Seminar
Timber Based Hybrid Structures
Stockholm, KTH
January 19th, 2018

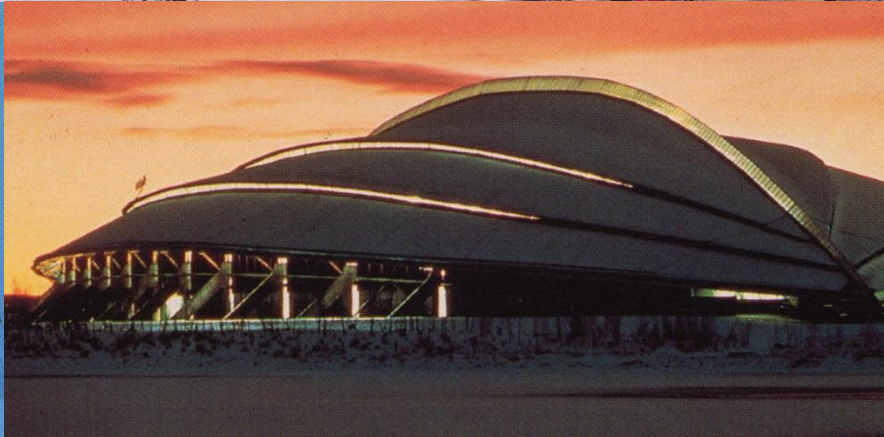
Gluing of softwood with other materials

Simon Aicher

MPA University of Stuttgart

Department Timber Constructions

Contents



Why bonding SW to other materials

In order to get benefits which we can not achieve with pure softwood materials

- To get improvements in
  - strength
  - stiffness
  - costs
- To open markets not feasible for pure SW constructions
- From a local and global economy and sustainability perspective it is important to enhance the material use of under-utized strongly increasing HW stands

Successful light-weight SW - OSB web I-beams

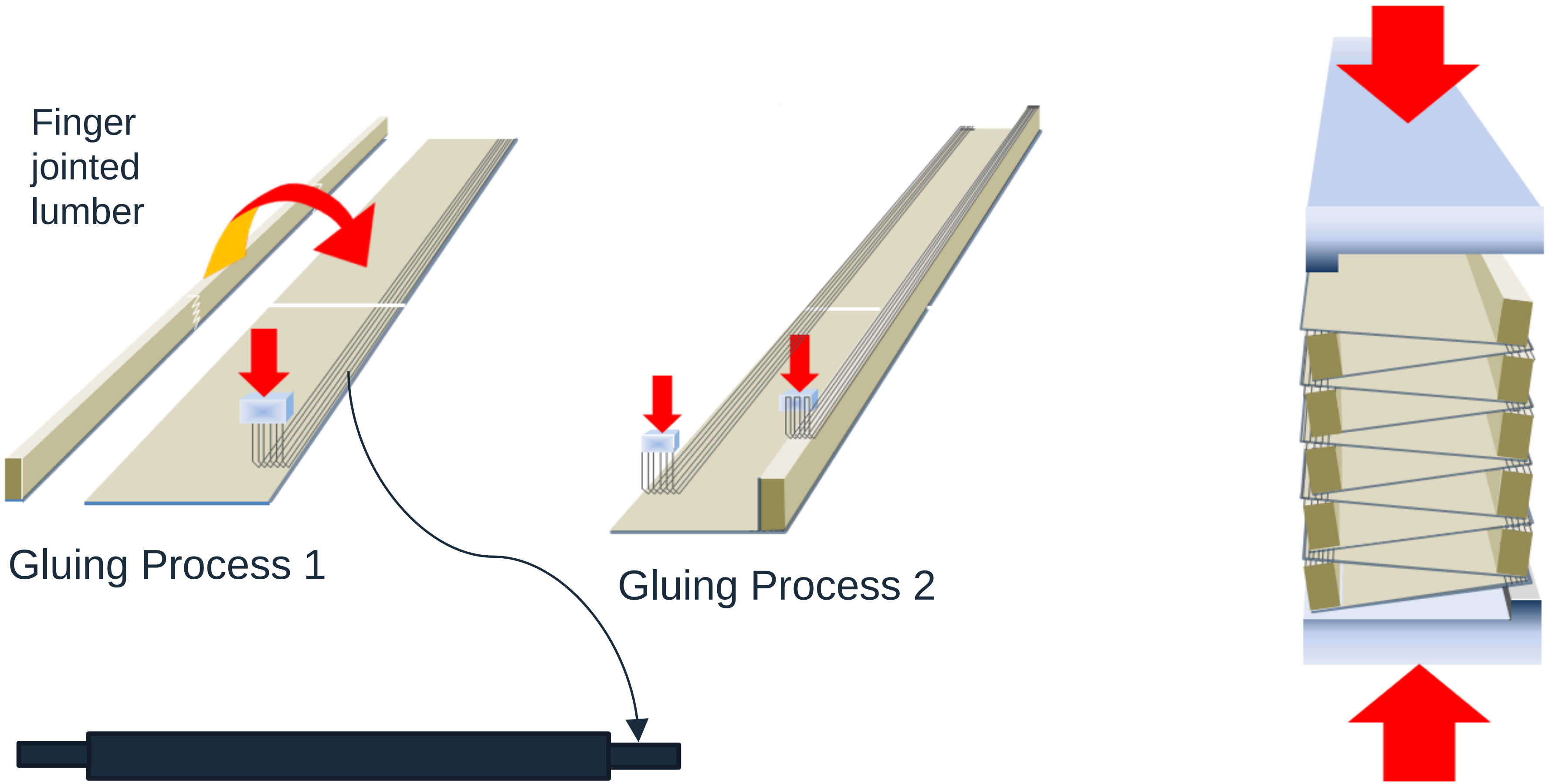
Successful light-weight SW - OSB keel-web-beams

Fully automated production process

Cambered press bed

Biaxial cramping

Schematic view of keel-web production process



Cramping

Milled recess in web panel for better bonding

plywood = 0.2 mm

OSB/3 = 0.4 mm

Planing of cambered 35 m long keel web element

Realized constructions with keel-web elements

Realized constructions with keel-web elements

PRF-, MUF-, UF- adhesive classes (EN 301:2017)

Adhesive type Designation	Application	Max. test temp.[c] °C	Max. glue line thickness Mm Test	Use	Service classes[a]
	Face lamination and finger jointing for general use				
EN 301 I 70 GP 0,6M EN 301 I 70 GP 0,3S	General purpose General purpose Special	70 70	1,0 1,0	0,6[d] 0,3	1,2,3 1,2,3
EN 301 I 90 GF 1,5M EN 301 I 90 GP 0,6M EN 301 I 90 GP 0,3S EN 301 I 90 FJ 0,1M EN 301 I 90 FJ 0,1S EN 301 I 70 FJ 0,1M EN 301 I 70 FJ 0,1S EN 301 II 50 GP 0,6M EN 301 II 50 GP 0,3S EN 301 II 50 FJ 0,1M EN 301 II 50 FJ 0,1S	Gap filling[d] General purpose General purpose Finger joint Finger joint Finger joint Finger joint General purpose General purpose Finger joint Finger joint	90 90 90 90 90 70 70 b b b b	2,0 1,0 1,0 0,3 0,3 0,3 0,3 1,0 1,0 0,3 0,3	1,5 0,6[d] 0,3 0,1 0,1 0,1 0,1 0,6[d] 0,3 0,1 0,1	1, 2, 3 1, 2, 3 1, 2, 3 1, 2, 3 1, 2, 3 1, 2, 3 1, 2, 3 1 1 1 1

[a] The application of the adhesive types in the different service classes can be restricted by national regulations applicable at the end use site of the bonded timber structures.

EPI - adhesive classes (EN 16254:2016)

EPI = Emulsion polymerized isocyanate

adhesive type designation	application	test temperature[a)]	glue line thickness mm		service classes
			test	use	
EN 16254 I 70 0,3	**normal use** general purpose	70	0,5	0,3	1,2
	special use				
EN 16254 I 90 0,3	general purpose	90	0,5	0,3	1,2
EN 16254 I 90 0,2	small dimension	90	0,3	0,2	1,2
EN 16254 I 90 0,1	finger joint	90	0,3	0,1	1,2
EN 16254 I 70 0,2	small dimension	70	0,3	0,2	1,2
EN 16254 I 70 0,1	finger joint	70	0,3	0,1	1,2
EN 16254 II 50 0,3	general purpose	50	0,5	0,3	1
EN 16254 II 50 0,2	small dimension	50	0,3	0,2	1
EN 16254 I 50 0,1	finger joint	50	0,3	0,1	1

a) Tested acc. to EN 15416-2 and annex A of EN 16254, A6, A7 und A8

Strength classes for SW from edgewise bending

	Class	C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
Strength properties in N/mm²													
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50
Tension parallel	$f_{t,0,k}$	7,2	8,5	10	11,5	13	14,5	16,5	19	22,5	26	30	33,5
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	24	25	27	29	30
Compression perpendicular	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,5	2,7	2,7	2,8	2,9	3,0
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/mm²													
Mean modulus of elasticity parallel bending	$E_{m,0,mean}$	7,0	8,0	9,0	9,5	10,0	11,0	11,5	12,0	13,0	14,0	15,0	16,0
5 percentile modulus of elasticity parallel bending	$E_{m,0,k}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,1	10,7
Mean modulus of elasticity perpendicular	$E_{m,90,mean}$	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	0,50	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00
Density in kg/m³													
5 percentile density	ρ_k	290	310	320	330	340	350	360	380	390	400	410	430
Mean density	ρ_{mean}	350	370	380	400	410	420	430	460	470	480	490	520

Strength classes for HW from edgewise bending

HWs only

	Class	D18	D24	D27	D30	D35	D40	D45	D50	D55	D60	D65	D70	D75	D80
Strength properties in N/mm²															
Bending	$f_{m,k}$	18	24	27	30	35	40	45	50	55	60	65	70	75	80
Tension parallel	$f_{t,0,k}$	11	14	16	18	21	24	27	30	33	36	39	42	45	48
Tension perpendicular	$f_{t,90,k}$	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6
Compression parallel	$f_{c,0,k}$	18	21	22	24	25	27	29	30	32	33	35	36	37	38
Compression perpendicular	$f_{c,90,k}$	4,8	4,9	5,1	5,3	5,4	5,5	5,8	6,2	6,6	10,5	11,3	12,0	12,8	13,5
Shear	$f_{v,k}$	3,5	3,7	3,8	3,9	4,1	4,2	4,4	4,5	4,7	4,8	5,0	5,0	5,0	5,0
Stiffness properties in kN/mm²															
Mean modulus of elasticity parallel bending	$E_{m,0,mean}$	9,5	10,0	10,5	11,0	12,0	13,0	13,5	14,0	15,5	17,0	18,5	20,0	22,0	24,0
5 percentile modulus of elasticity parallel bending	$E_{m,0,k}$	8,0	8,4	8,8	9,2	10,1	10,9	11,3	11,8	13,0	14,3	15,5	16,8	18,5	20,2
Mean modulus of elasticity perpendicular	$E_{m,90,mean}$	0,63	0,67	0,70	0,73	0,80	0,87	0,90	0,93	1,03	1,13	1,23	1,33	1,47	1,60
Mean shear modulus	G_{mean}	0,59	0,63	0,66	0,69	0,75	0,81	0,84	0,88	0,97	1,06	1,16	1,25	1,38	1,50
Density in kg/m³															
5 percentile density	ρ_k	475	485	510	530	540	550	580	620	660	700	750	800	850	900
Mean density	ρ_{mean}	570	580	610	640	650	660	700	740	790	840	900	960	1020	1080

Strength classes for SW from tension tests

	Class	T 8	T 9	T 10	T 11	T 12	T 13	T 14	T 14,5	T 15	T 16	T 18	T 21	T 22	T 24	T 26	T 27	T 28	T 30
Strength properties in N/mm²																			
Bending	$f_{m,k}$	13,5	14,5	16	17	18	19,5	20,5	21	22	23	25,5	29	30,5	33	35	36,5	37,5	40
Tension parallel	$f_{t,0,k}$	8	9	10	11	12	13	14	14,5	15	16	18	21	22	24	26	27	28	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	0,4	0,4	0,4	0,4	0,4	0,4
Compression parallel	$f_{c,0,k}$	16	17	17	18	19	20	21	21	21	22	23	25	26	27	28	29	29	30
Compression perpendicular	$f_{c,90,k}$	2,0	2,1	2,2	2,2	2,3	2,4	2,5	2,5	2,5	2,6	2,7	2,7	2,7	2,8	2,9	2,9	2,9	3,0
Shear	$f_{v,k}$	2,8	3,0	3,2	3,4	3,6	3,8	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Stiffness properties in kN/mm²																			
Mean modulus of elasticity parallel tension	$E_{t,0,mean}$	7,0	7,5	8,0	9,0	9,5	10,0	11,0	11,0	11,5	11,5	12,0	13,0	13,0	13,5	14,0	15,0	15,0	15,5
5 percentile modulus of elasticity parallel tension	$E_{t,0,k}$	4,7	5,0	5,4	6,0	6,4	6,7	7,4	7,4	7,7	7,7	8,0	8,7	8,7	9,0	9,4	10,1	10,1	10,4
Mean modulus of elasticity perpendicular	$E_{t,90,mean}$	0,23	0,25	0,27	0,30	0,32	0,33	0,37	0,37	0,38	0,38	0,40	0,43	0,43	0,45	0,47	0,50	0,50	0,52
Mean shear modulus	G_{mean}	0,44	0,47	0,50	0,56	0,59	0,63	0,69	0,69	0,72	0,72	0,75	0,81	0,81	0,84	0,88	0,94	0,94	0,97
Density in kg/m³																			
5 percentile density	ρ_k	290	300	310	320	330	340	350	350	360	370	380	390	390	400	410	410	420	430
Mean density	ρ_{mean}	350	360	370	380	400	410	420	420	430	440	460	470	470	480	490	490	500	520

Build-up of homogeneous SW-GLT classes

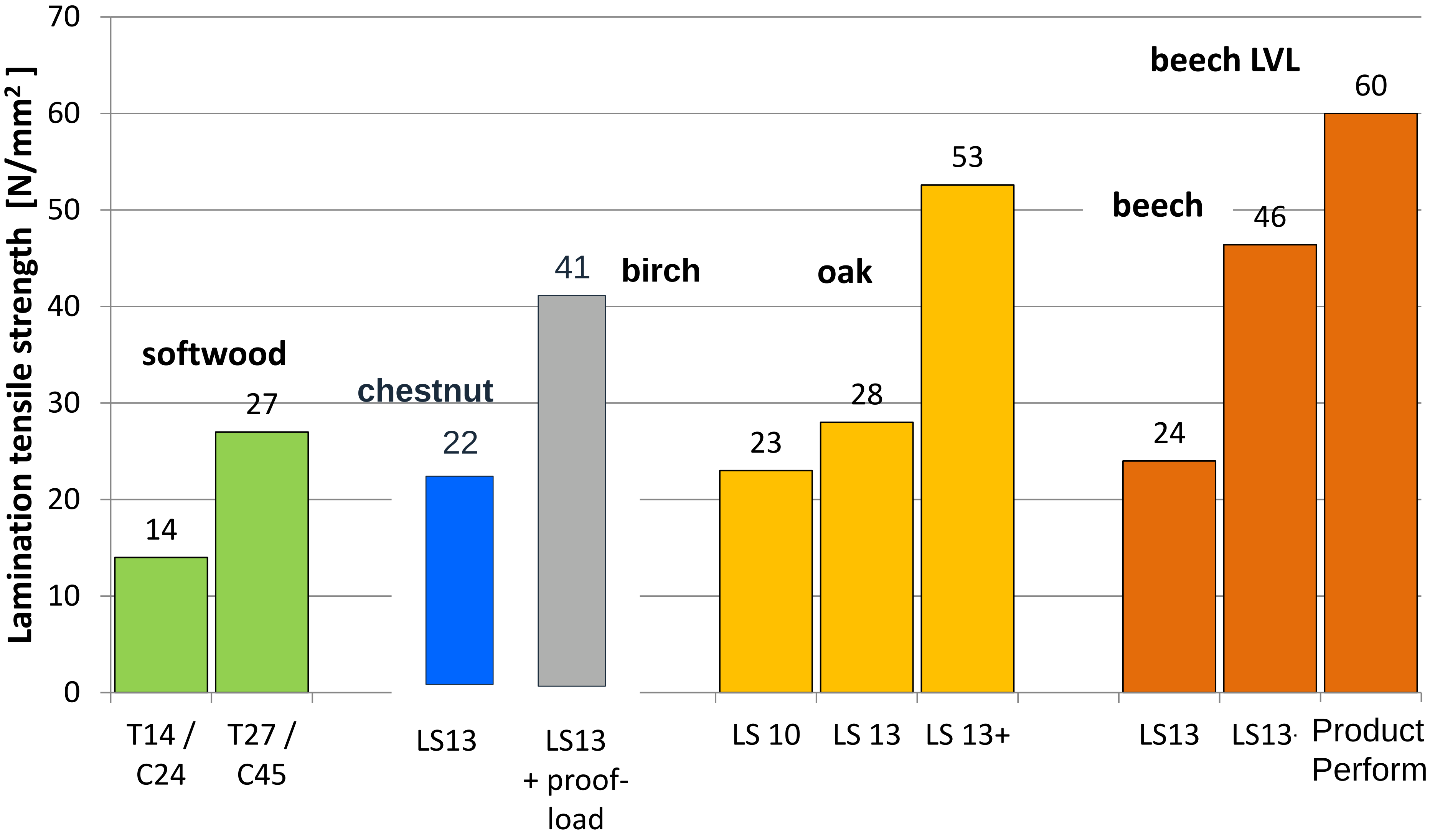
EN 14080

Strength class of GLT	Lamination strength class	Required 5%quantile of finger joint bending strength
GL 20h	T10	25
GL 20h	T11	22
GL 22h	T13	25
GL 24h	T14	30
GL 26h	T16	33
GL 28h	T18	36
GL 30h	T21	38
GL 30h	T22	37
GL 32h	T24	41
GL 32h	T26	38

Build-up of inhomogeneous SW-GLT classes

Glued laminated timber	Outer zones of laminations			Intermediate zones of laminations			Inner zone of laminations		
Strength class	Strength class	Propor-tion [%]	$f_{m,j,k}$ [N/mm^2]	Strength class	Propor-tion [%]	$f_{m,j,k}$ [N/mm^2]	Strength class[a]	Propor-tion [%]	$f_{m,j,k}$ [N/mm^2]
GL 20c	T13	2x33	21	-	-	-	T8	34	18
GL 22c	T13	2x33	26	-	-	-	T8	34	18
GL 24c	T14	2x33	31	-	-	-	T9	34	19
GL 26c	T16	2x33	34	-	-	-	T11	34	22
GL 28c	T18	2x25	37	-	-	-	T14	50	28
GL 28c	T21	2x17	36	-	-	-	T14	66	26
GL 28c	T21	2x17	38	-	-	-	T13	66	25
GL 28c	T21	2x25	35	-	-	-	T11	50	22
GL 28c	T21	2x20	35	T14	2x20	28	T11	20	22
GL 28c	T22	2x20	35	-	-	-	T13	60	25
GL 30c	T22	2x17	40	-	-	-	T15	66	27
GL 30c	T22	2x17	41	-	-	-	T14	66	28
GL 30c	T22	2x20	40	T14	2x20	30	T11	20	22
GL 30c	T22	2x17	42	T14	2x23	31	T11	20	22
GL 32c	T24	2x17	44	-	-	-	T18	66	31
GL 32c	T26	2x17	45	-	-	-	T14	66	26
GL 32c	T26	2x10	48	T18	2x20	32	T11	40	22

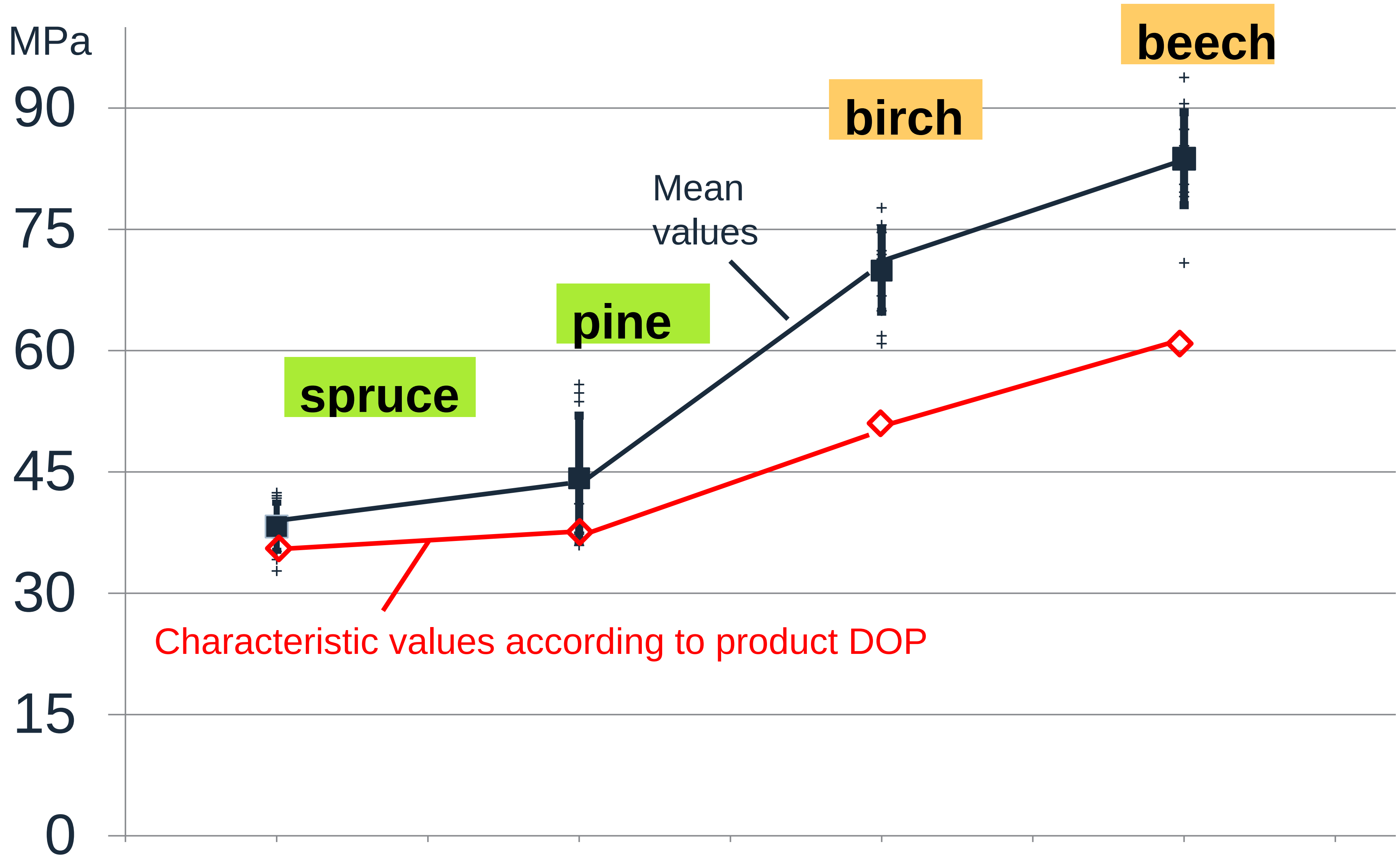
Tensile strength of European HW laminations



LVL properties - SW and HW

LVL		characteristic tensile strength parallel to fiber	mean MOE parallel to fiber	characteristic density
species	producer			
-	-	[MPa]	[MPa]	[kg/m³]
spruce	Metsä Wood	35	13800	480
pine	Steico	37	15600	550
birch	MLT	52	17500	600
beech	Pollmeier	60	16800	730

Tensile strength of LVL laminations (unjointed)

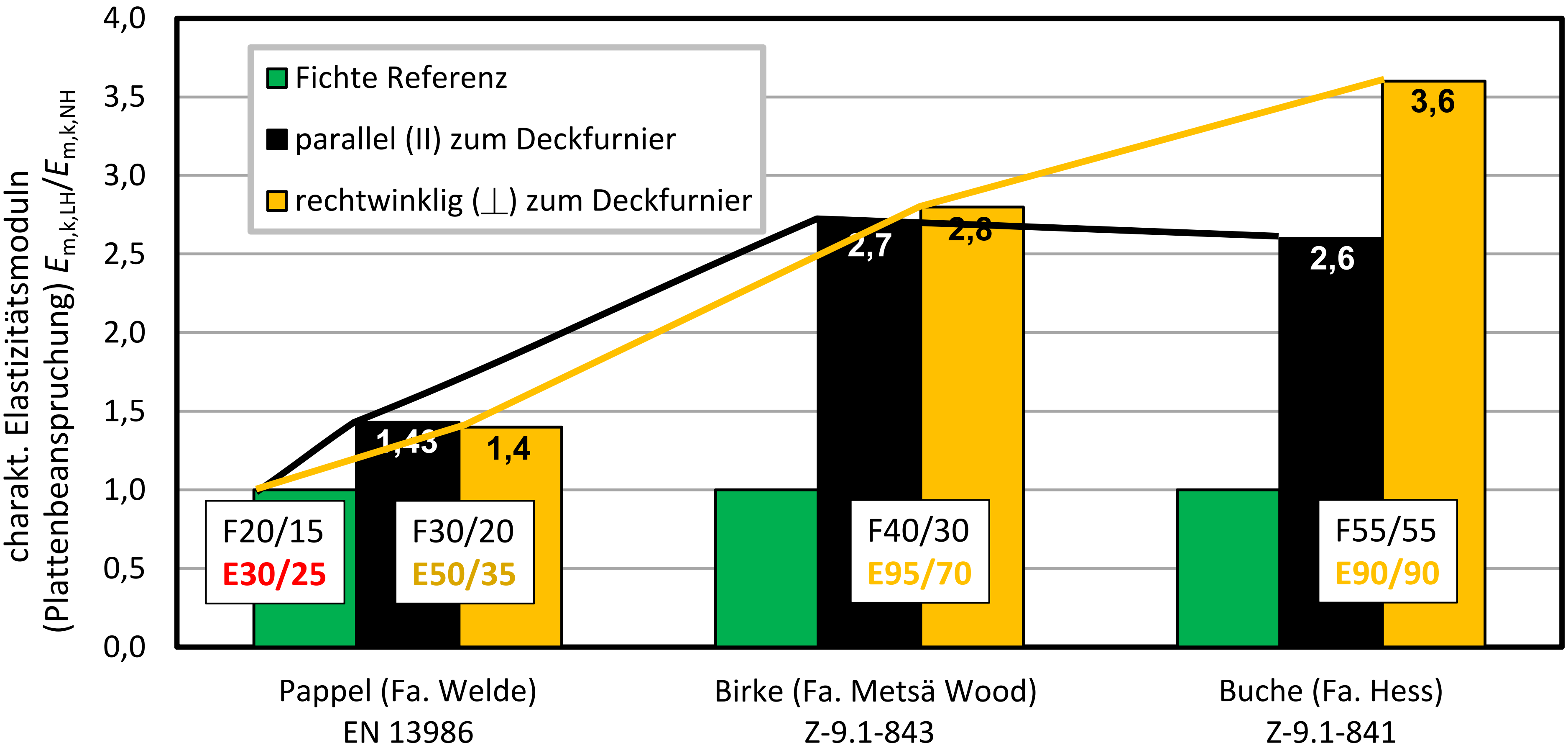


SW-GLT enhanced by (HW-) LVL laminations

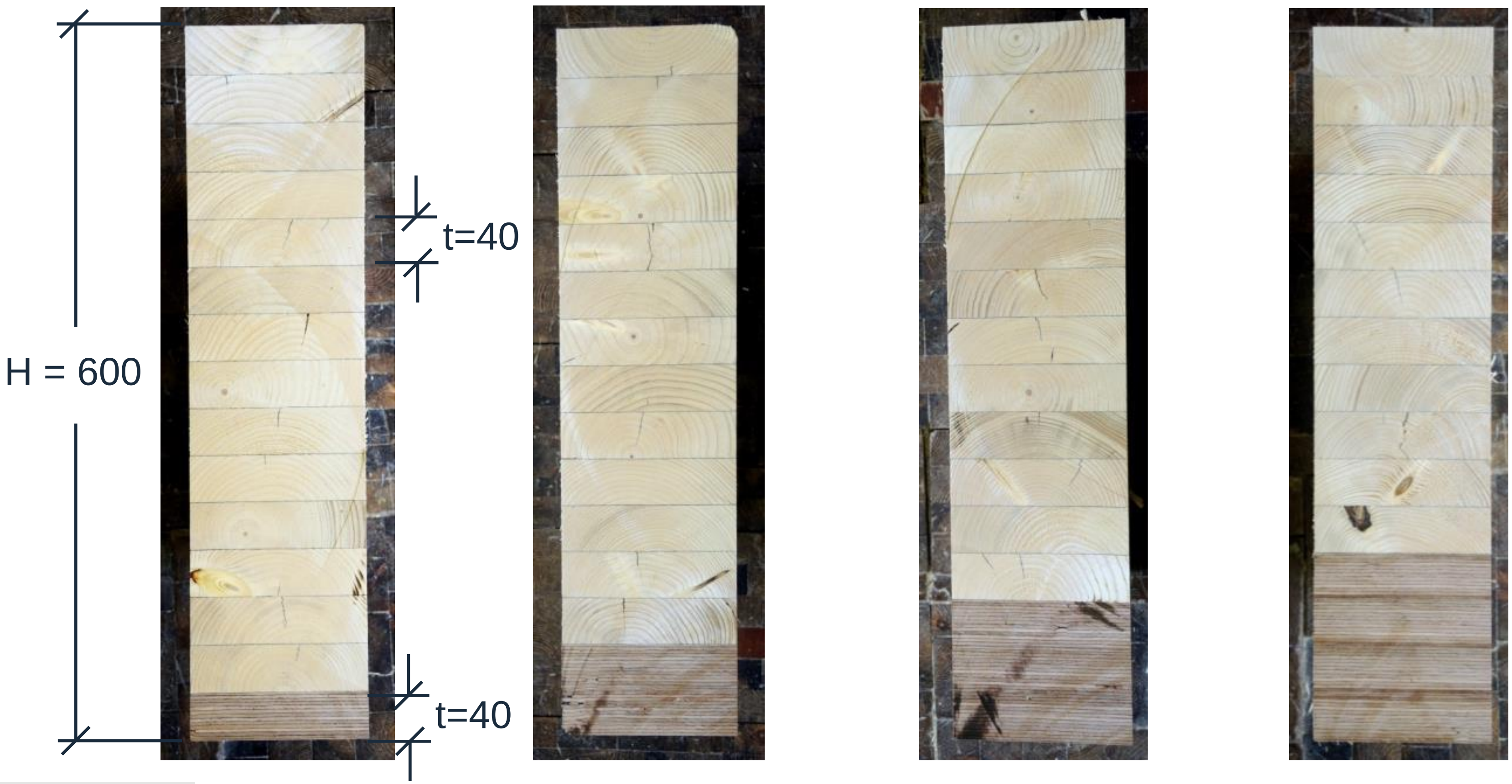
SW-lamination limits: T22 to max. T30

LVL-lamination limits: T35 to T60 and more

Stiffness and strength potential of HW plywood



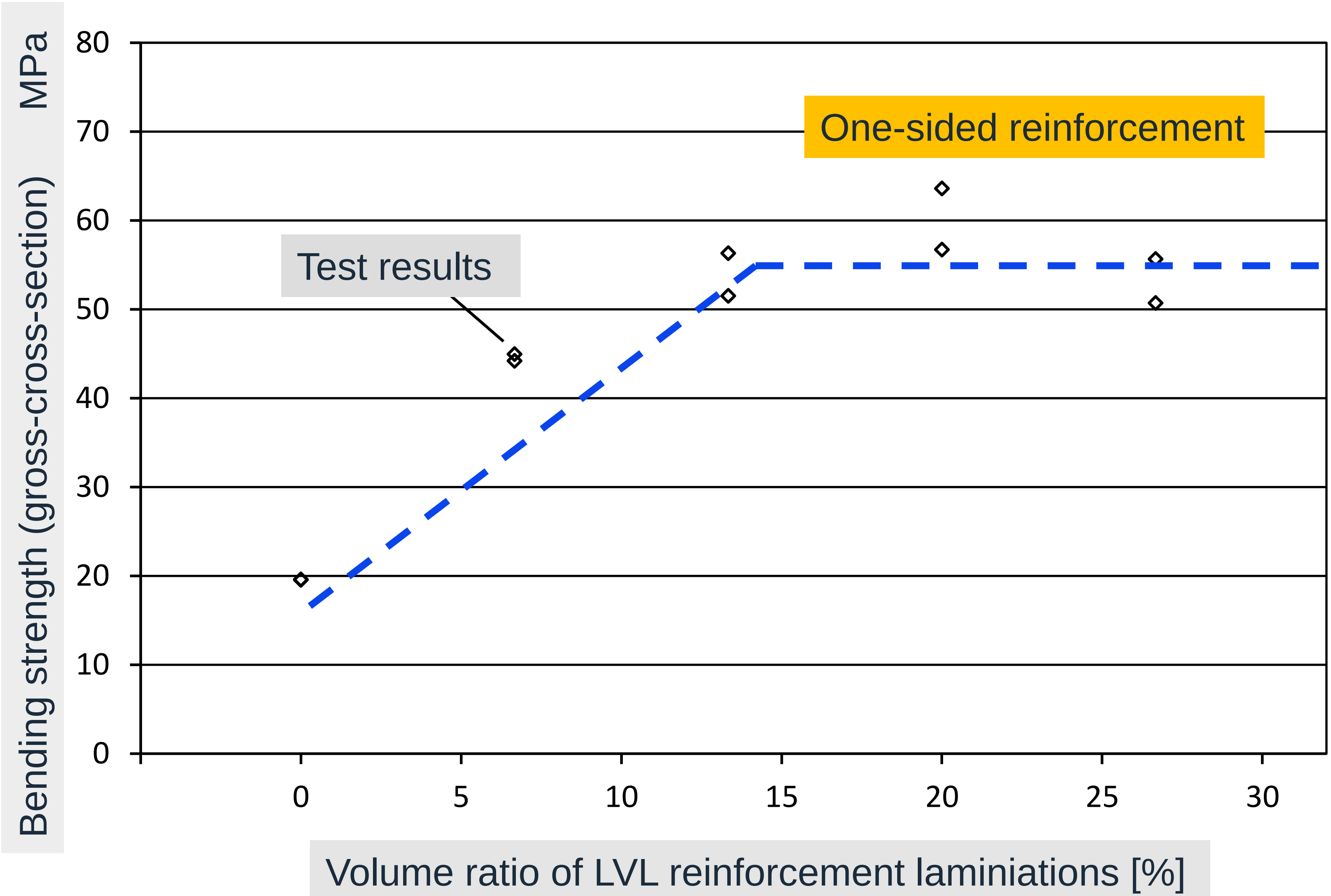
One-sided HW-LVL substitution of SW GL 24



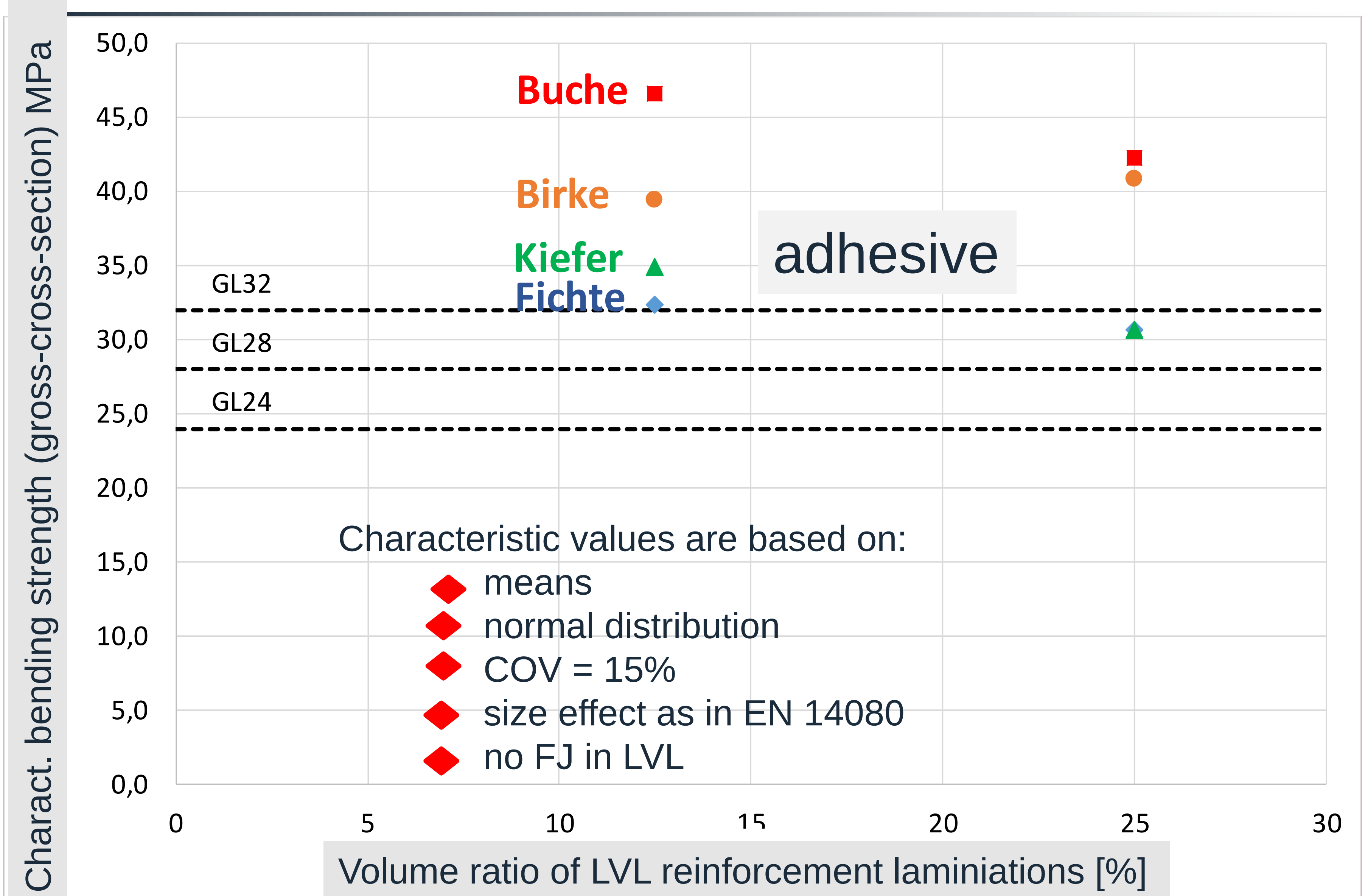
Ratio of beech LVL lams: **6,7%** **13,3%** **20,0%** **26,7%**

Bending compression failure at/beyond 13 % HW LWL ratio

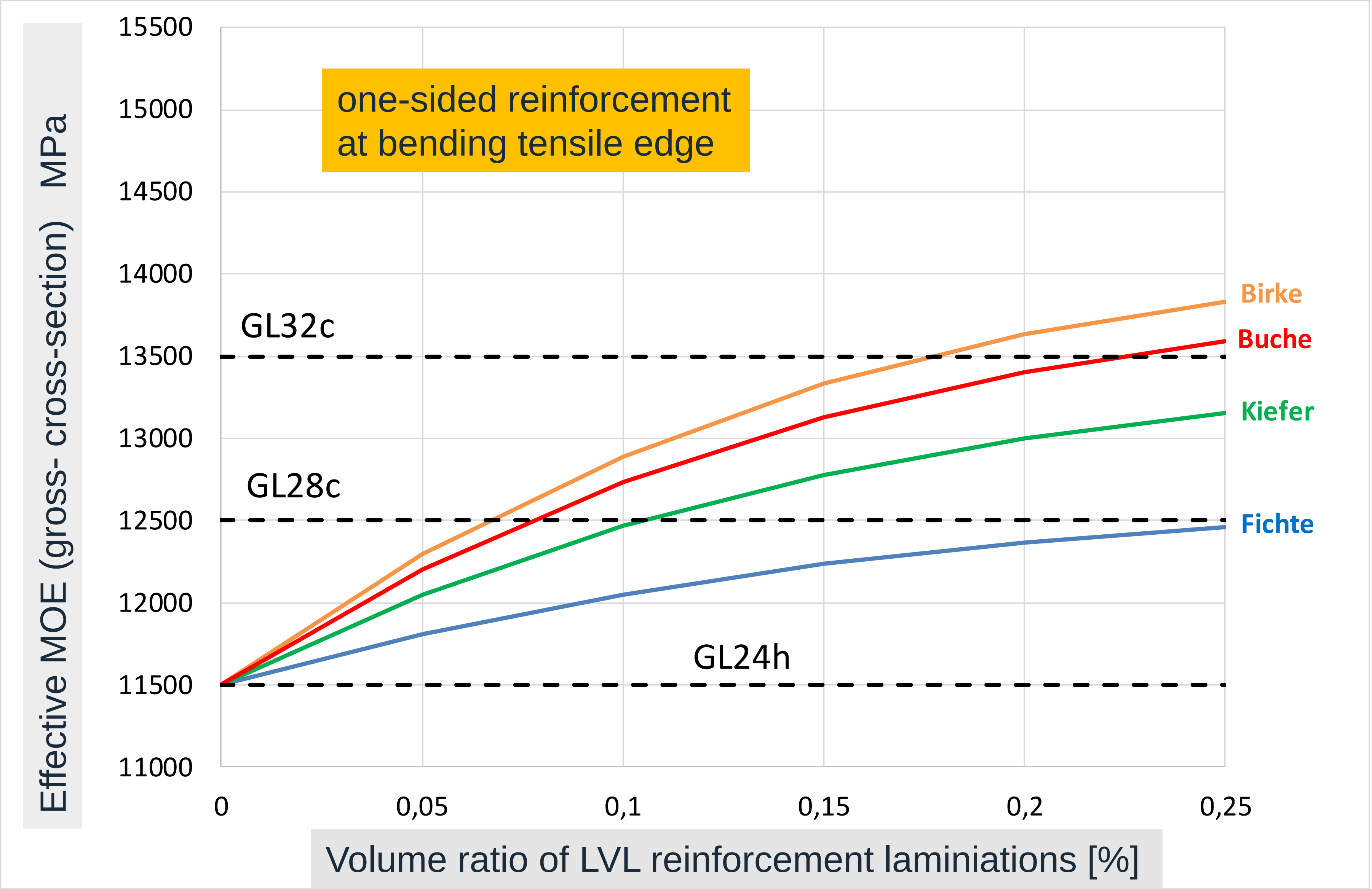
GLT bending strength dependant on HW-LVL ratio



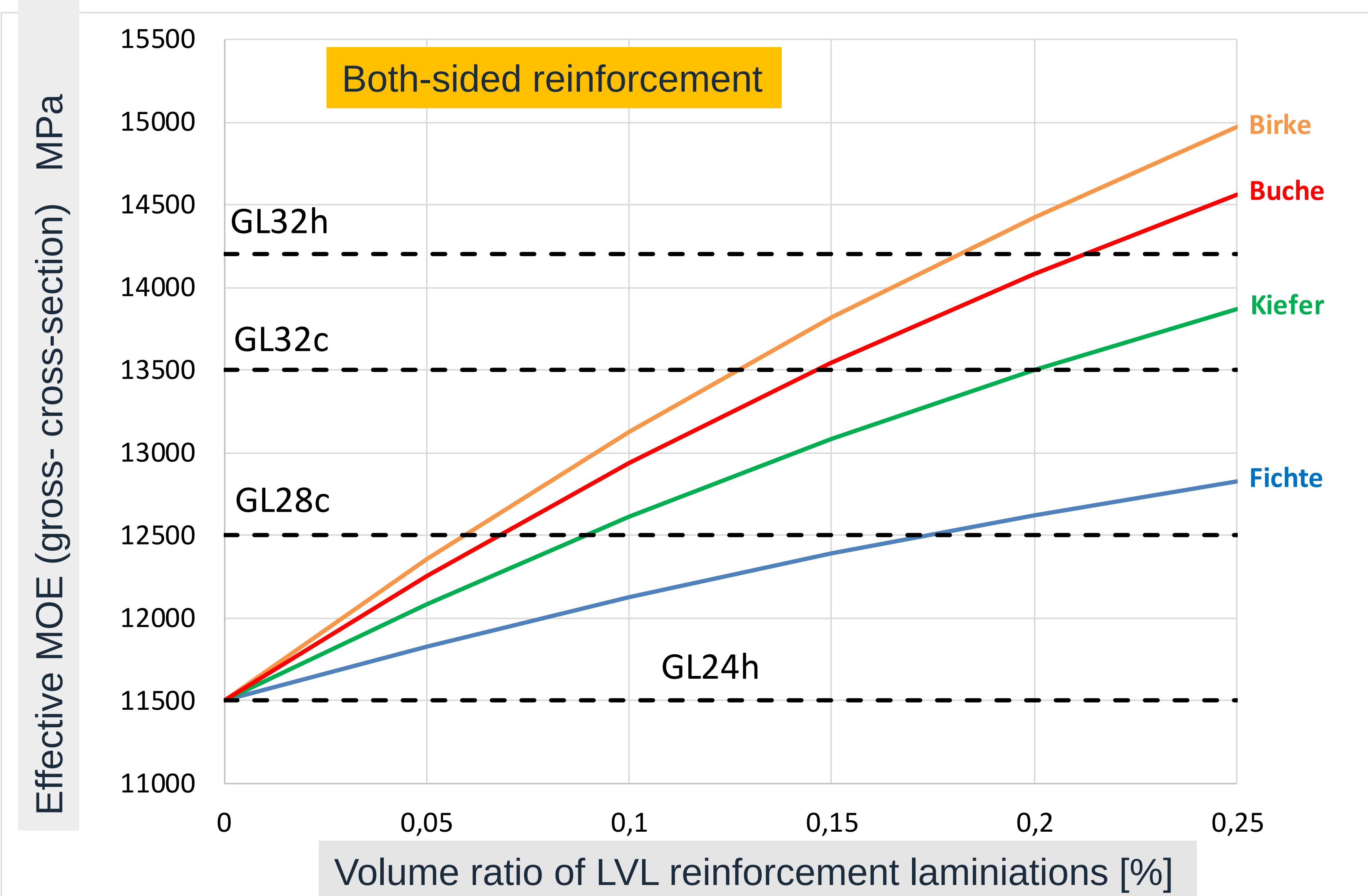
5 %quant. bending strength of LVL reinforced SW-GLT



Effective MOE acc. compound theory



MOE at symmetric LVL- SW-GLT-LVL build-up



Bending strength and MOE of LVL- SW GLT beams

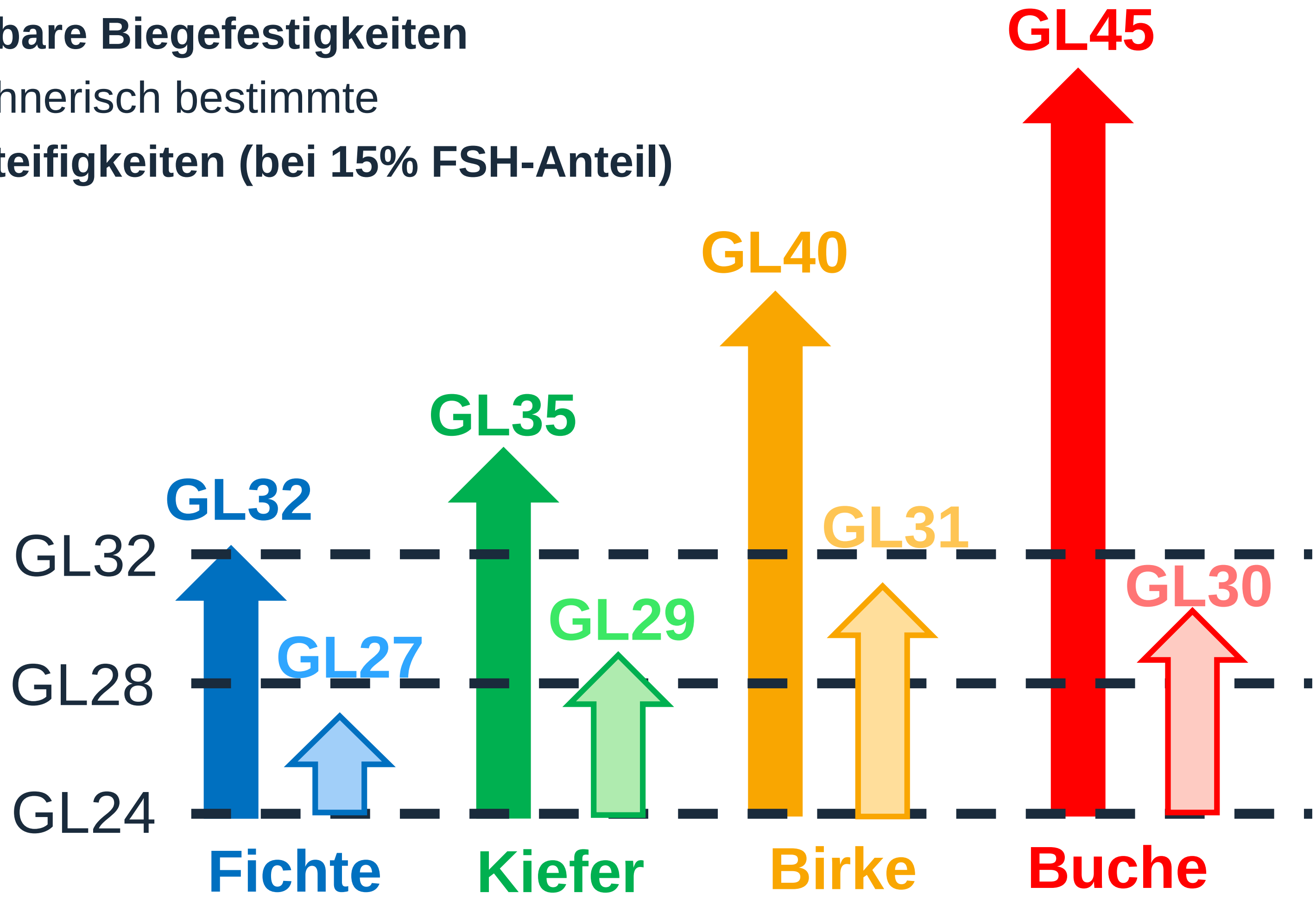
Zwischenergebnis:

Aus den Versuchsergebnissen abgeschätzt:

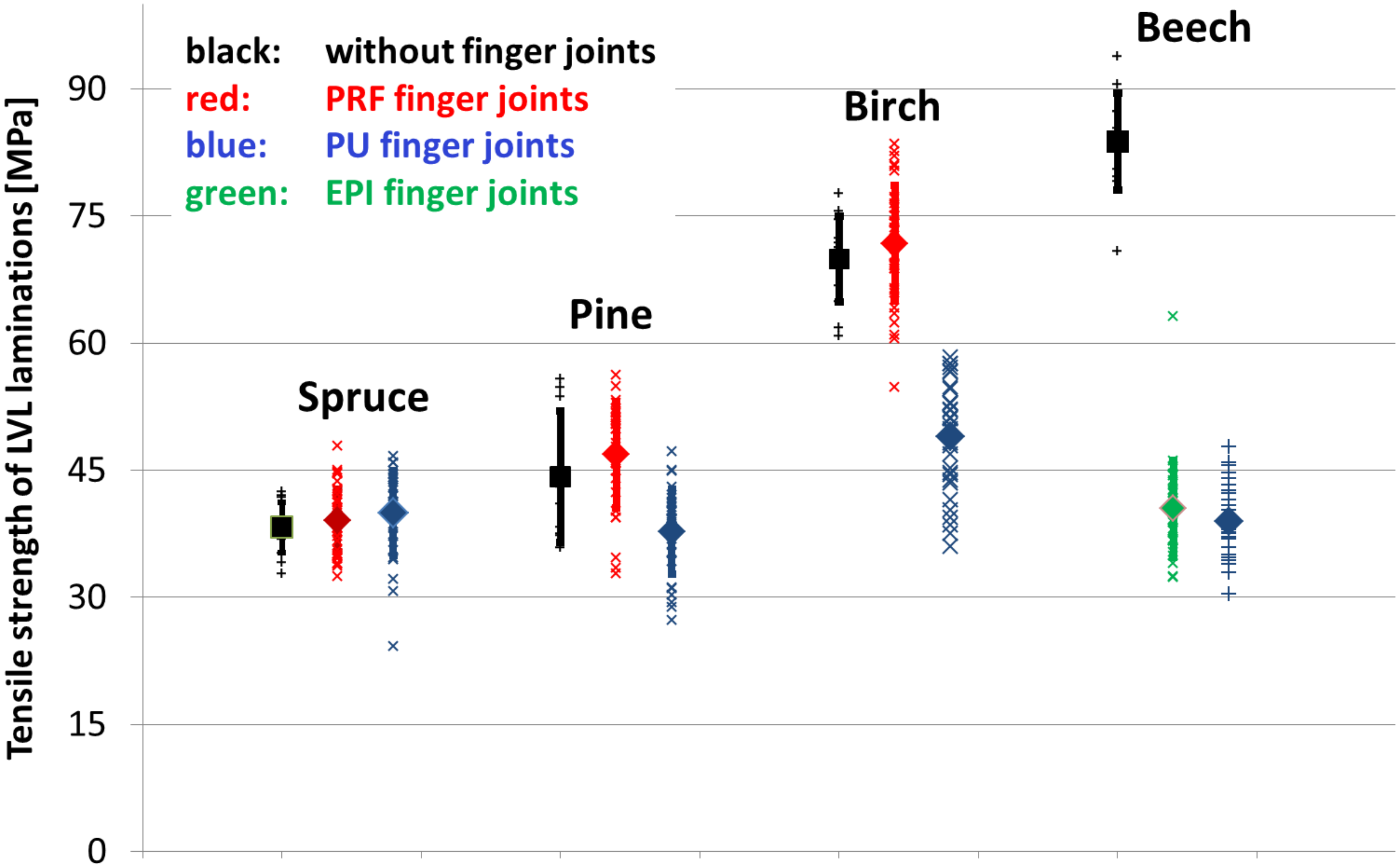
erreichbare Biegefestigkeiten

und rechnerisch bestimmte

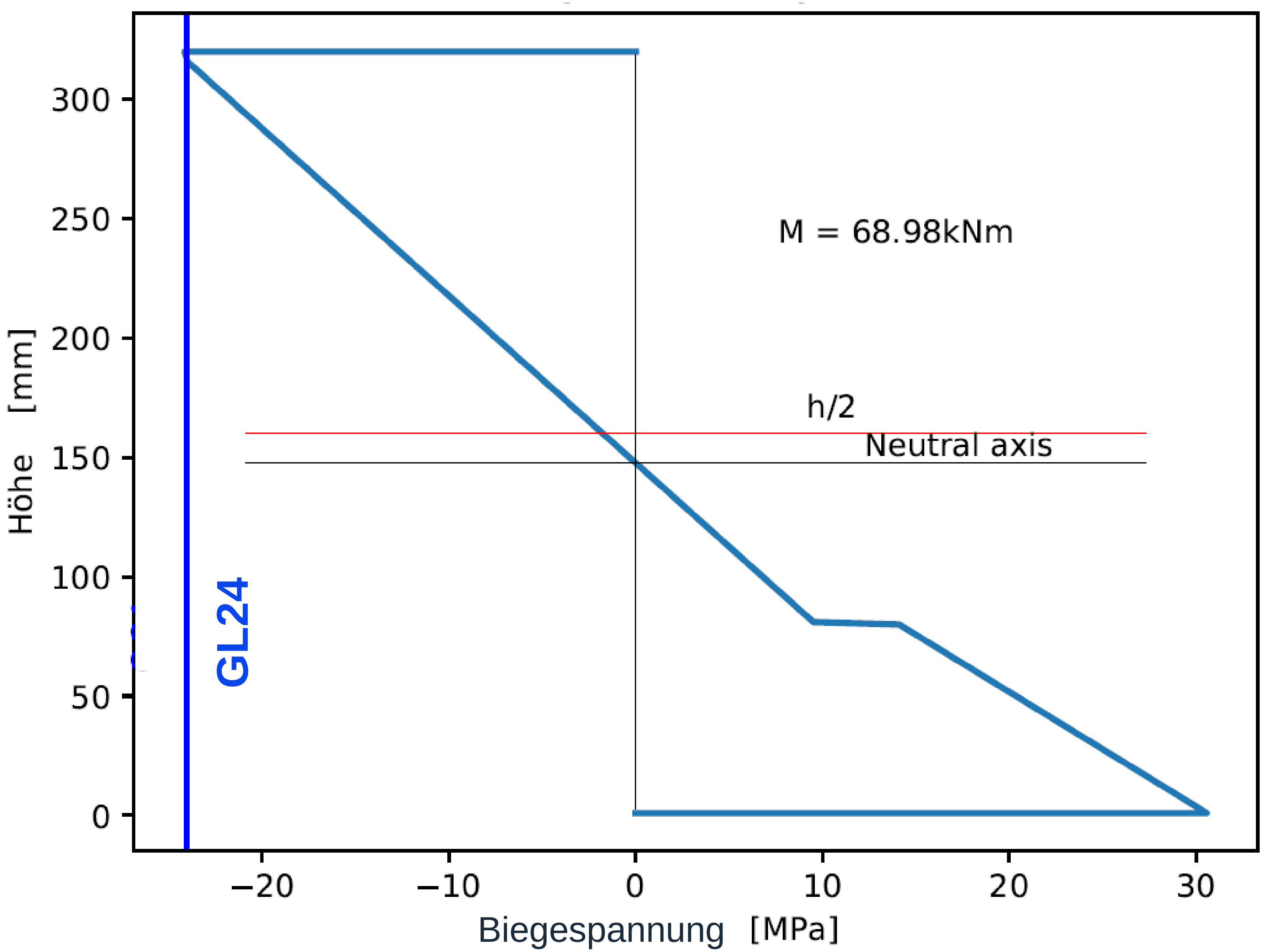
Biegesteifigkeiten (bei 15% FSH-Anteil)



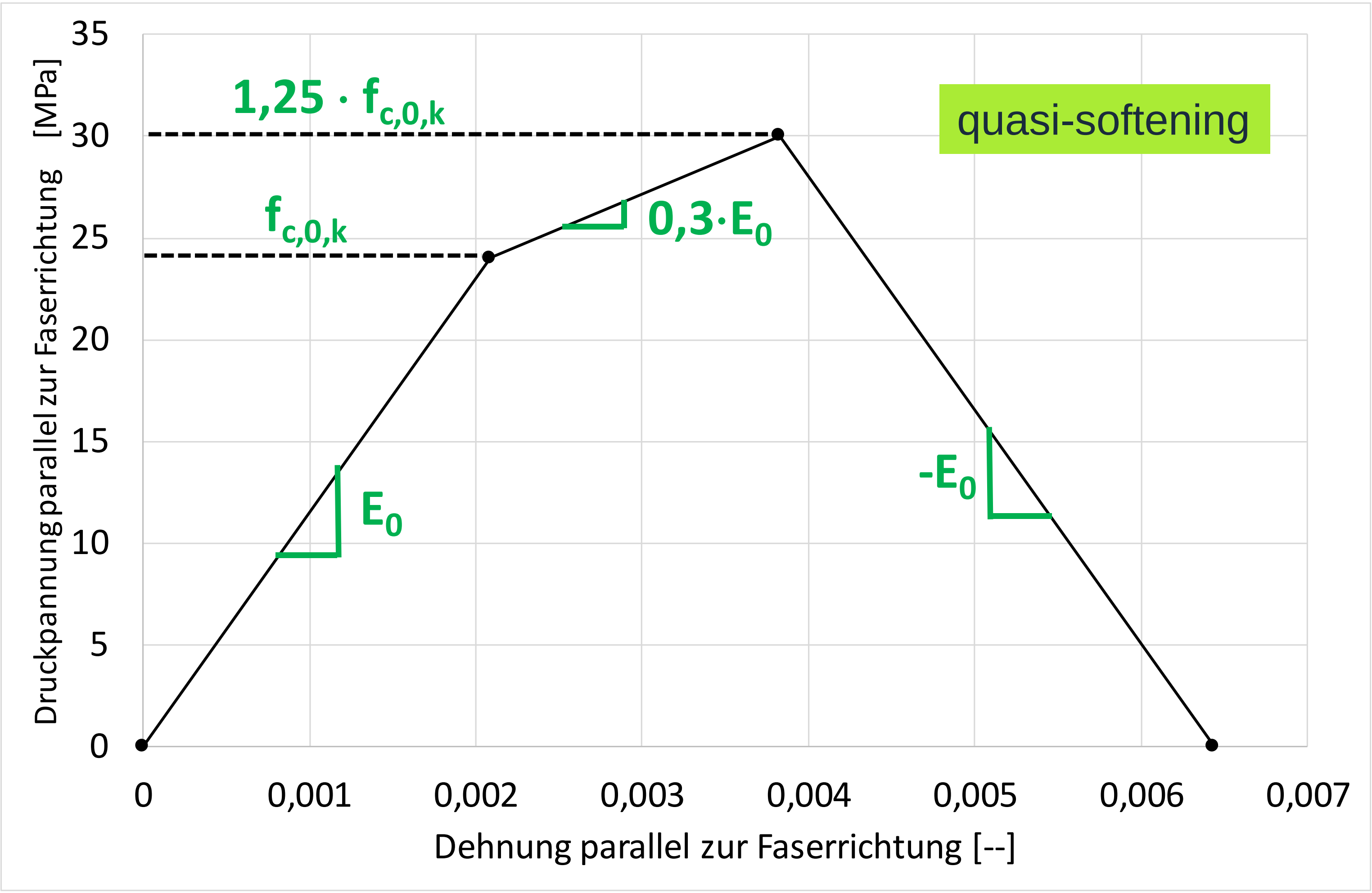
Tensile strength of LVL lams with finger joints



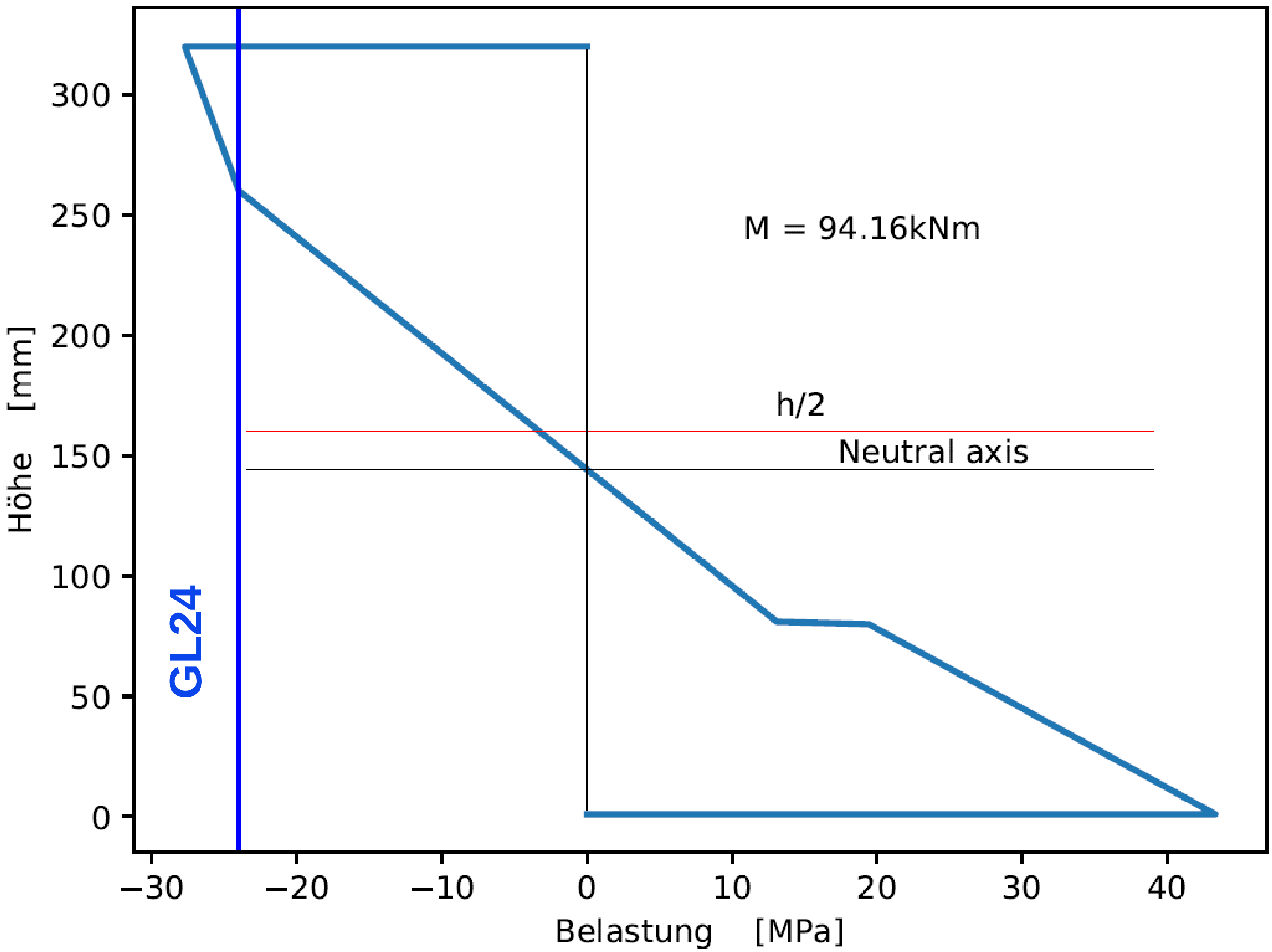
Linear compound theory limit



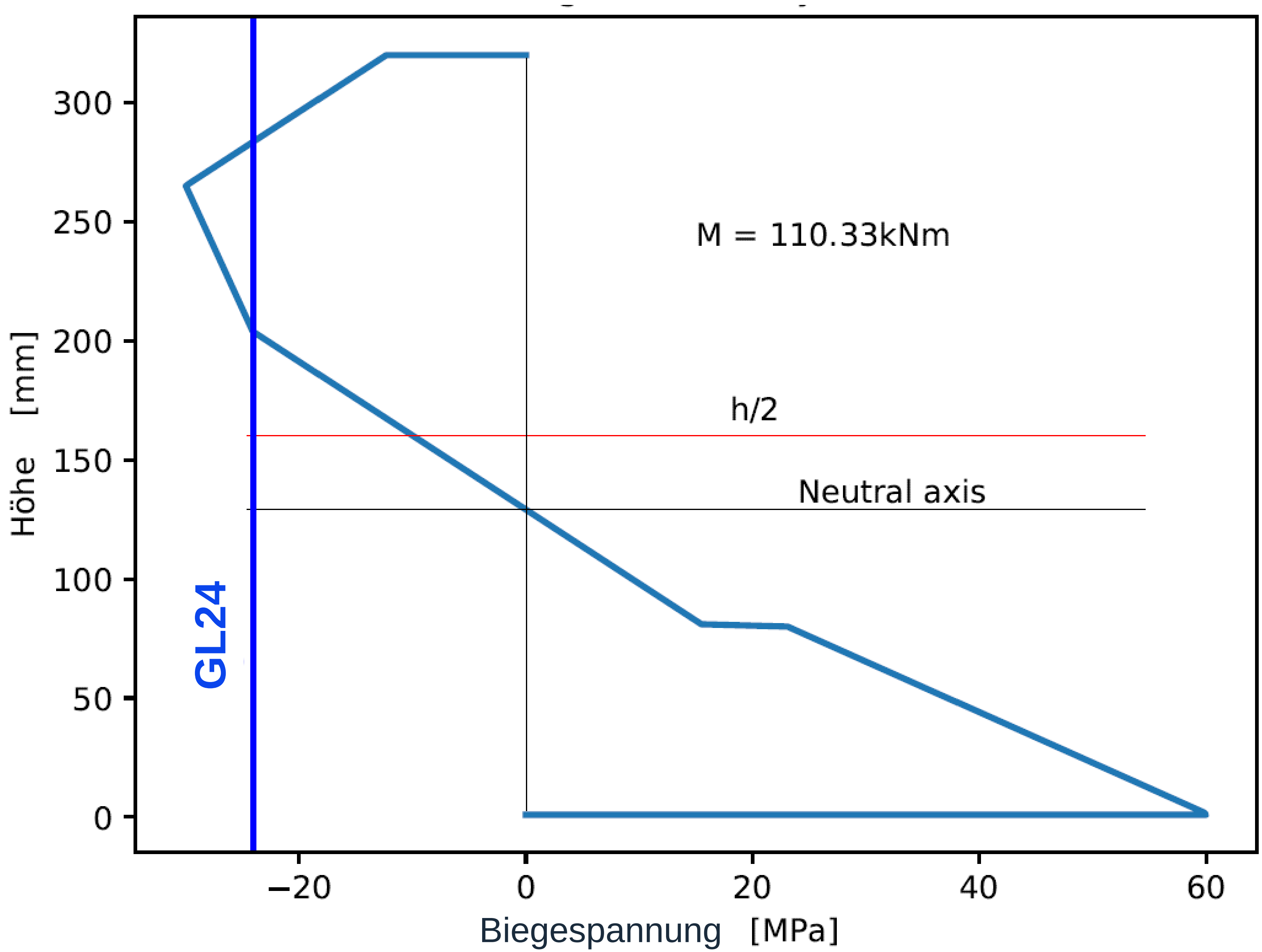
Compressive stress- strain law for SW



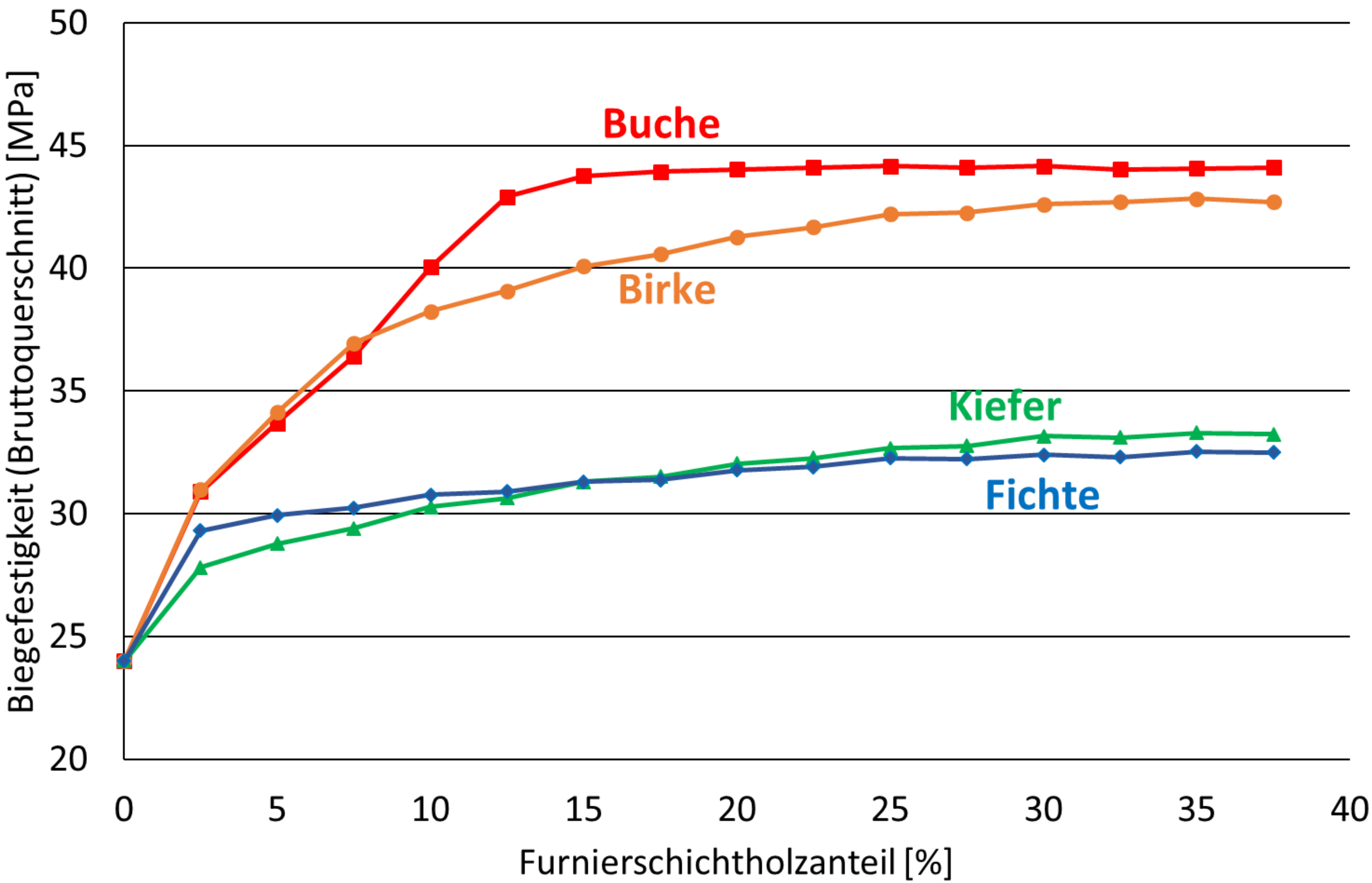
Non-linear compression range (I)



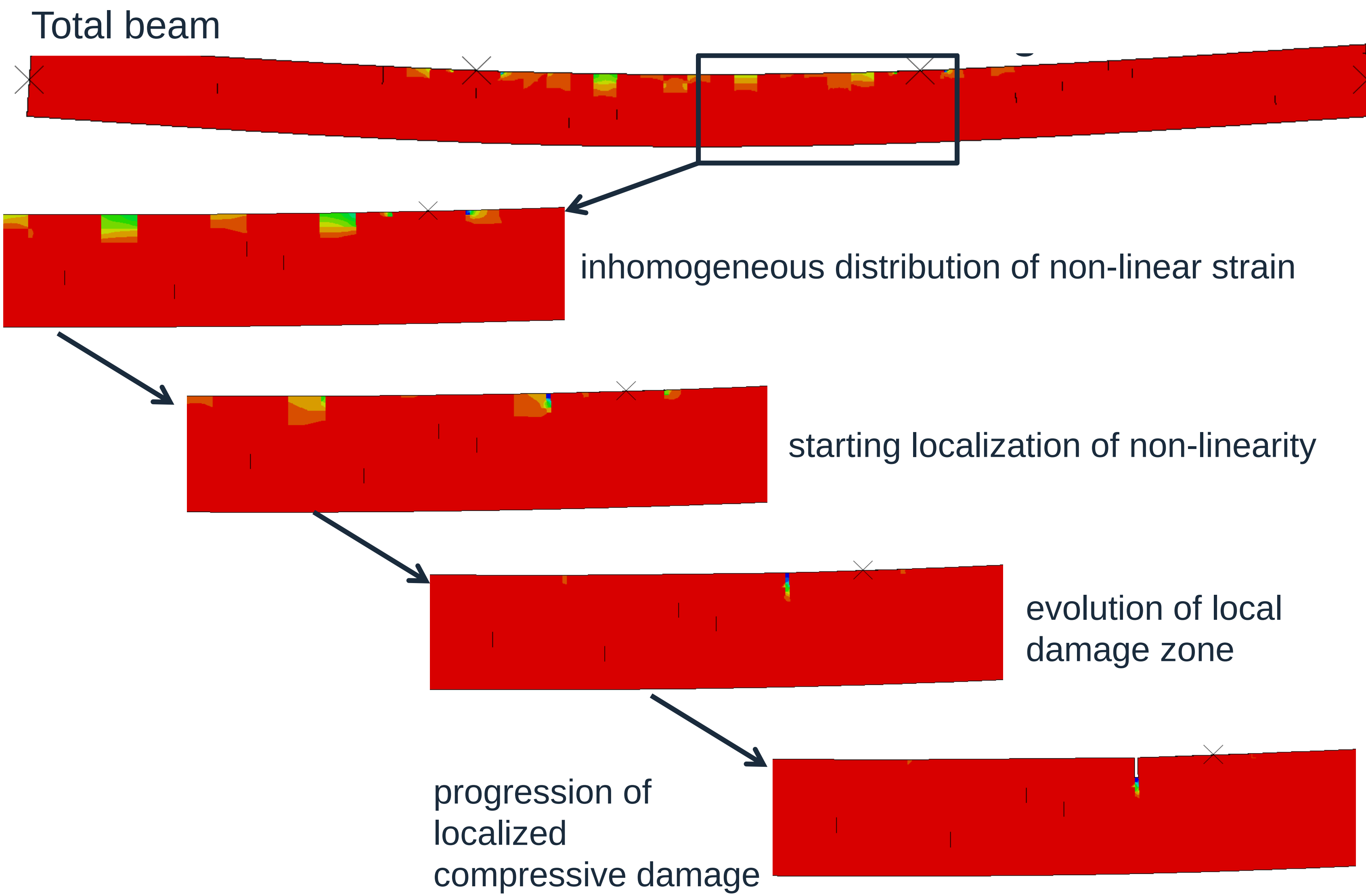
Non-linear compression range (II)



Bending capacity from non-linear compressive law



Stochastic XFEM results of compressive damage



CLT rolling shear failure at support areaa

Close upof SW rolling shear failure

Rolling shear propteries of SW-CLT

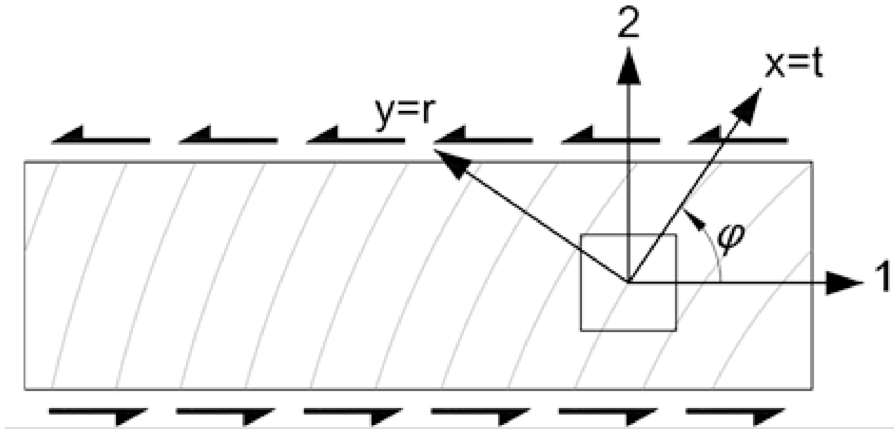
$f_{v,r}$ = 0,7 ….1.,1…. max. 1,4 N/mm²

G_r = 50 ….max. 80 N/mm²

How to increase cross-layer rolling shear properties?!

the solution: CLT cross - layers from beech /birch

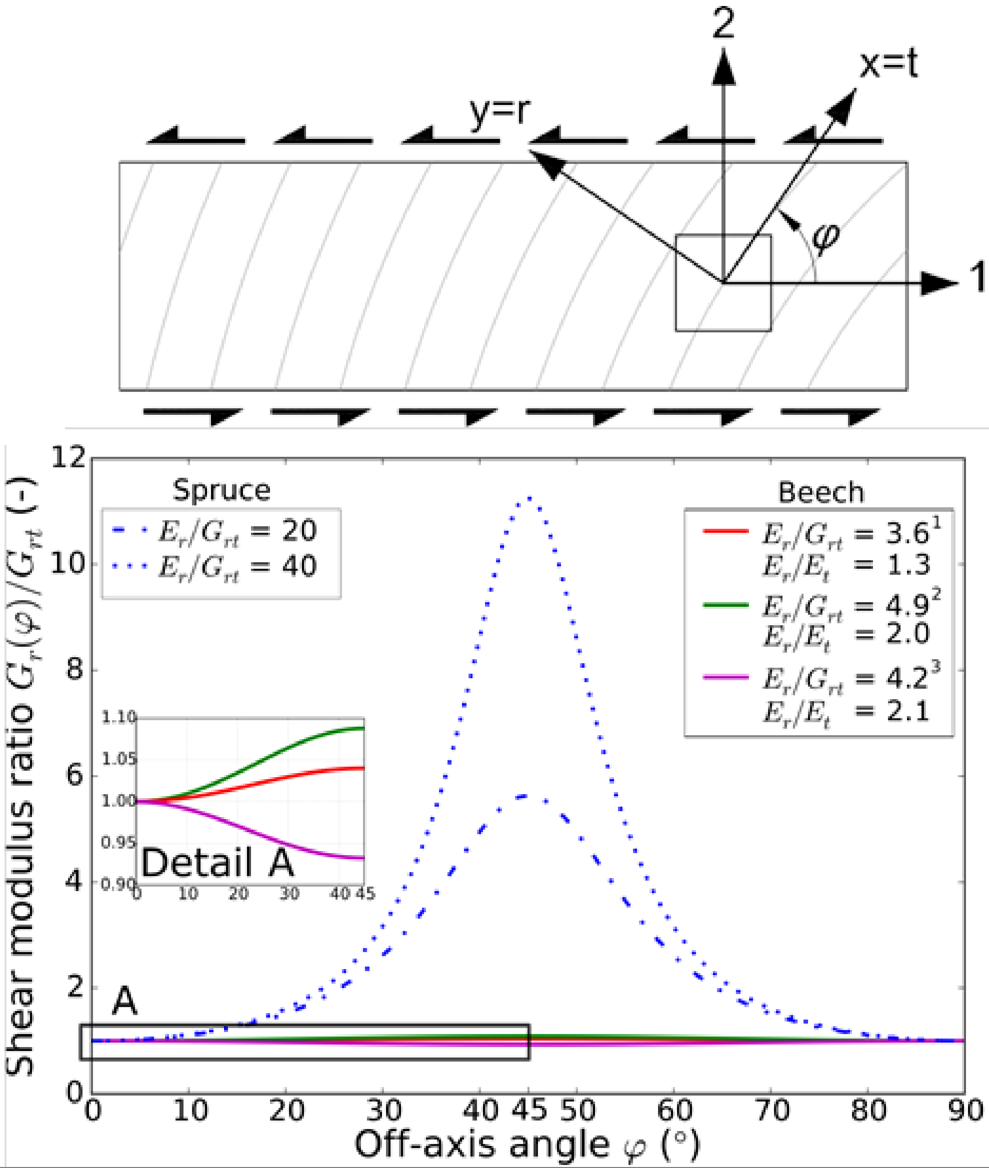
Differences of SW-HW face grain stiffness numbers

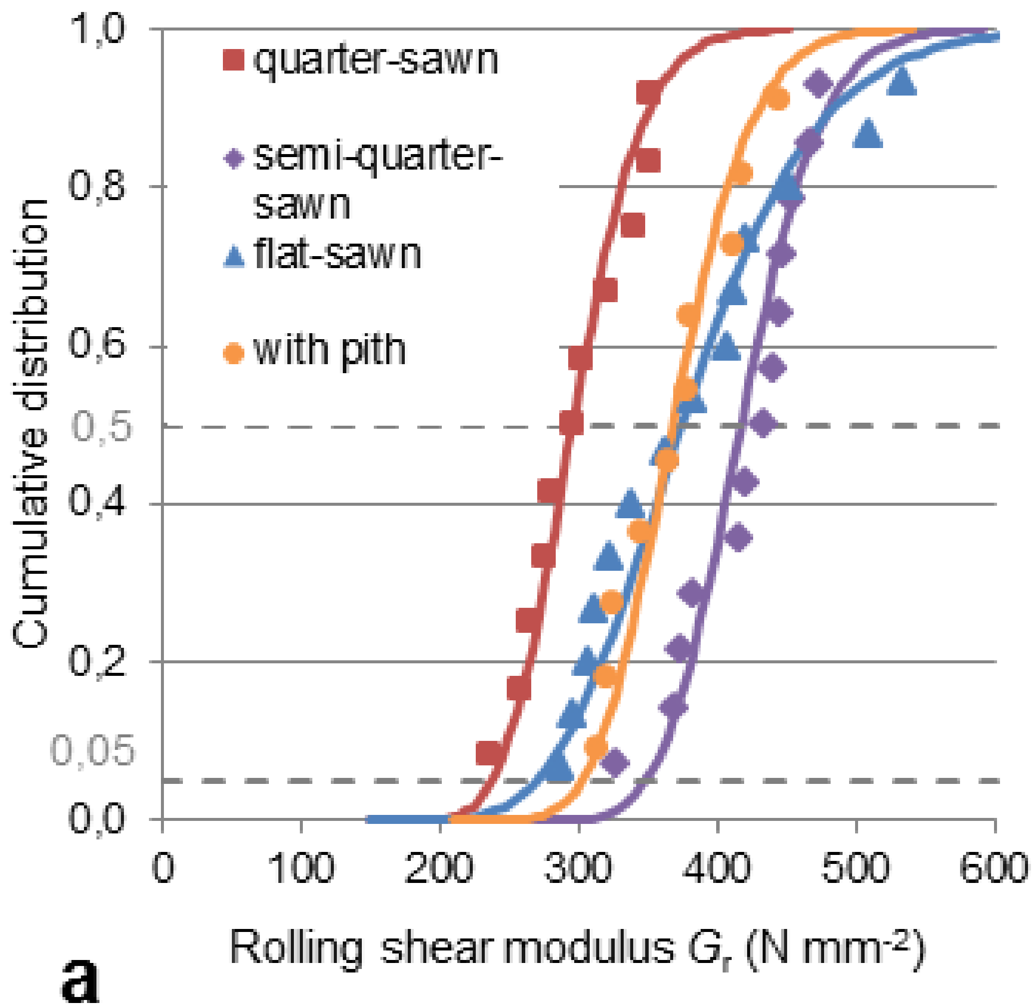


Bound to meso-structural differences

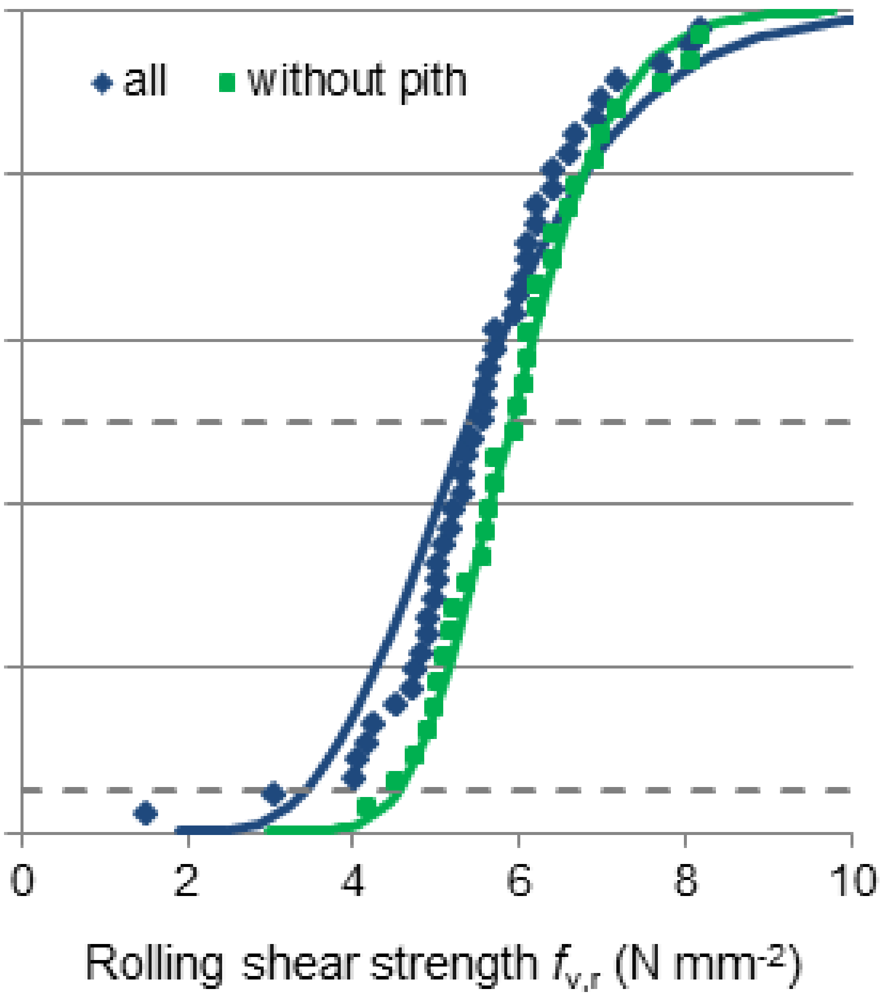
Species	Density ρ_{12} (kg m^{-3})	Modulus of elasticity E_r (N mm^{-2})	E_t (N mm^{-2})	Shear modulus G_{rt} (N mm^{-2})	Poisson's ratio ν_{rt} (-)	ν_{tr} (-)	Stiffness ratio E_r/E_t (-)	E_r/G_{rt} (-)
Beech	760	2280	1160	470	0.38	0.71	2	4.9
	720	1700	1290	470	0.44	0.58	1.3	3.6
	640-690	1580	740	380	0.31	0.61	2.1	4.2
Spruce	540	1451	1024	40	0.34	0.48	1.41	36
	450	1080	800	45	0.37	0.5	1.35	24
	470	-	-	55	-	-	-	-

In-plane shear modulus of spruce vs. beech

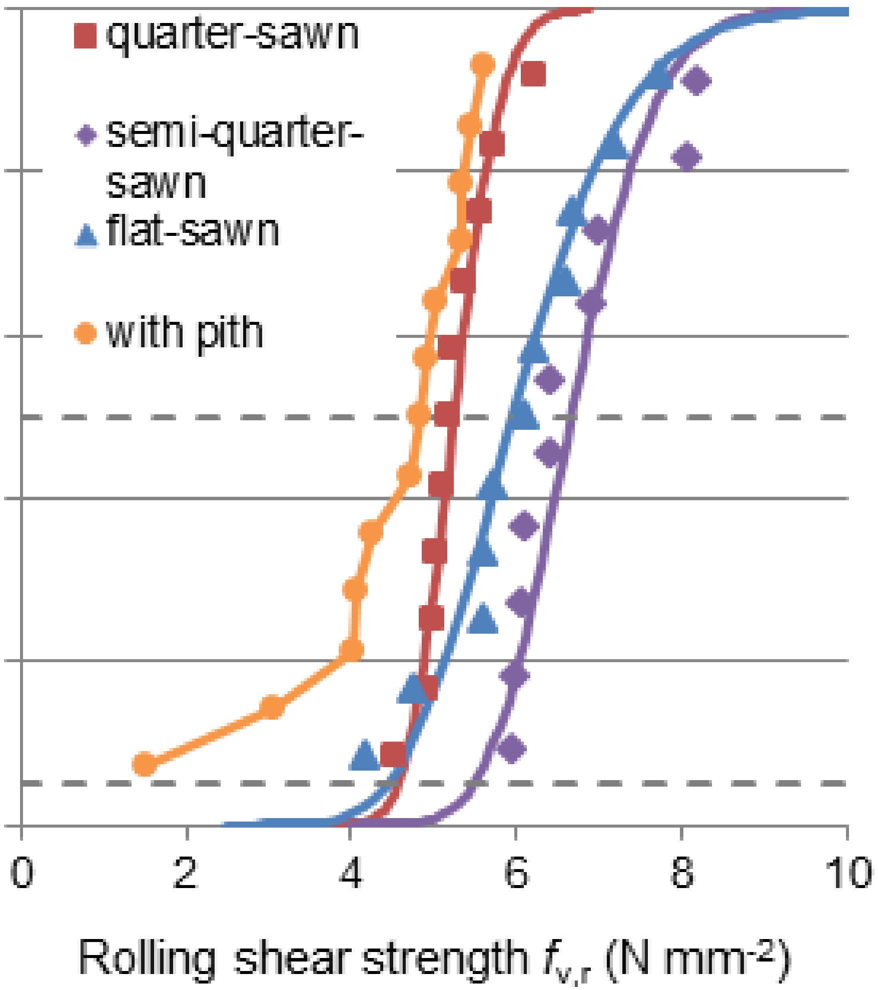




1,0
0,8
0,6
0,5
0,4
0,2
0,05
0,0
quarter-sawn
semi-quarter-sawn
flat-sawn
with pith
Cumulative distribution
0
100
200
300
400
500
600
Rolling shear modulus G_r (N mm^{-2})
a

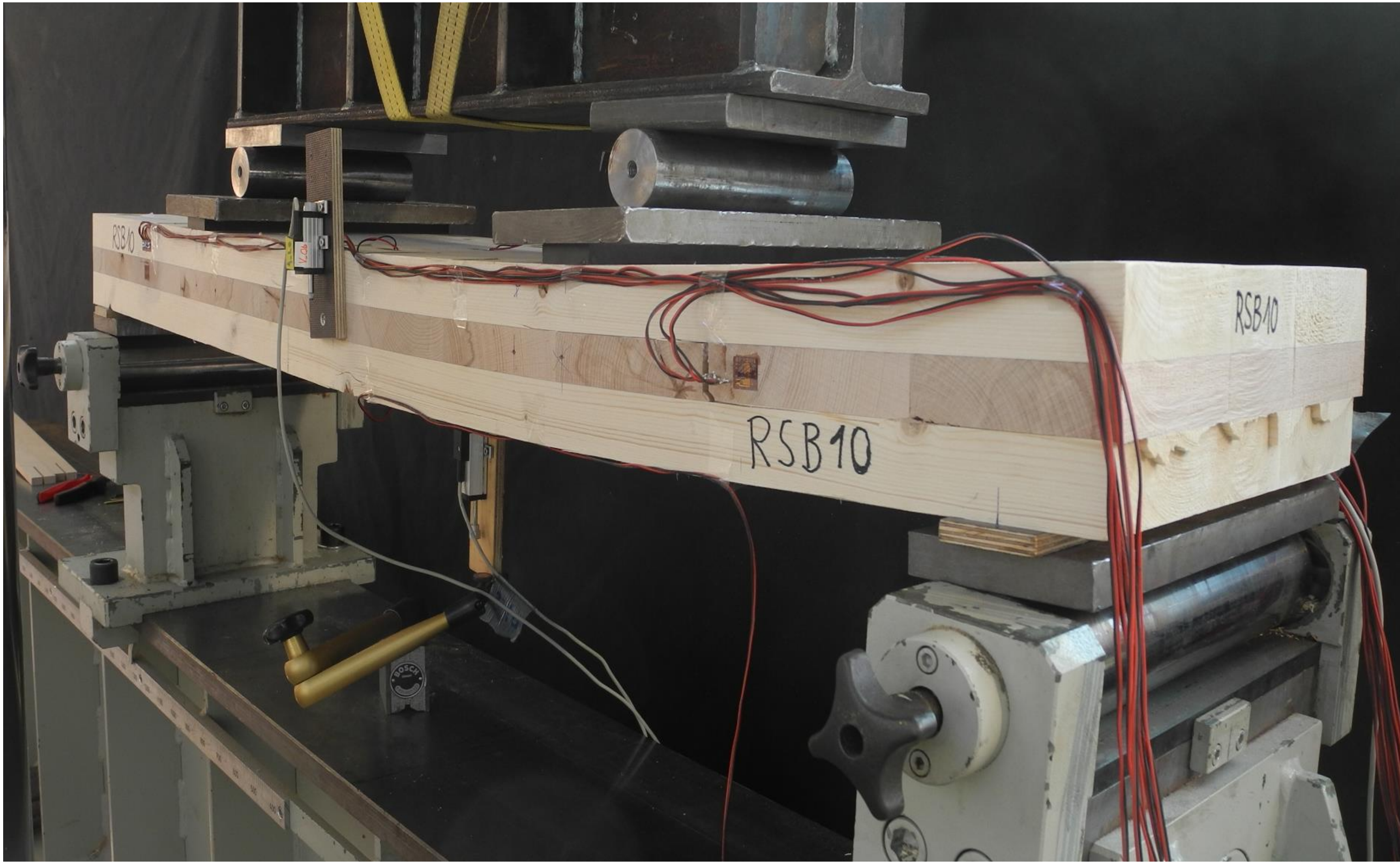


all
without pith
0
2
4
6
8
10
Rolling shear strength $f_{v,r}$ (N mm^{-2})



quarter-sawn
semi-quarter-sawn
flat-sawn
with pith
0
2
4
6
8
10
Rolling shear strength $f_{v,r}$ (N mm^{-2})

Typical hybrid SW- beech CLT rolling shear failure



Typical hybrid SW- beech CLT rolling shear failure

Typical hybrid SW- beech CLT rolling shear failure

Out of plane shear prop. of hybrid SW-beech CLT

MPA STUTTGART

Rolling shear modulus G_r [N/mm²]

Bending shear:	$G_{r,strain}$	419
	$G_{r,def,E0,def}$	349
	$G_{r,def,E0,strain}$	250
2-plate shear:	$G_{r,2\text{-}plate}$	370

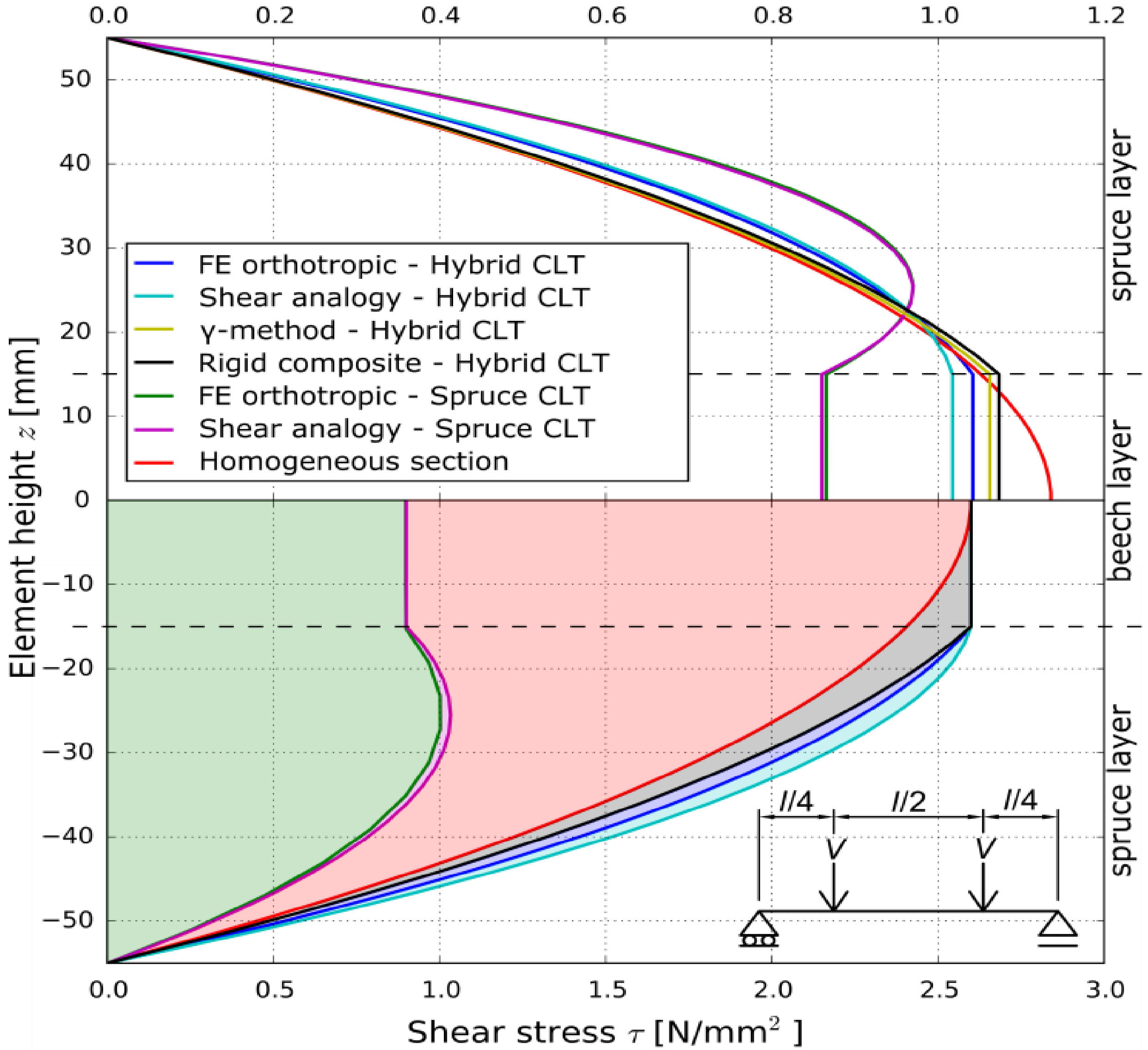
$G_{r,spruce}$ = 50 N/mm²

Rolling shear strength $f_{v,r,05}$ [N/mm²]

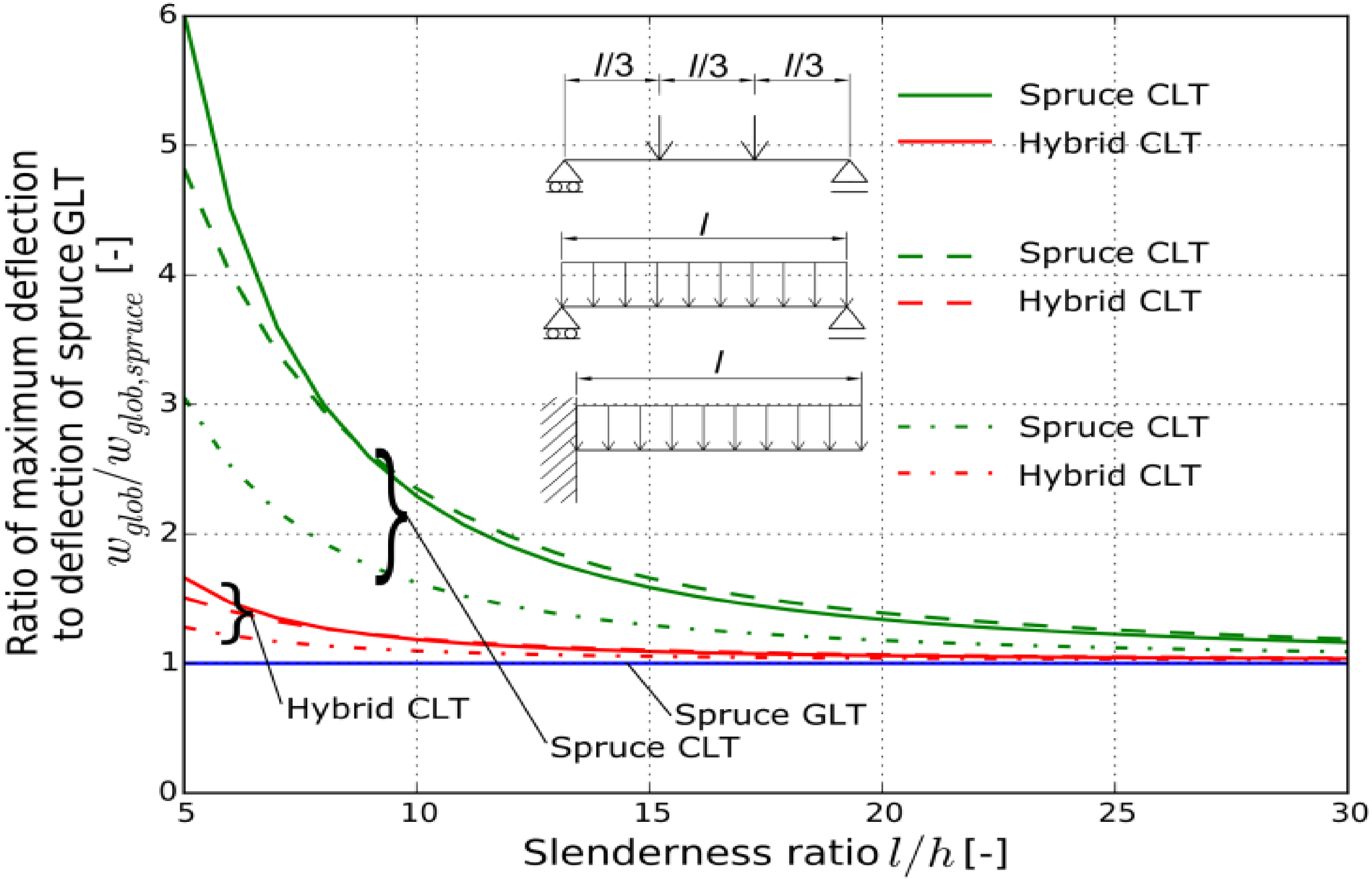
Bending shear:	$f_{v,r,2,05}$	2.61
Compression shear:	$f_{v,r,A,05}$	2.30
	$f_{v,r,B,05}$	3.54
2-plate shear:	$f_{v,r,05(with\ pith)}$	3.30

$f_{v,r,spruce}$ = 0.9 N/mm²

Shear stress distributions in SW and hybrid CLT



Implications of beech cross-layers on deflections

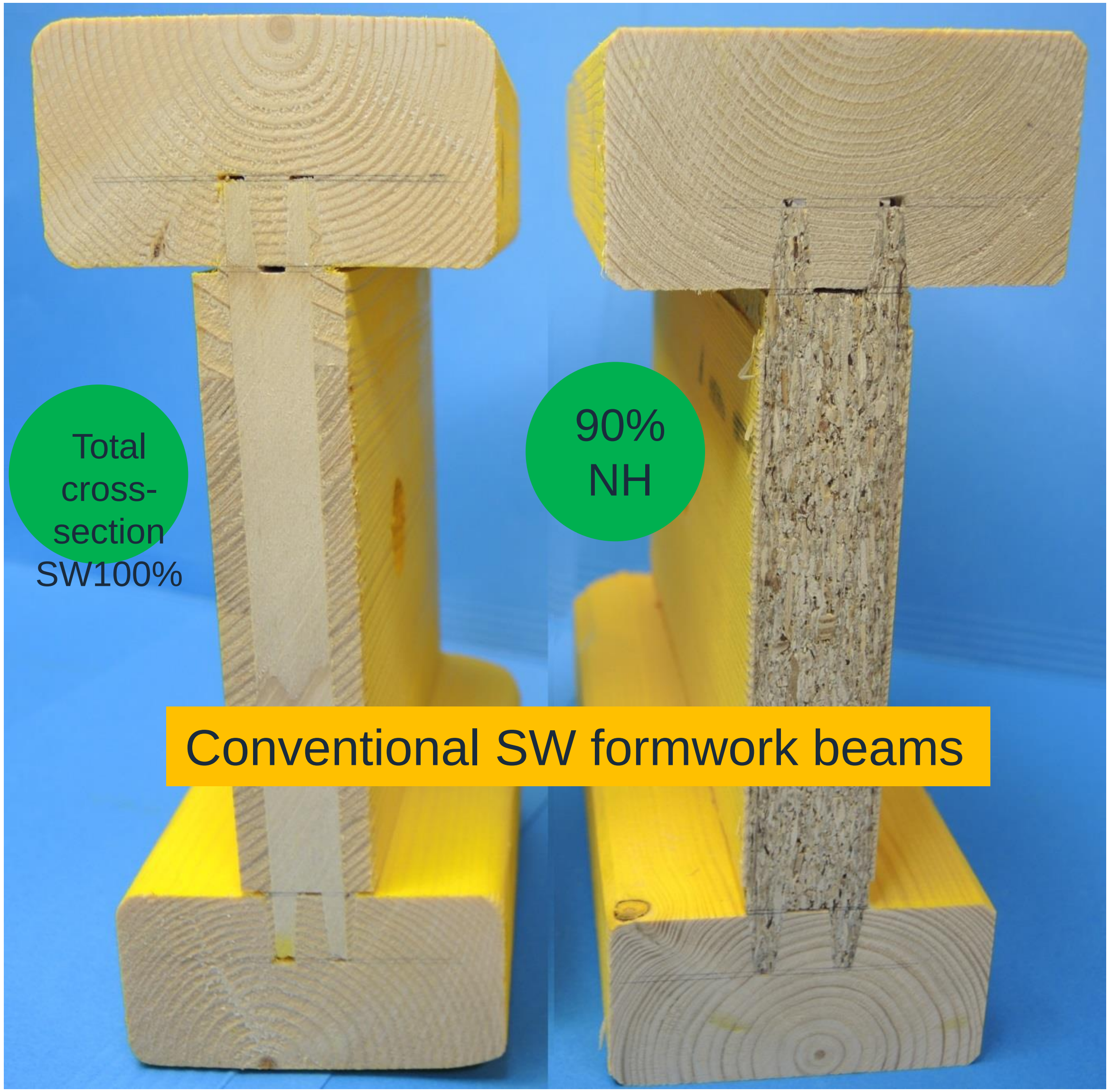


Deflection ratio SW-CLT and hybrid SW-HW-CLT vs. SW-GLT

Slender-ness ratio *l*/*h*	Four point bending		Single span, uniform load		Cantilever, uniform load	
	spruce CLT	hybrid CLT	spruce CLT	hybrid CLT	spruce CLT	hybrid CLT
10	2.29	1.18	2.35	1.19	1.62	1.10
15	1.59	1.09	1.66	1.10	1.30	1.06
20	1.34	1.06	1.39	1.07	1.18	1.04
25	1.22	1.05	1.26	1.05	1.12	1.03
30	1.16	1.04	1.19	1.04	1.09	1.03

3-layer plates

high performance hybrid SW-WW formwork beam

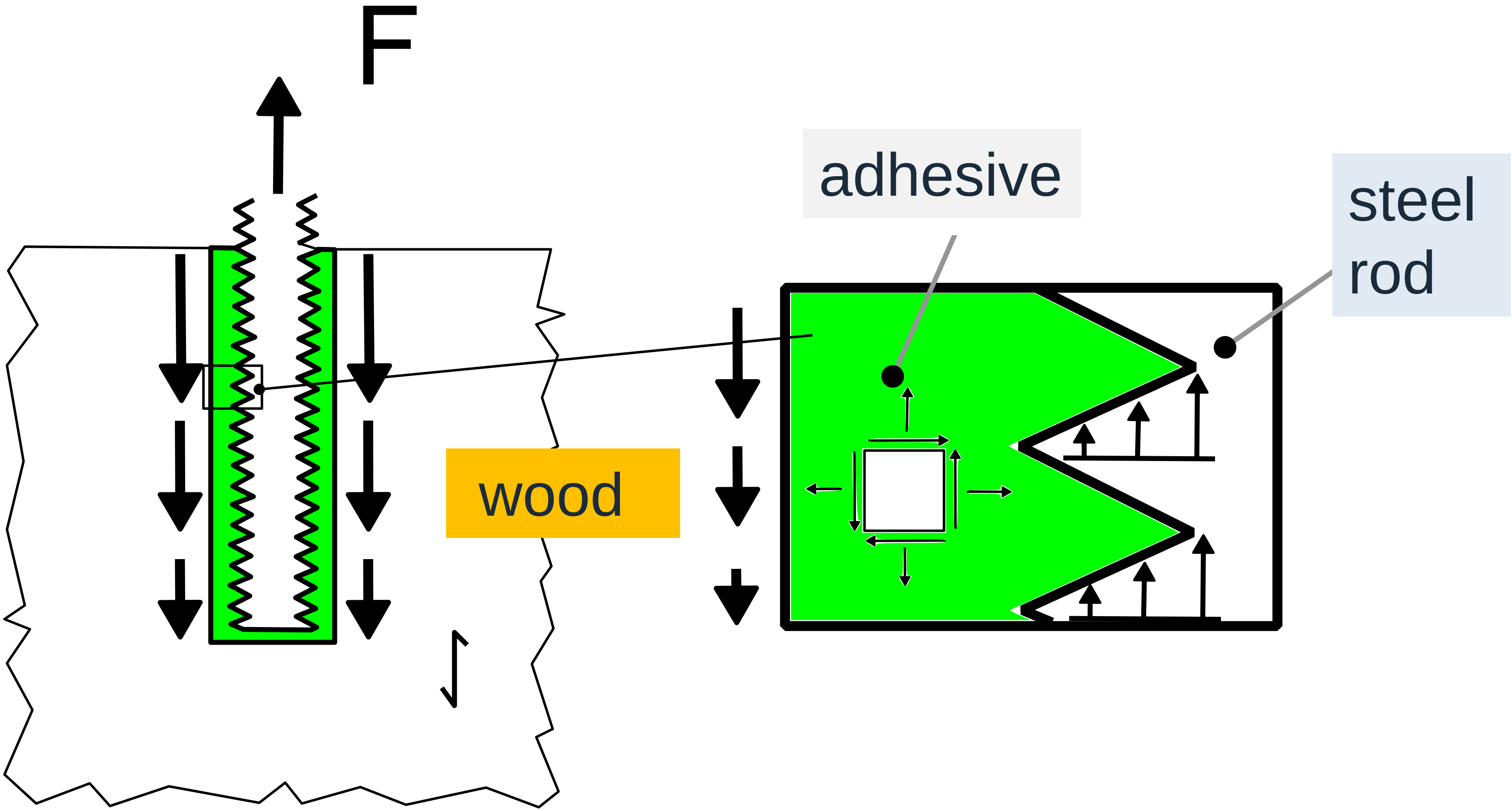



PERI VT20
doka H20 top P
I tec 20
Eurex 20
350

Capacity comparison of formwork beams

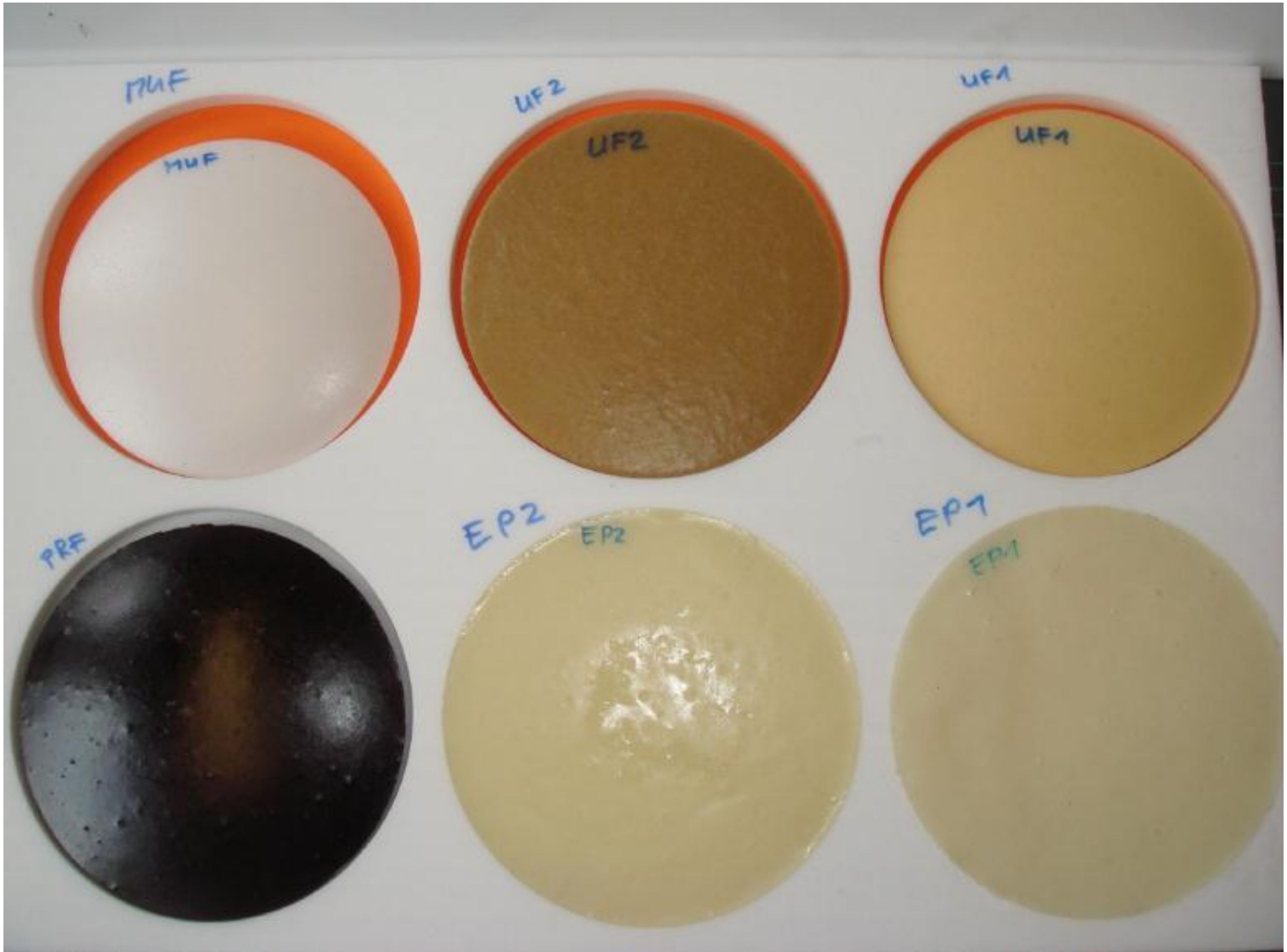
Characteristic Resistances	Usual beam According to EN 13377	Itec beam Z-9.1-773
Moment [kNm]	10,9	19,5
Shear [kN]	23,9	44,0
Bearing [kN]	47,8	86,6
Bend. Stiffness [kNm^2]	450	640

Glued-in rods



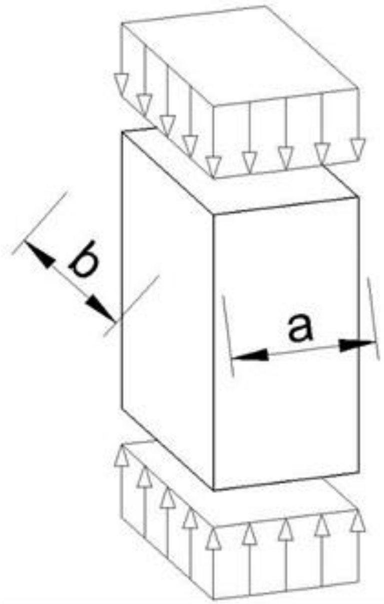
SW-GLT / CLT glued-in rod bonds to concrete

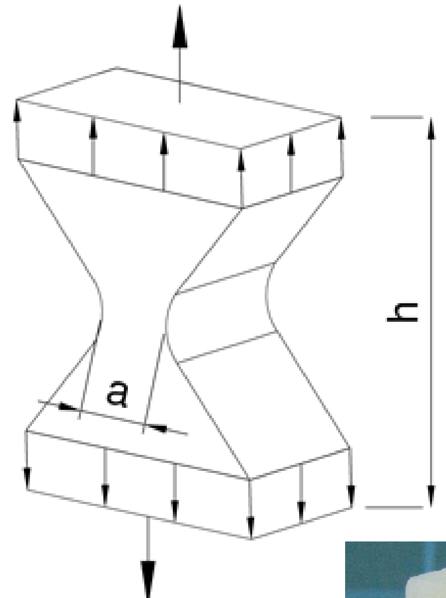
Shrinkage behavior of different adhesives

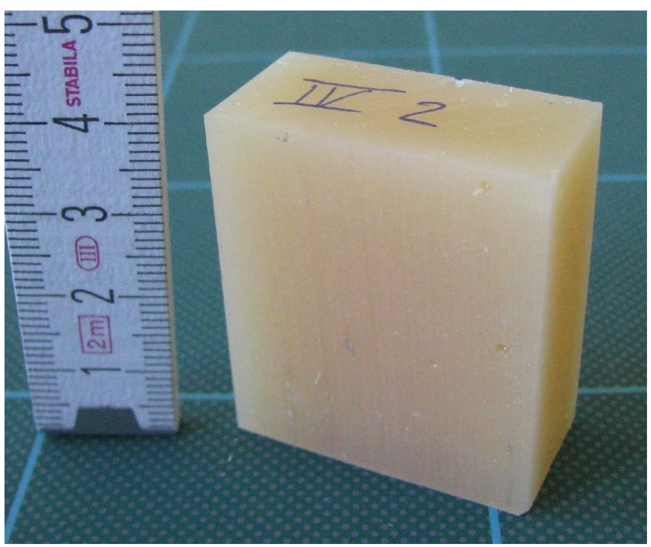



8
6
4
2
8
6
4
2

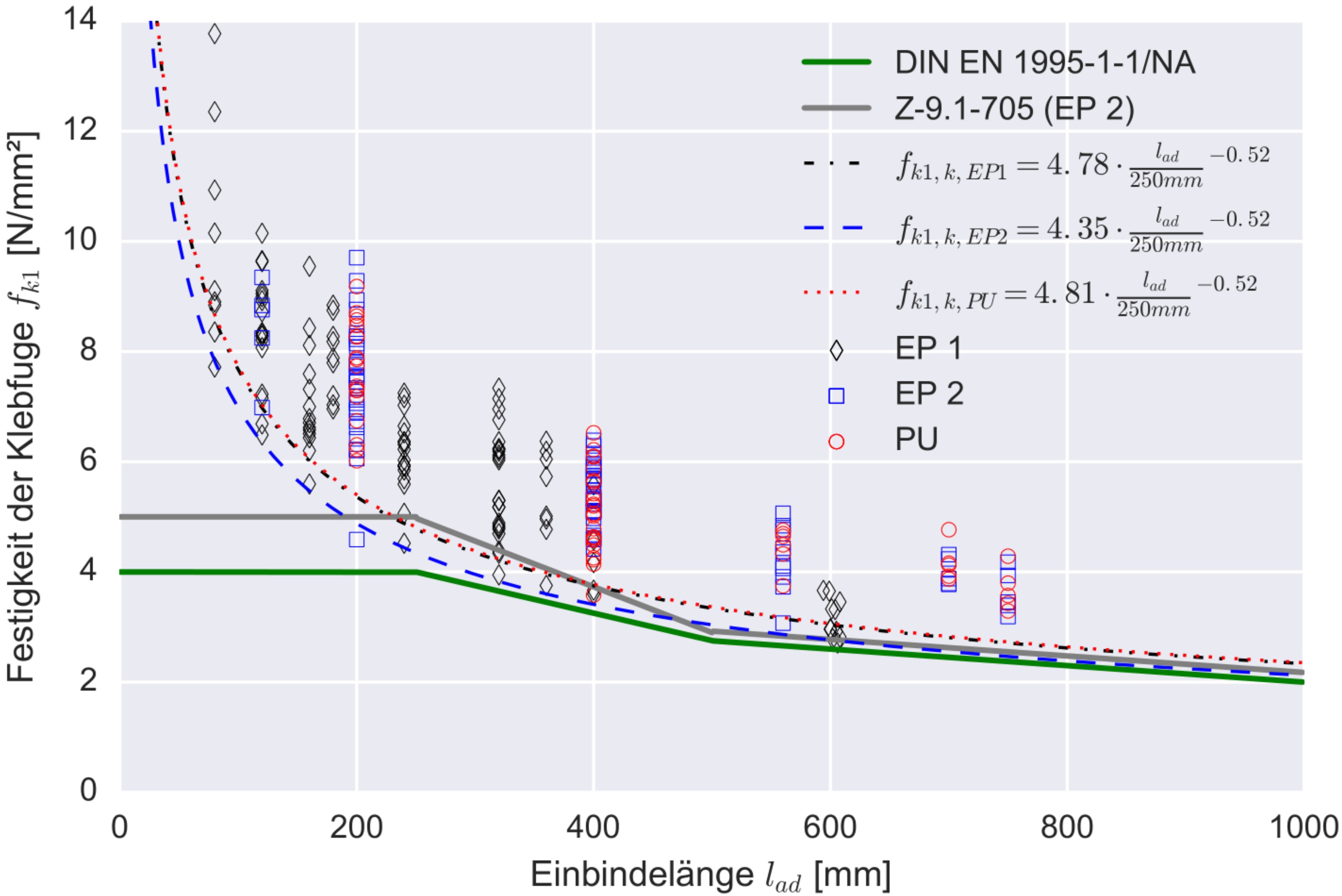
Epoxy - compact cohesive property specimens







Berücksichtigung des Klebstoffs (charakteristisch)

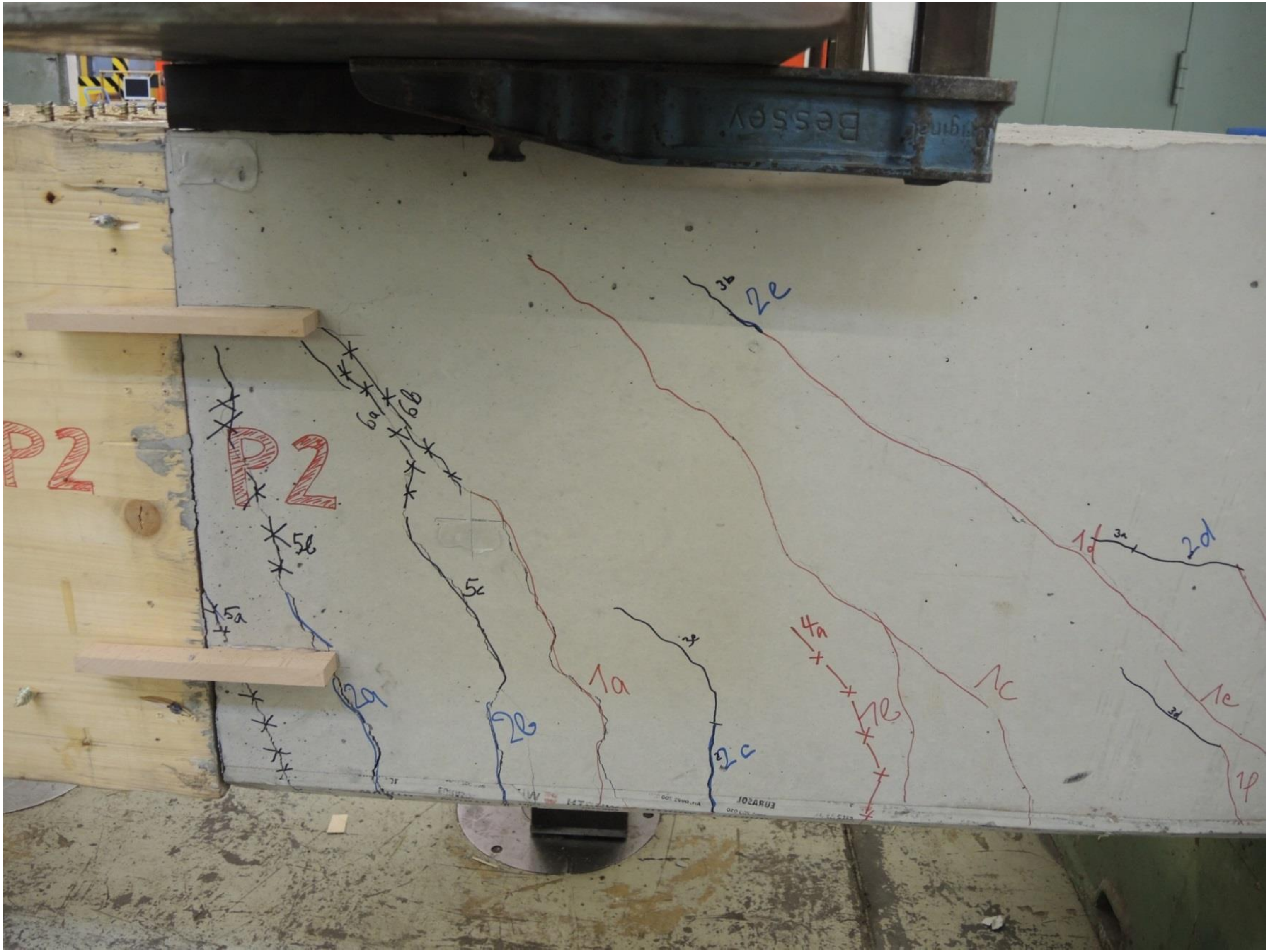


Pre-tests to Stuttgart semi-integral bridge

Pre-tests to Stuttgart semi-integral bridge

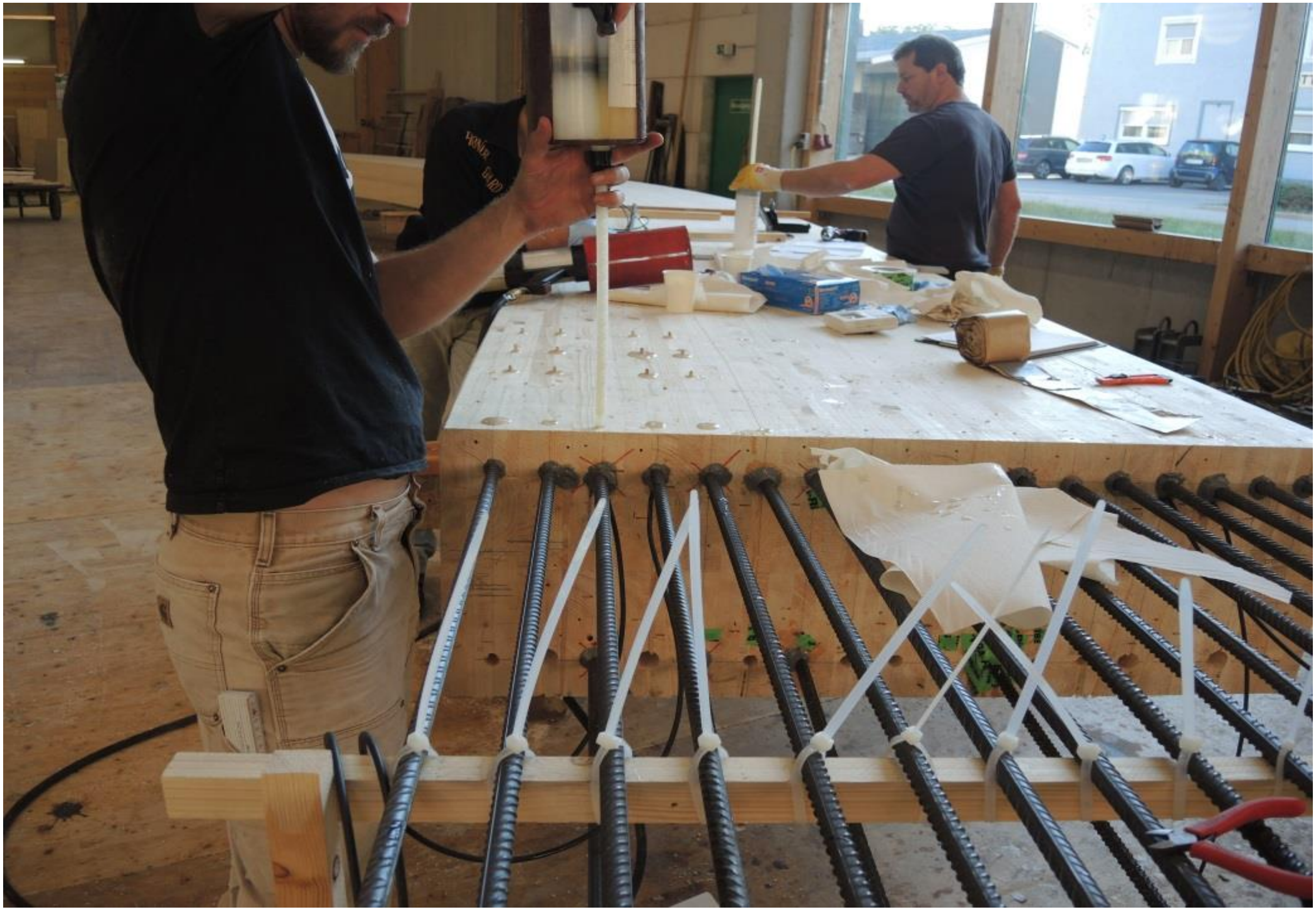
Pre-tests to Stuttgart semi-integral bridge

Pre-tests to Stuttgart semi-integral bridge

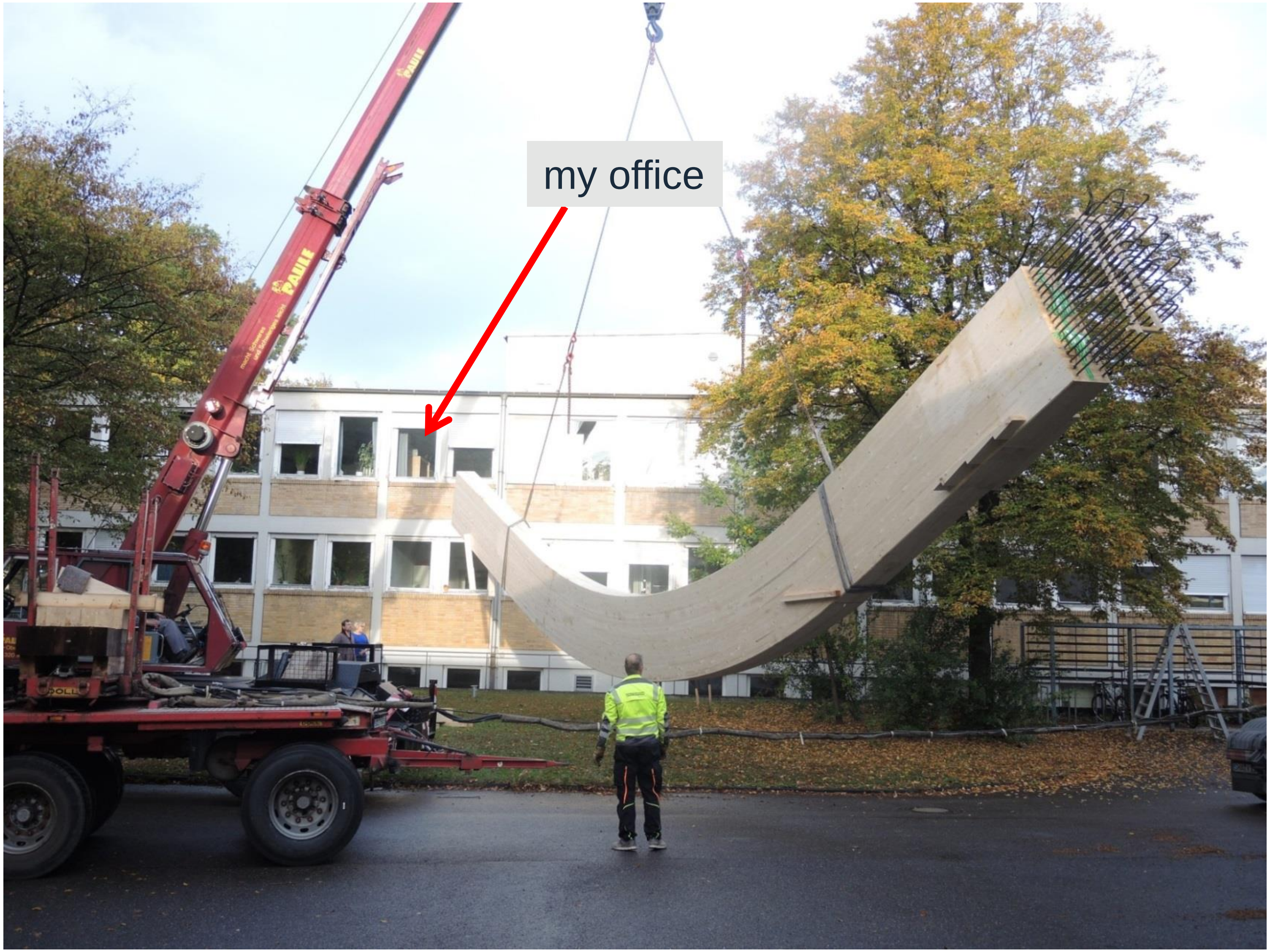


The Stuttgart bridge

Bonding of rebars in main bridge beam

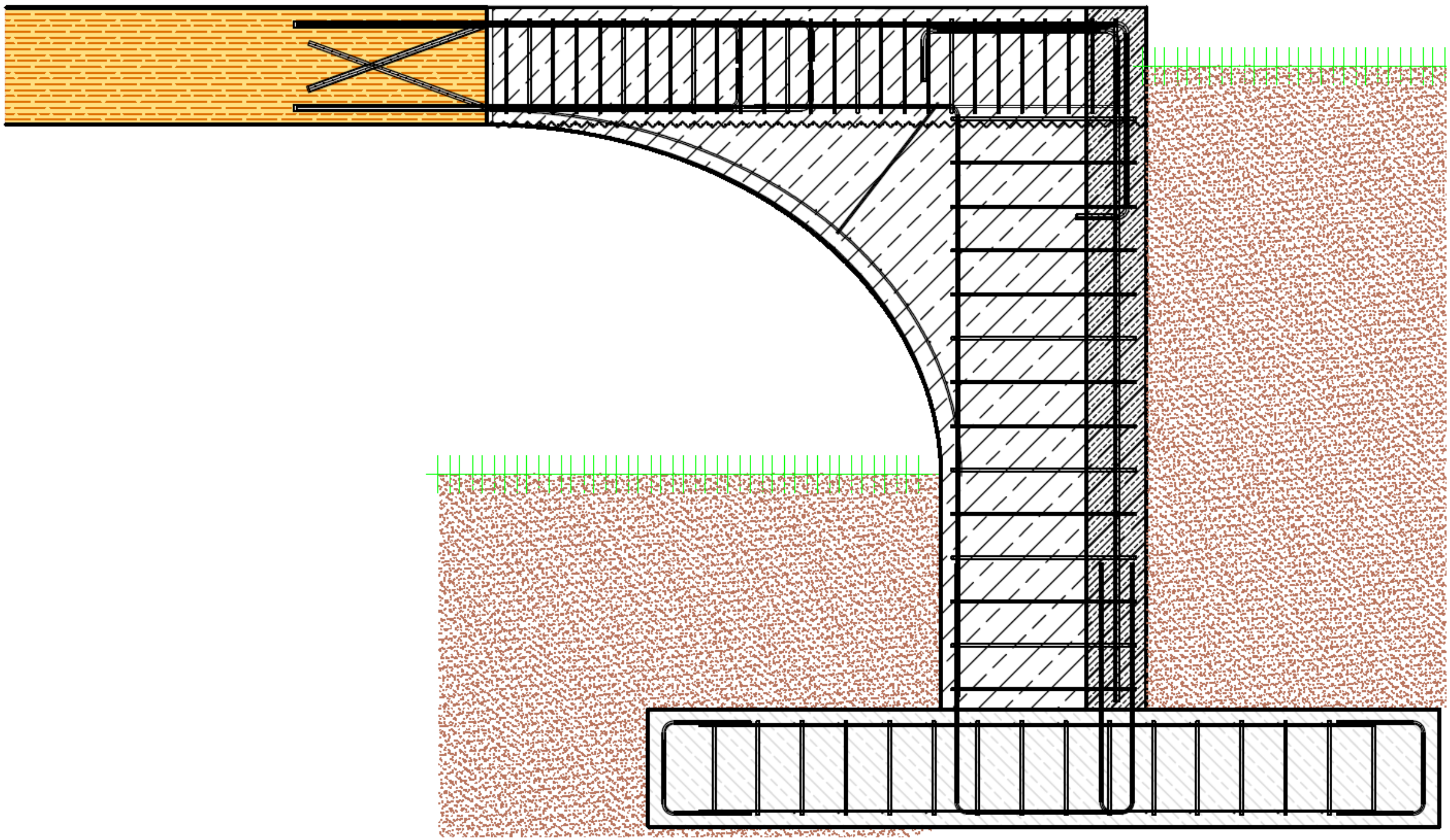


Manufacture of the Stuttgart bridge



The Stuttgart bridge beam before casting

Schematic drawing of abutment



Abutment

Joining beam end with abutment

MPA STUTTGART

Casted / bonded SW- concrete connection


electric drive

Thank you all for your attention!