CV[$f_{t,0,\ell}$] =		25 ± 5 %	35 ± 5 %
Property [-]	Symbol [-]	CL 24h	CL 28h
Bending strength	$f_{m,CLT,k}$ [N/mm ²]	24.0	28.0
Tensile strength perpendicular to grain	$f_{t,90,CLT,k}$ [N/mm ²]	0.5	
Compression strength perpendicular to grain	$f_{c,90,CLT,k}$ [N/mm ²]	3.0	
Shear strength	$f_{v,CLT,k}$ [N/mm ²]	3.5	
Rolling shear strength	$f_{r,CLT,k}$ [N/mm ²]	1.40, for $w_{\ell} / t_{\ell} \geq 4$	
	$f_{r,lay,k}$ [N/mm ²]	0.80, for $w_{\ell} / t_{\ell} < 4$	
Modulus of elasticity parallel to grain	$E_{0,CLT,mean}$ [N/mm ²]	11,600	
	$E_{0,lay,mean}$ [N/mm ²]		

$$f_{m,CLT,k} = k_{m,CLT} f_{t,0,l,k}^{0.8}$$

$$f_{m,CLT,k} = 3.5 \times 8^{0.8} = 18.47 \text{ MPa}$$

CLT bending strength empirical equation (Unterwieser and Schickhofer, 2013)

Proposed strength grade for Norway spruce CLT (Schickhofer et al. 2016)

	Class	C14	C16	C18	C20	C22	C24	T14	T8
Strength properties in N/mm²									
Bending	$f_{m,k}$	14	16	18	20	22	24	20,5	13,5
Tension parallel	$f_{t,0,k}$	7,2	8,5	10	11,5	13	14,5	14	8
Tension perpendicular	$f_{t,90,k}$	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	21	16
Compression perpendicular	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,5	2,0
Shear	$f_{v,k}$	3,0	3,2	3,4	3,6	3,8	4,0	4,0	2,8

Strength grade in EN 338

Conclusions for secondary timber

- Local MoE is not a recommended stiffness indicator for secondary timber.
- The sMoE and dMoE shows strong directly proportional relationship.
- dMoE and MoR shows less relevance when compared to sMoE.
- The density is a less representative value for grading when compared to dMoE.
- The transverse acoustic method can be used for the structural property estimation.
- Secondary timber shows great potential when using as feedstock for CLT.