Concentrated load introduction in CLT elements perpendicular to plane

EUROMECH Colloquium 556

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Theoretical, Numerical and Experimental Analyses in Wood Mechanics

http://556.euromech.org

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Das Kompetenzzentrum für Holzbau und Holztechnologie
im Bautechnikzentrum der Technischen Universität Graz

- **Introduction Cross Laminated Timber (CLT)**
  - Short introduction/motivation
  - Verifications (ULS) of CLT plates under bending/shear (engineering level)
  - Research of Mestek (PhD at Munich University of Technology, 2011)
- **Test configuration**
  - bending configuration geometry, typ of CLT plate, chosen cross sections
  - linear elastic analysis
  - ULS verifications (bending, shear), expected failure modes
  - Outlook: shear configuration
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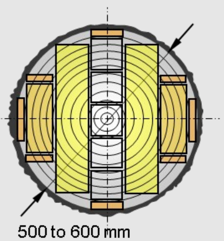
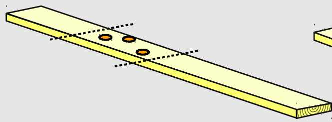
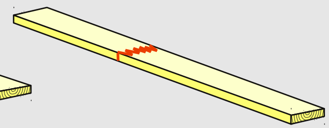
  - Material parameters/length-effect of brittle material (timber tension members)
  - Numerical model and comparison to test results
- **Summary and outlook**

Cross Laminated Timber (CLT)



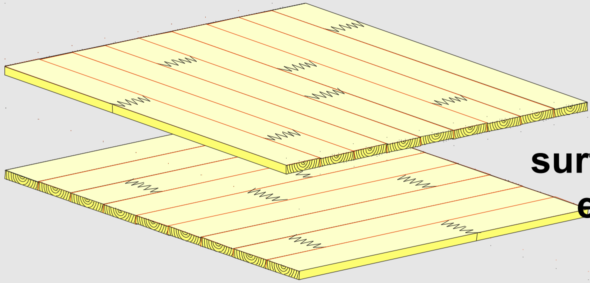


classification / grading trimming

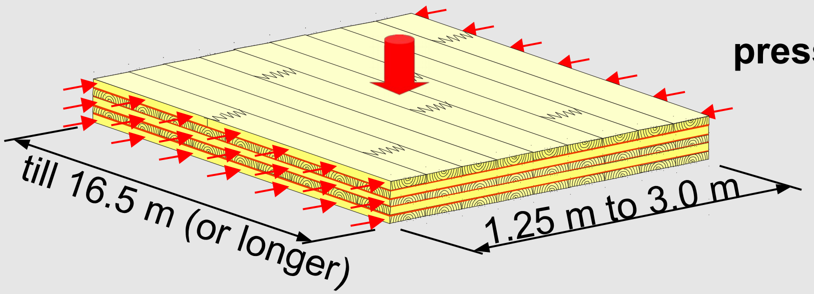


finger jointing

storage, charging and transport ….



surface bonding/ edge bonding (optional)



pressure

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… examples of implementation

with / without transverse pressure

in and / or across the direction of production

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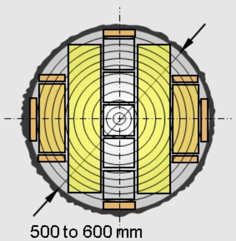

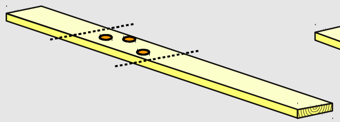

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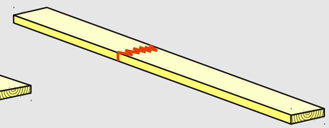

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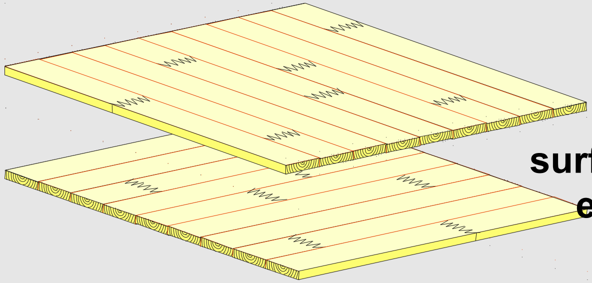

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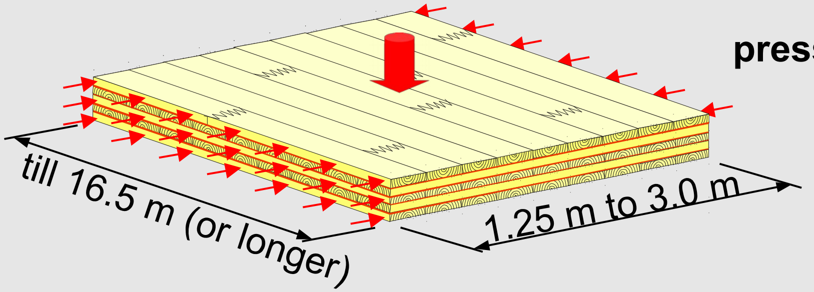

pressure

with / without transverse pressure

in and / or across the direction of production

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… examples of implementation

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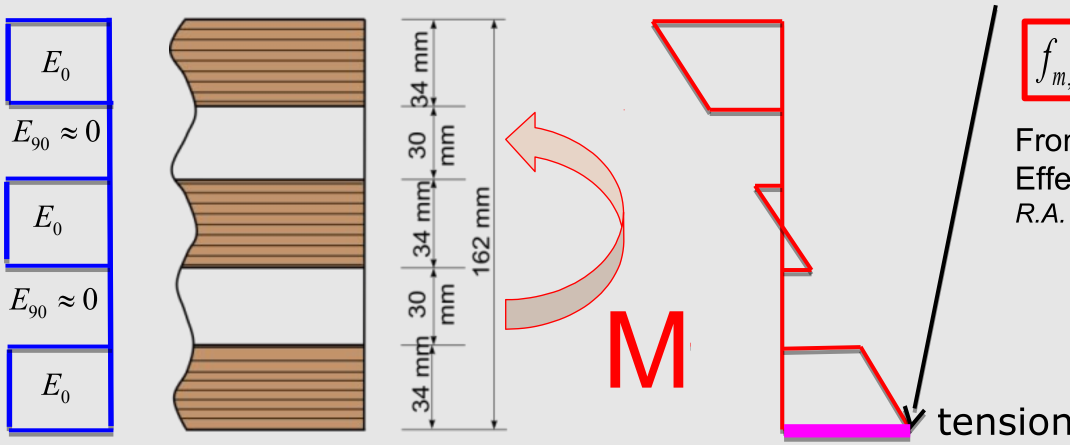
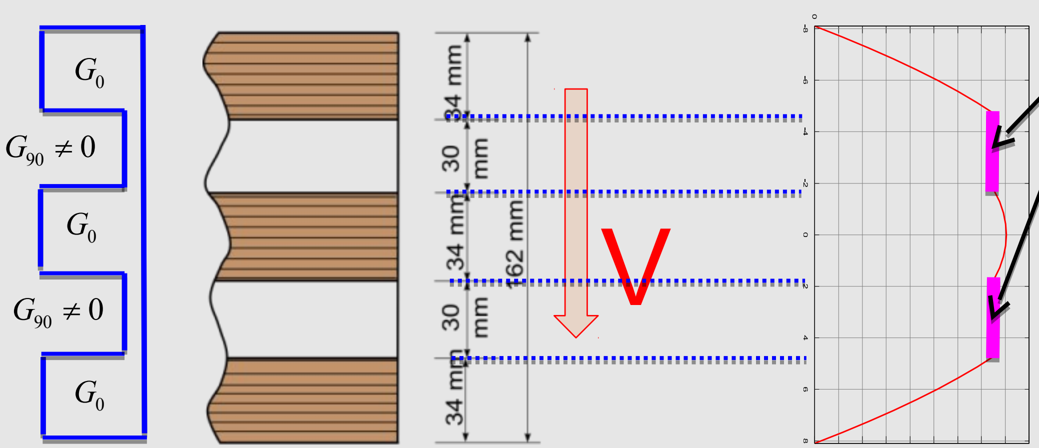
Verifications (ULS) of CLT plates under bending/shear (engineering level)



critical bending stress (tension)

$$f_{m,c,05} = 3{,}5 \cdot 14{,}0^{0{,}8} = 28{,}9 \quad \text{N/mm²}$$

From: A Contribution to the Design and System Effect of Cross Laminated Timber (CLT)
R.A. Jöbstl, et al, CIB meeting 39 Florence, Italy (2006)

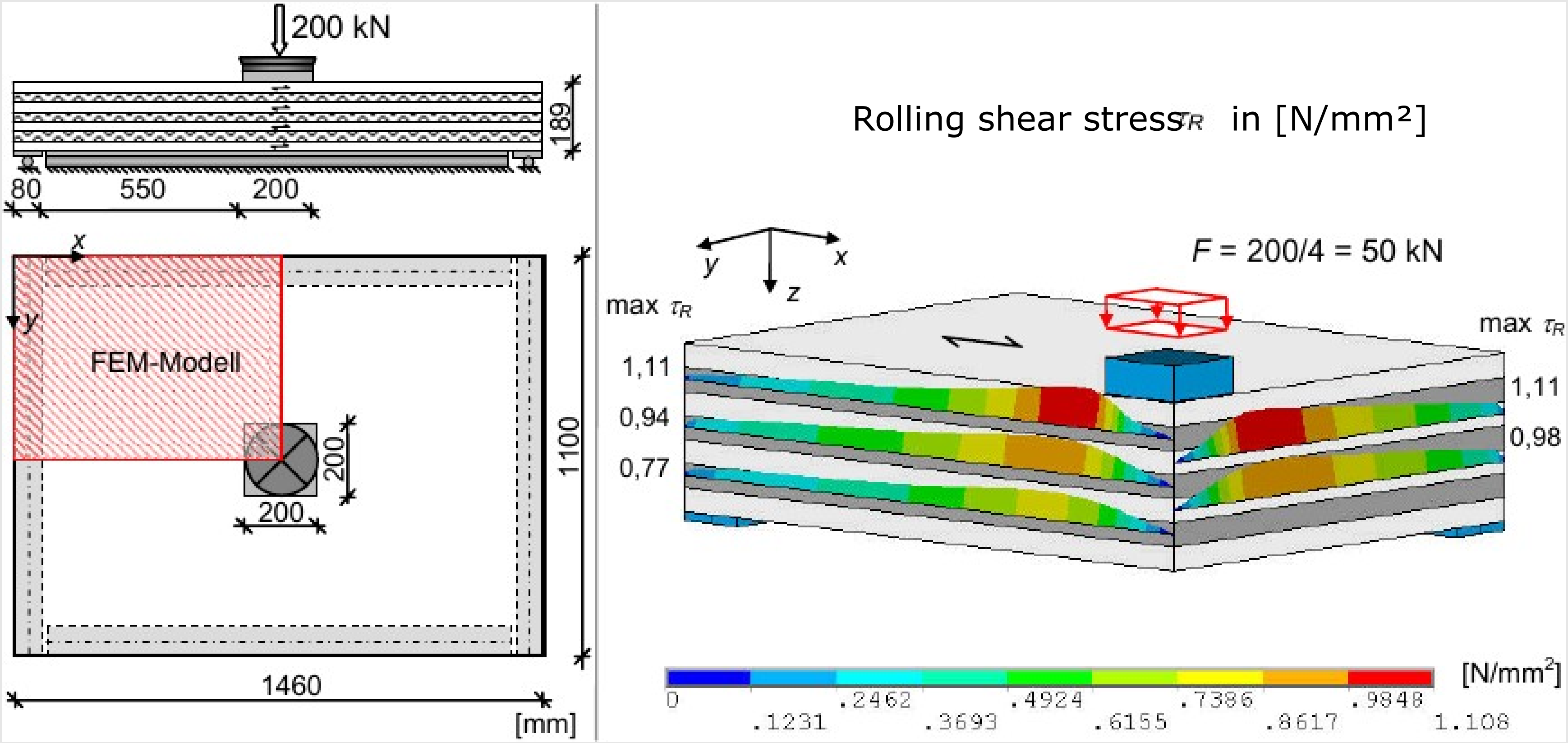


critical shear stress (rolling shear stress)

$$f_{v,90,05} = 1{,}25 \quad \text{N/mm²}$$

From: CLT Handbook (in german language)
Schickhofer, Bogensperger, Moosbrugger (2010)

Research of P. Mestek (PhD at Munich University of Technology, 2011)

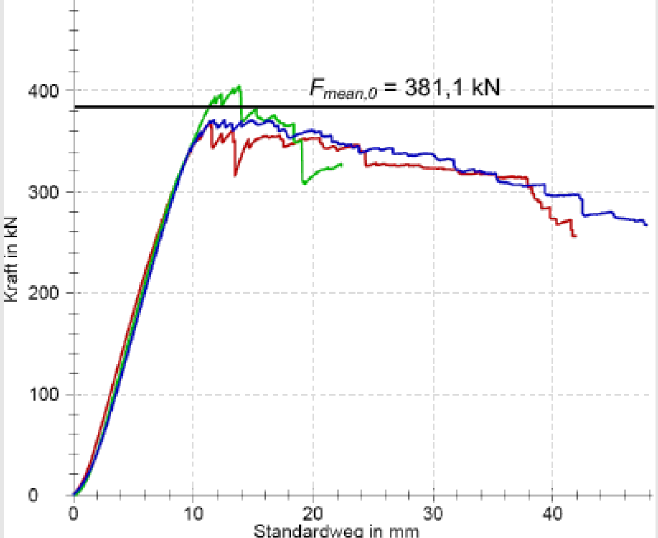


PhD Mestek: (punching) shear behaviour of (vacuum-pressed) CLT with reinforcement (45° screws) → only few tests without reinforcement

Our focus: (punching) shear behaviour of CLT without reinforcement

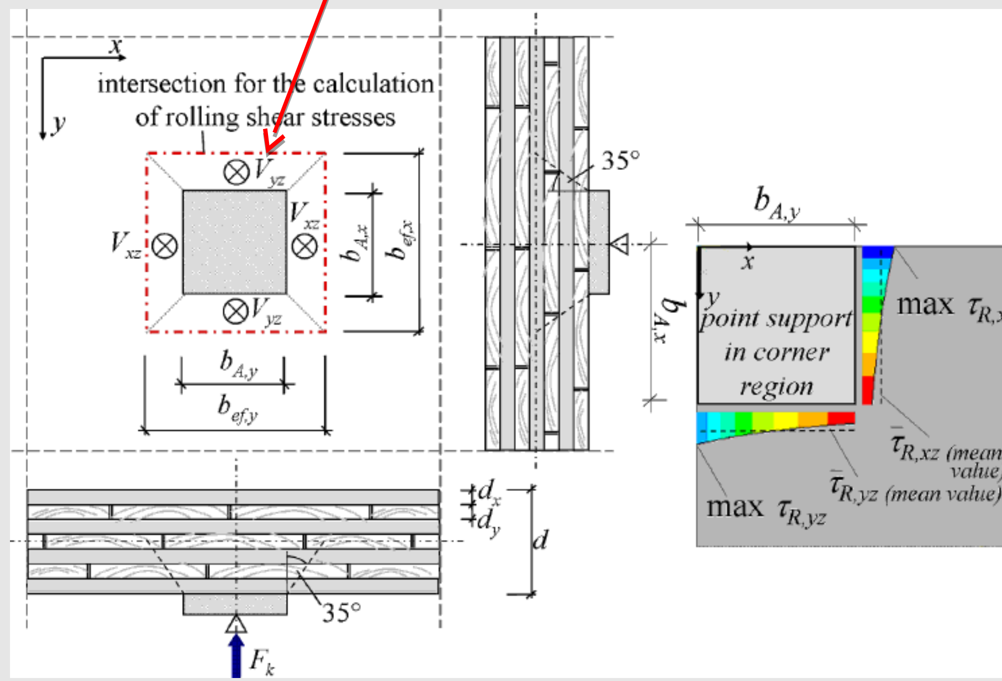
Research of P. Mestek (PhD at Munich University of Technology, 2011)

estimated mean value:
F_{mean}=381 kN
$F_{0,05}$=350 – 330 kN (estimated)
Based on COV of 5 − 8%



Legende	F_{max} kN	Probenbezeichnung	Serie n = 3	F_{max} kN
red	367,42	189_P - A-0	x̄	381,12
green	404,56	189_P - B-0	s	20,40
blue	371,36	189_P - C-0	v	5,35

Control perimeter for verification of punching through CLT plate



Based on test results in Mestek an elastic **rolling shear strength** of 2,06 – 2,25 N/mm² can be concluded.

$f_{v,90,05} \approx 2{,}25$ N/mm² (+80% for our investigations)

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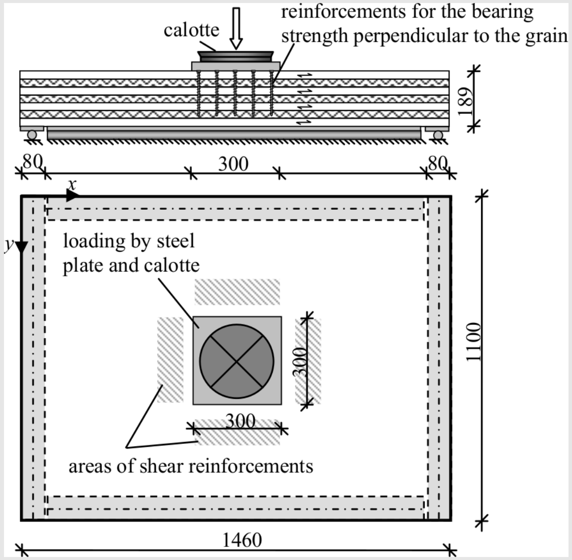
Parameters of test configuration

- Failure mechanism (bending failure, shear (punching) failure)
- Size and thickness of test elements
- Number of layers (CLT 5s, CLT 7s)
- Support of CLT (two-four side boundary condition, …)
- Load introduction (local reinforcement)
- …

Numerical study (FEM) for investigation of these parameters ….

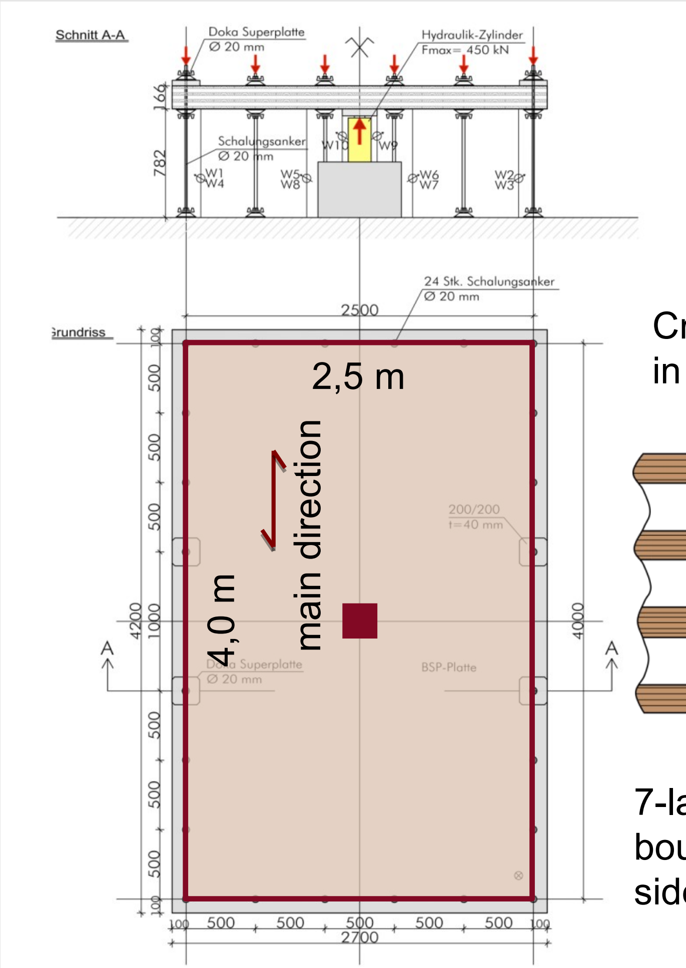
Test configuration Phd Mestek



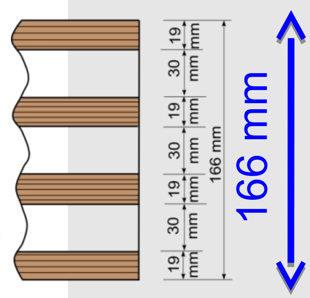
Test configuration in Graz

bending configuration geometry

CLT 7s



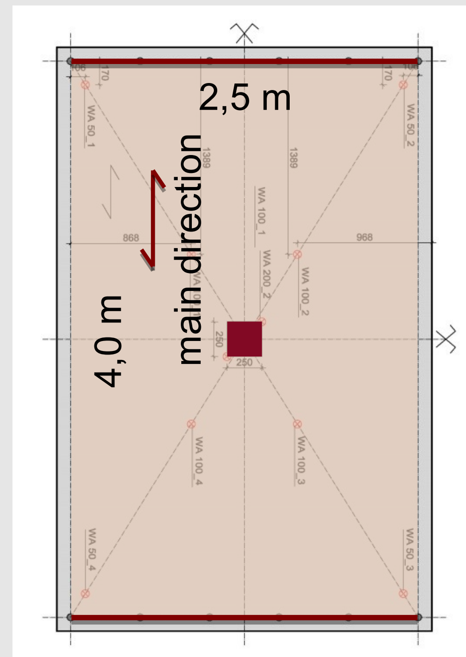
Cross section
in main direction



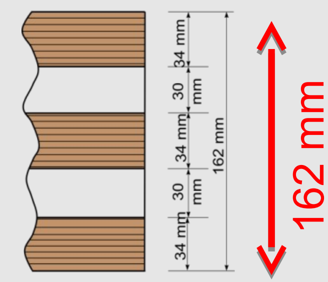
7-layered build up
boundaries at all sides

- type of CLT plate
- chosen cross sections
- chosen load introduction
  (25/25 cm and reinforcement with screws)
- solution of support
  (tension rods)

CLT 5s



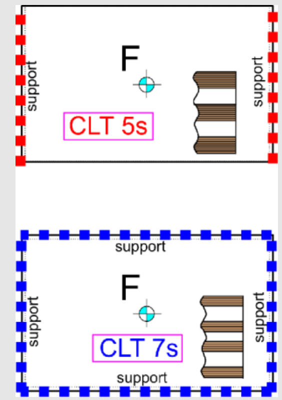
Cross section
in main direction



5-layered build up
boundaries only at short sides

ULS verifications (bending, shear), expected failure modes

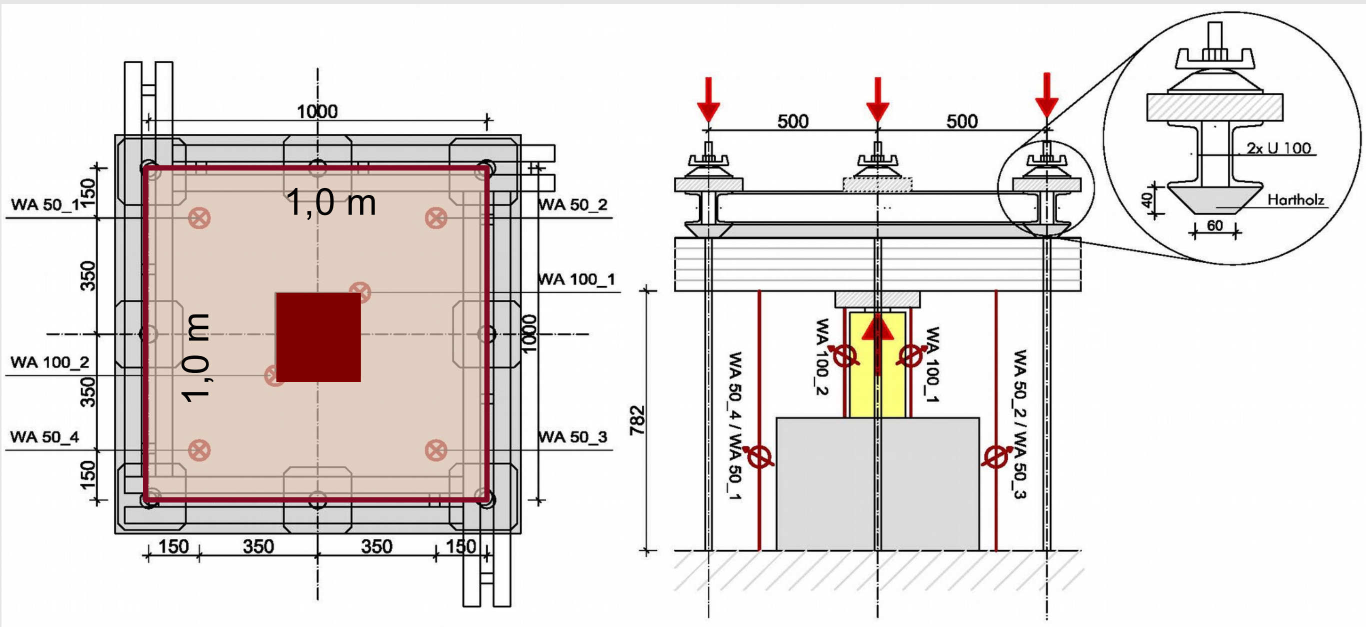
type	calulated max load		m_x [kNcm/cm]	m_y [kNcm/cm]	q_x [kN/cm]	q_y [kN/cm]
CLT-5s	188,9 *kN*	m_{Ed}	102,53	29,16	1,57	1,05
		m_{Rd}	102,53	40,41	2,98	1,55
		utilisation	**100,0%**	**72,2%**	**52,7%**	**68,2%**
CLT-7s	304,50 *KN*	m_{Ed}	61,06	67,87	1,55	1,59
		m_{Rd}	79,94	67,87	2,78	2,31
		utilisation	**76,4%**	**100,0%**	**55,6%**	**69,1%**



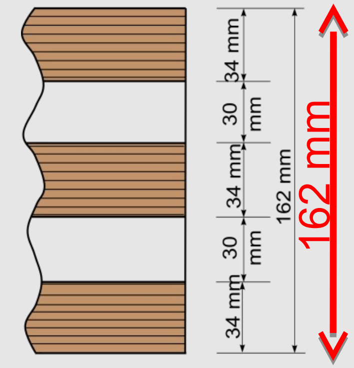
conclusions:

- **CLT-5s**
  support only along two short sides
  bending failure in main span direction can be predicted
- **CLT-7s**
  support along all four sides
  bending failure perpendicular to main span direction can be predicted

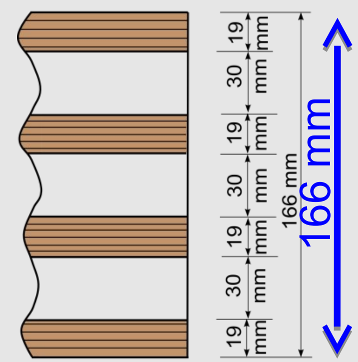
Outlook: shear configuration



CLT-5s



CLT-7s



Properties of chosen CLT sections

element	E_0	E_{90}	G_0	G_{90}	#	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_{ges}
	N/mm²	N/mm²	N/mm²	N/mm²		mm	mm	mm	mm	mm	mm	mm	**mm**
CLT-5s	11.600	300	690	50	5	34	30	34	30	34	-	-	**162**
CLT-7s	11.600	300	690	50	7	19	30	19	30	19	30	19	**166**

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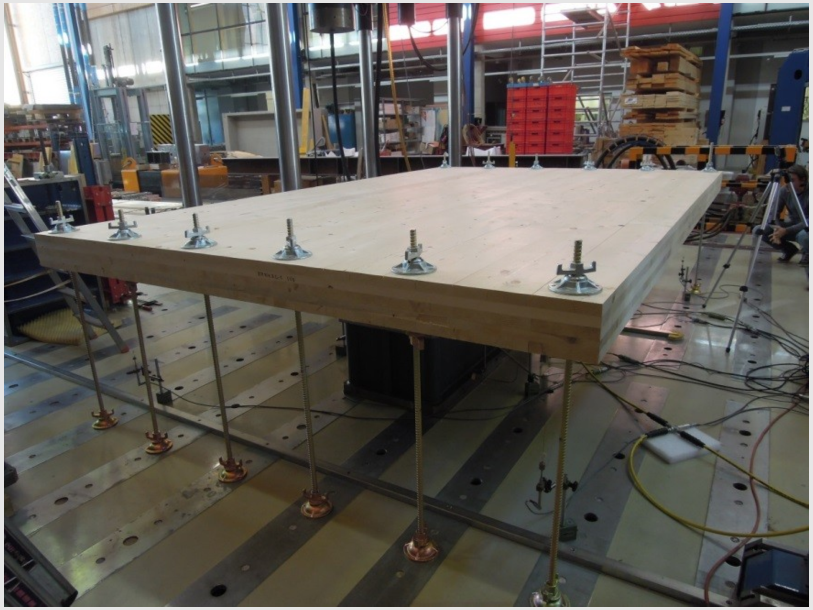
Executed test program



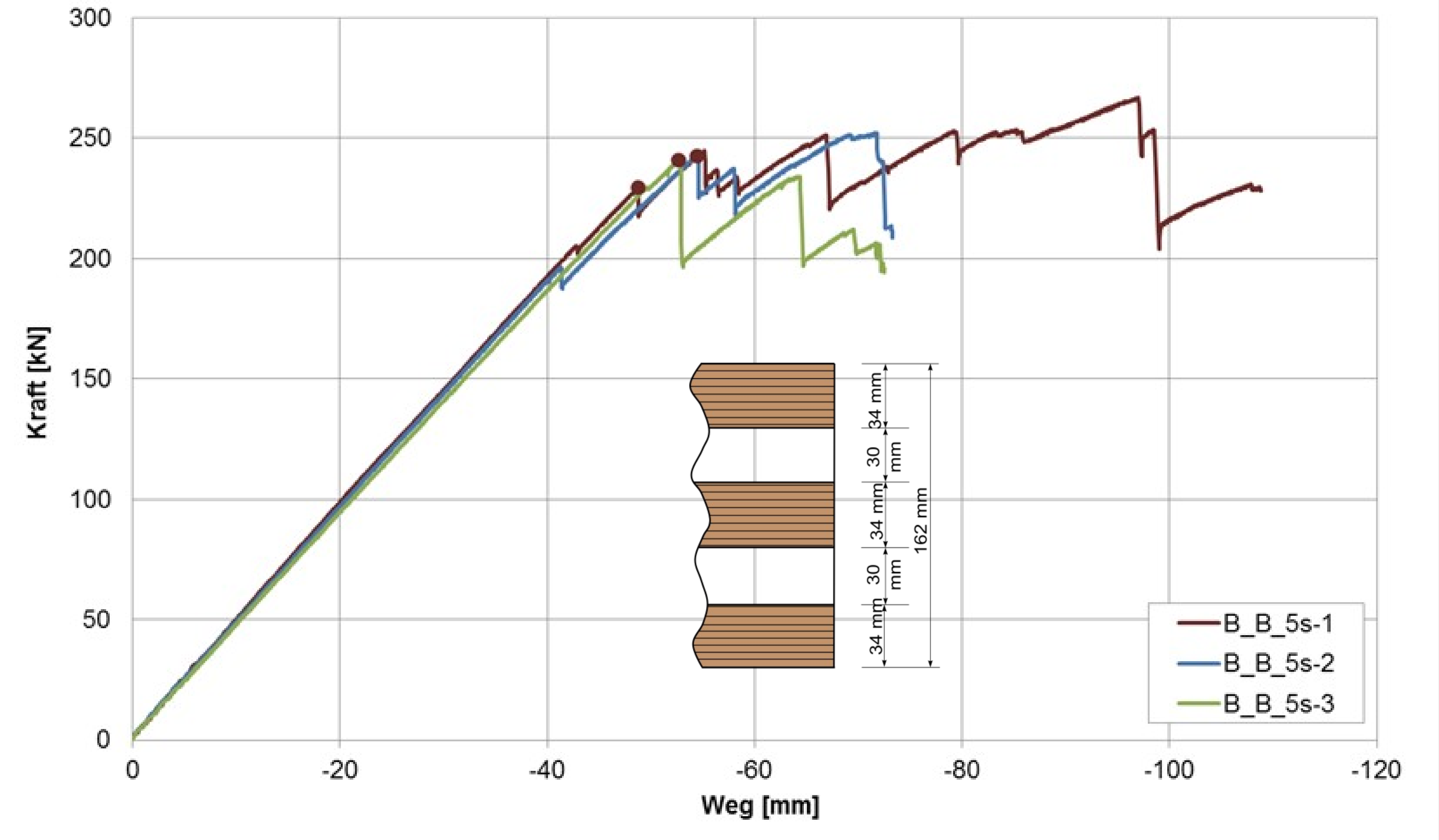
5-layered, uniaxial loaded CLT **(CLT 5s)**

7-layered, biaxial loaded CLT **(CLT 7s)**

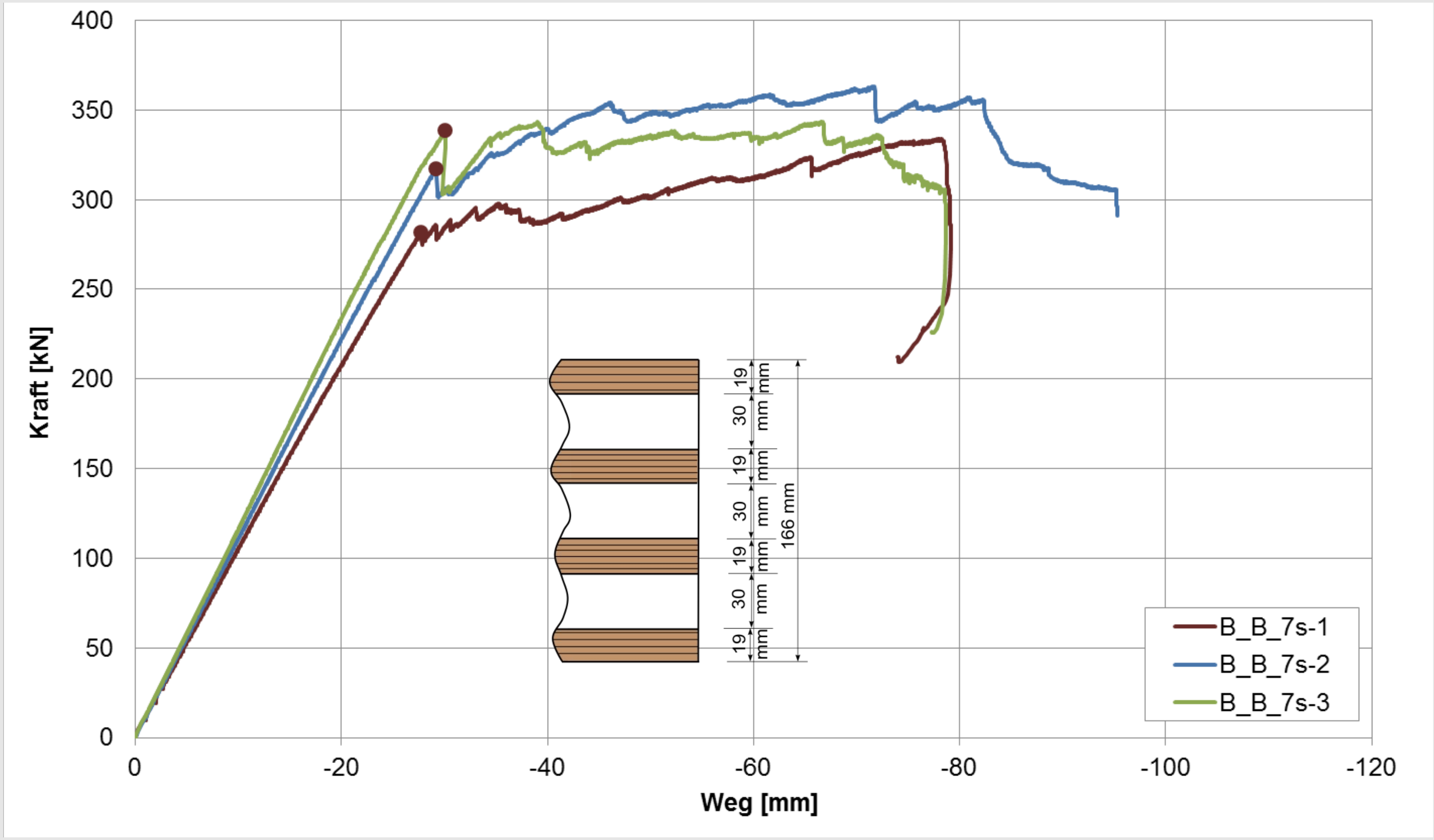
cross sections of CLT elements

CLT	producer	quantity	#layers	t_{ges}	t_1	t_2	t_3	t_4	t_5	t_6	t_7
		[-]	[-]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
B_B_5s	producer 1	3	5	162	34	30	34	30	34		
B_B_7s	producer 1	3	7	166	19	30	19	30	19	30	19
C_B_7s	producer 2	3	7	170	20	30	20	30	20	30	20
Sum		**9 pieces**									

Experimental load − displacement curves for CLT 5s



Experimental load – displacement curves for CLT 7s



Test results versus linear elastic FEM predictions

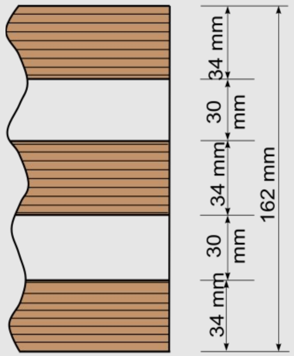
	$F_{failure}$ [kN]	Observed failure in labor	Predicted failure based on FEM	$F_{0,05}$ [kN] *(Prediction)*
5s-1 (producer 1)	229,5	Bending (longitudinal, finger joint)	Longitudinal bending	
5s-2 (producer 1)	242,7	Bending (longitudinal, finger joint)	Longitudinal bending	
5s-3 (producer 1)	241,0	Bending (longitudinal, knot failure)	Longitudinal bending	
Mean value	**237,7**	← ← ~ 26% → →		***188,9***
COV [%]	**3,0**			
7s-1 (producer 1)	281,8	Bending (longitudinal, finger joint)	transverse bending	
7s-2 (producer 1)	317,1	Bending (transverse)	transverse bending	
7s-3 (producer 1)	338,6	Bending (transverse)	Transverse bending	
Mean value	**312,5**	← ← 38% → →		***227,0***
COV [%]	**9,2**			
7s-1 (producer 2)	336,4	Bending (longitudinal)	transverse bending	
7s-2 (producer 2)	353,0	Bending (longitudinal)	transverse bending	
7s-3 (producer 2)	393,1	Bending (longitudinal)	transverse bending	
Mean value	**360,8**			
COV [%]	**8,1**			

Observed primary failures of CLT 5s

uniaxial load behaviour

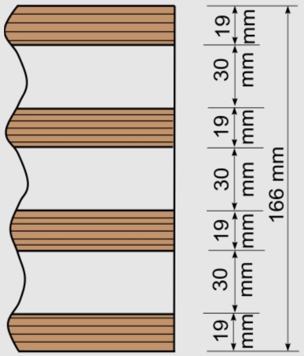
Bending failure in top layer (primary failure)

Failure due to rolling shear (secondary failure)



failure of CLT 5s

Observed primary failures of CLT 7s



- Bending failure in top layer
  - (primary failure, 4x)
- Bending failure in second layer
  - (primary failure, 2x)
- Failure due to rolling shear (secondary failure)

failure of CLT 7s

Observed secondary rolling shear failures (e.g. CLT 7s)

cross section perpendicular to top/bottom lamella

cross section parallel to top/bottom lamella

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Elastic values and mean tension strength (in fibre direction)

Elastic constants of CLT

Stiffness	value
E_0	12000 N/mm²
E_{90}	370 N/mm²
G_0	690 N/mm²
G_{90} (G_R)	50 N/mm²

Various tests results bending tension of CLT

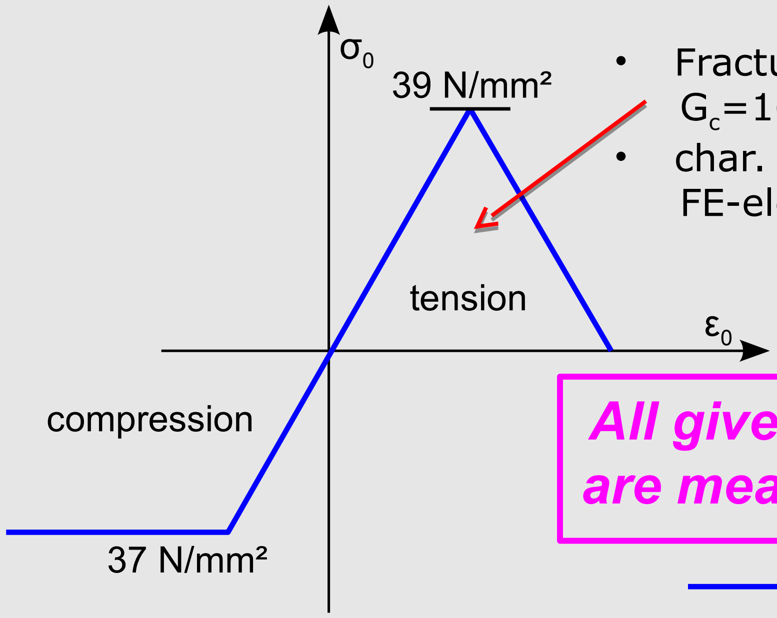
client	Number	Mean value N/mm²
1	4	44,2
1	8	40,6
2	*10*	*56,46*
3	41	37,2
3	20	39,4
4	9	37,4

Effects due to poisson numbers are neglected!

→ mean value over all tests: 39 N/mm²

Mean Tension and compression strength

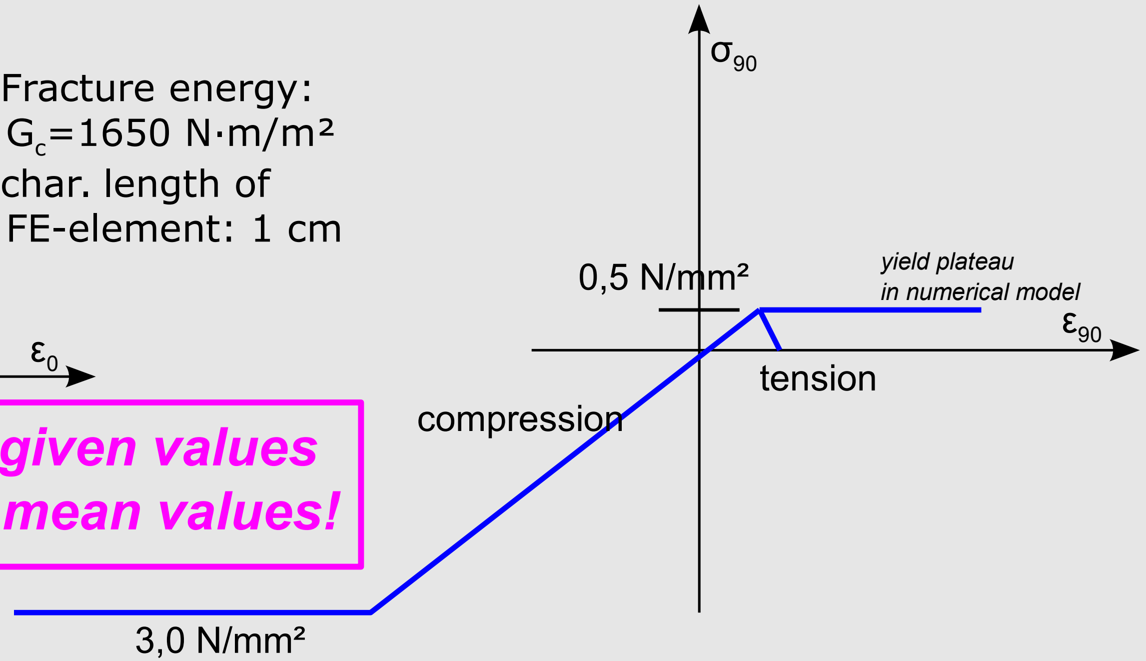
in fibre direction



- Fracture energy: G_c=1650 N·m/m²
- char. length of FE-element: 1 cm

All given values are mean values!

perpendicular to fibre direction

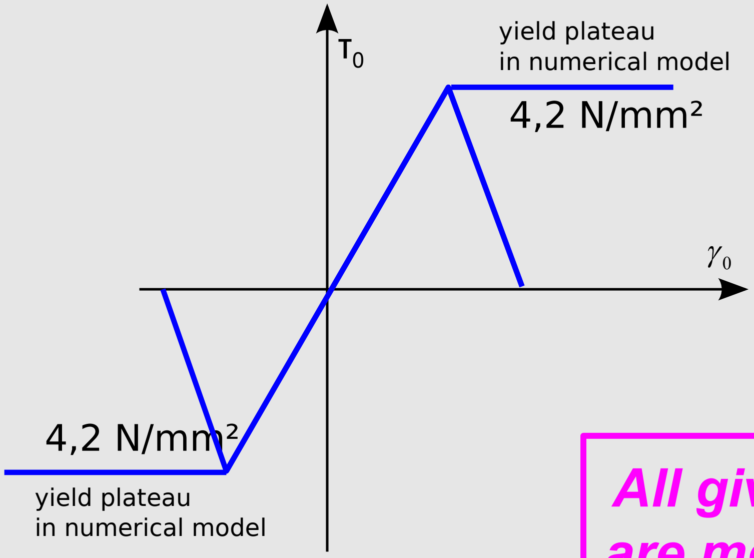


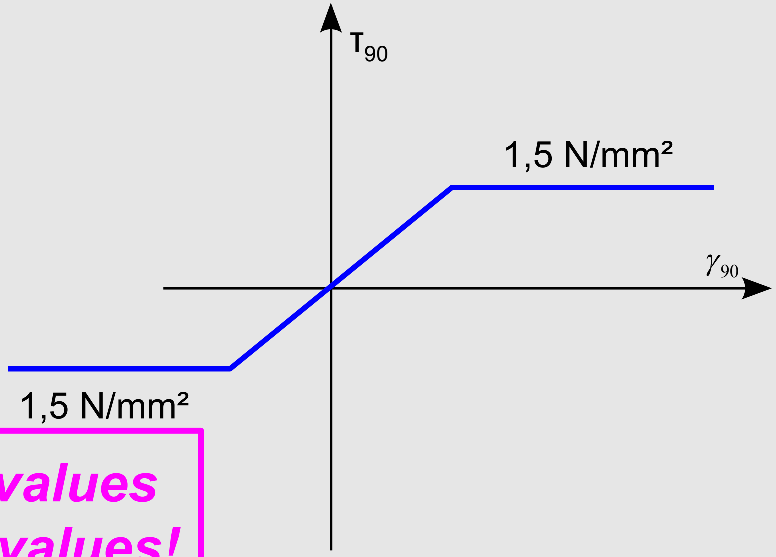
Sources for strength values:

- **in fibre direction:** scientific test program (**Comet P01, LS0231**) at competence centre holz.bau forschung and Diploma thesis **RULI** 2008 at Institut for timber engineering and wood technology at TU GRAZ
- **Perpendicular to fibre direction:** Diploma thesis **RULI** 2008/Master thesis **STUEFER** 2011

Mean shear strength in fibre direction

perpendicular to fibre direction (Rolling shear strength)





All given values are mean values!

Shear failure happens subsequently → softening behaviour not considered in models with bending failure

Sources for strength values:

- **in fibre direction:** G. **Schickhofer**: Determination of Shear Strength Values for GLT using Visual and Machine Graded Spruce Laminations, CIB W18 34th, Venice, 2001
- **Perpendicular to fibre direction:** Master thesis **Ehrhard** 2014 Institut for timber engineering and wood technology at TU GRAZ

Length effect

Test site/arrangement for experimental investigation of length effect of brittle materials (2005-07)

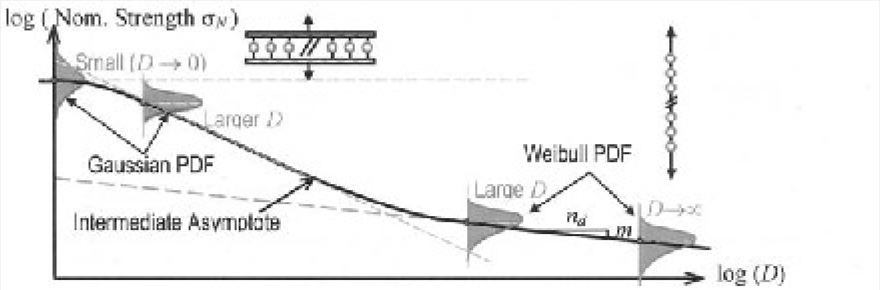
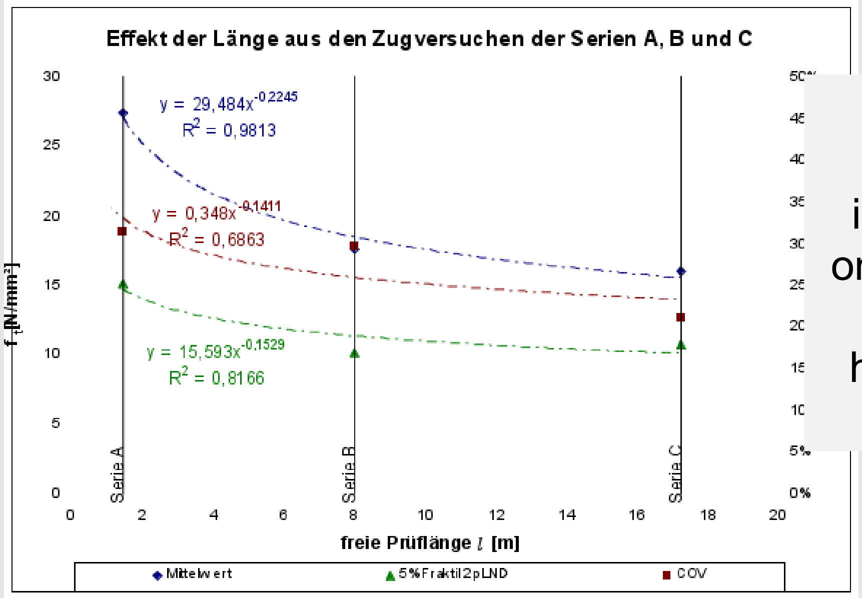


Illustration of mean size effect of brittle materials (acc. to Bažant)



Experimental exploration of influence of length on strength (project qm_online 2007, holz.bau forschung Graz)

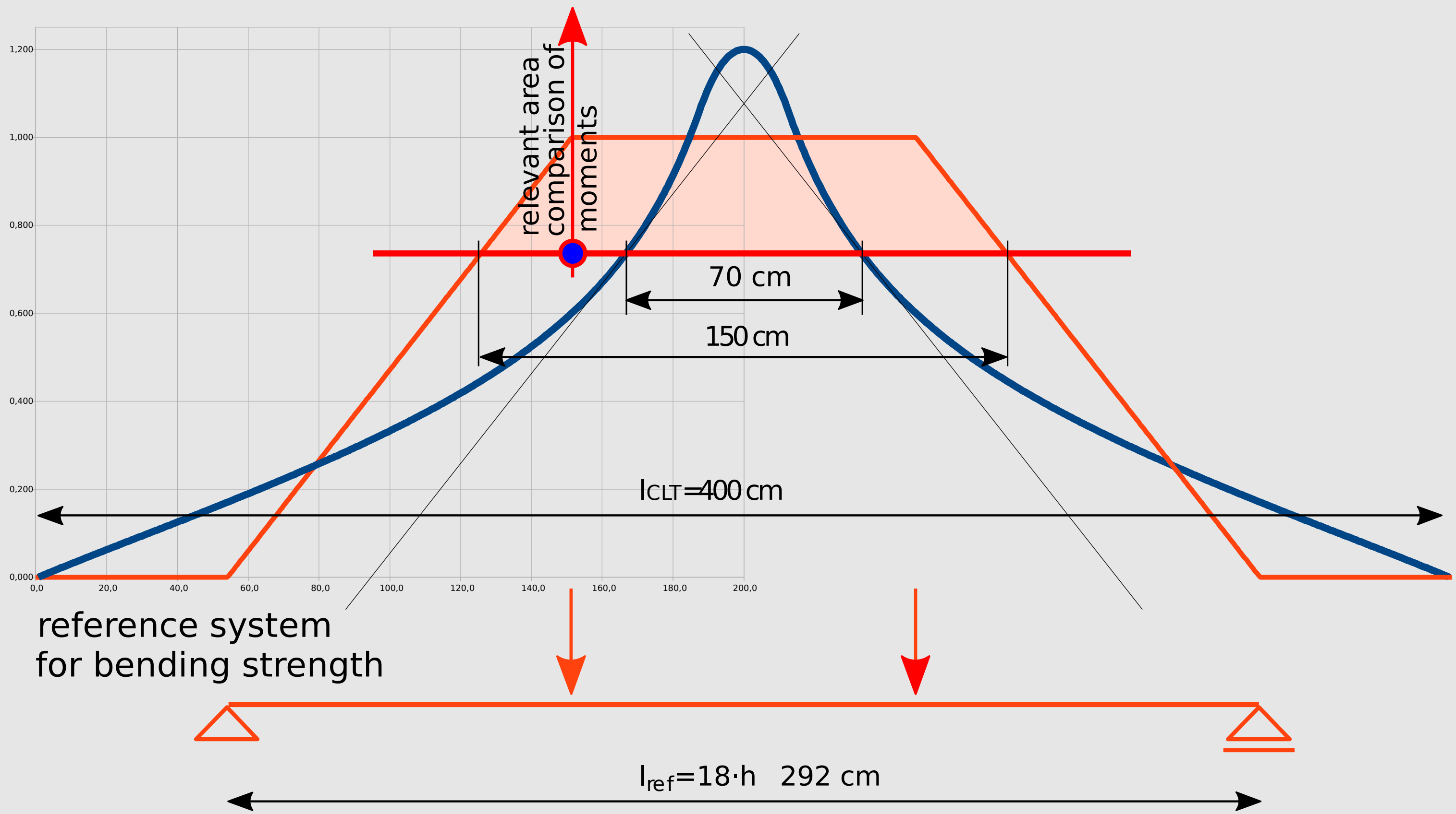
length effect: $$\frac{f_{t,k,mean}}{f_{t,k,ref,mean}} = \left(\frac{l}{l_{ref}}\right)^{-\alpha}$$

With exponent

$\alpha \approx 0,15$ 5 % quantile values

$\alpha \approx 0,22$ for mean values

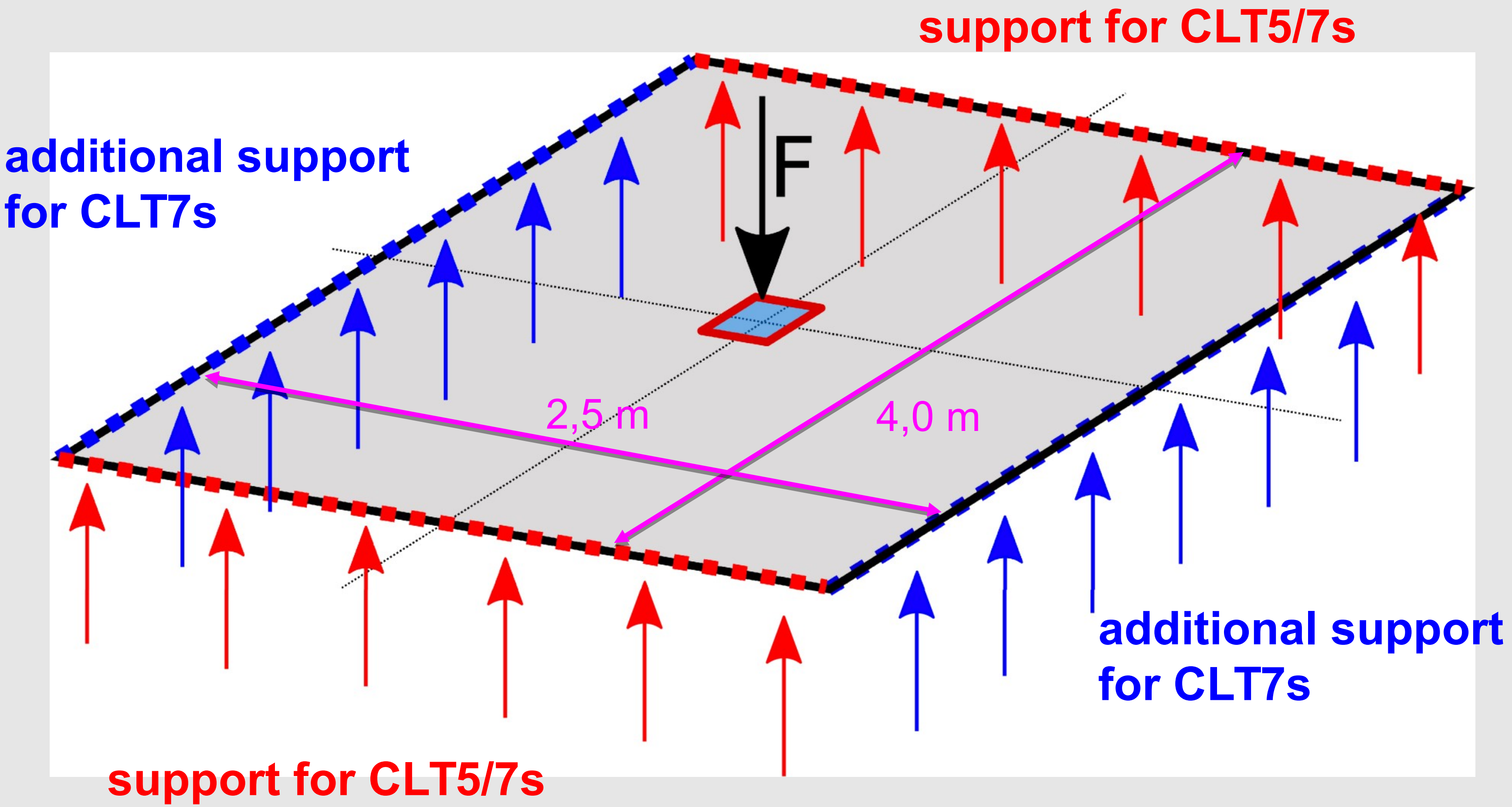
Length effect



$$\frac{f_{t,k,mean}}{f_{t,k,ref,mean}} = \left(\frac{l}{l_{ref}}\right)^{-\alpha} = \left(\frac{70}{150}\right)^{-0,20} = 1,16$$

Tension strength
39 → 45 N/mm²

FEM Model: shell-solid elements



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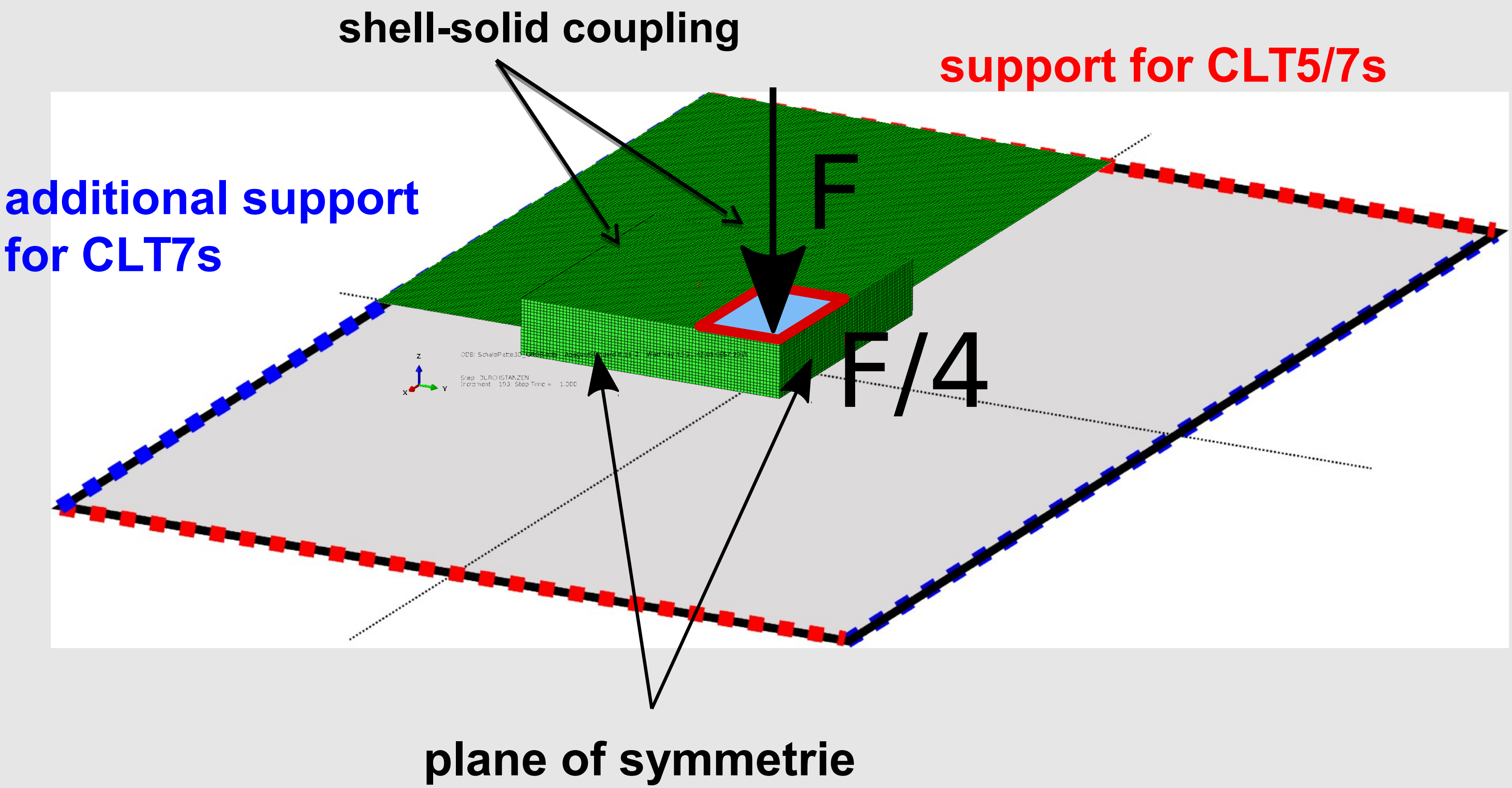
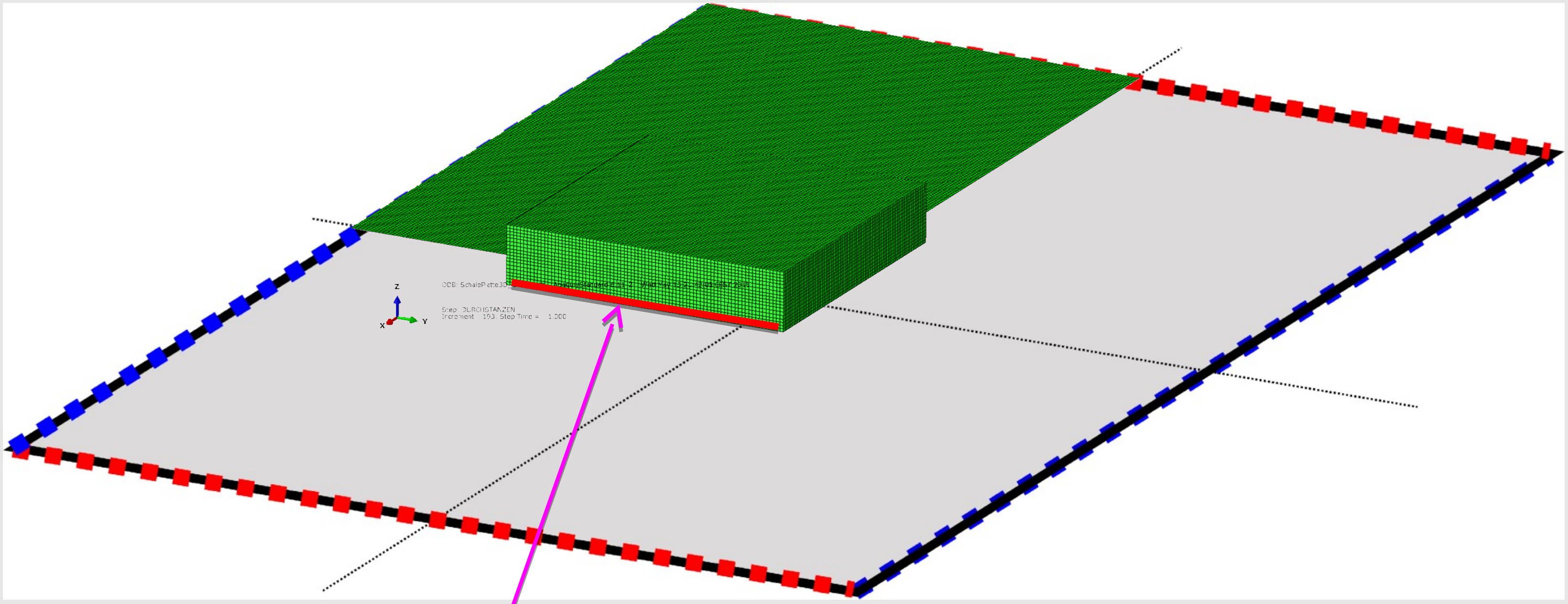
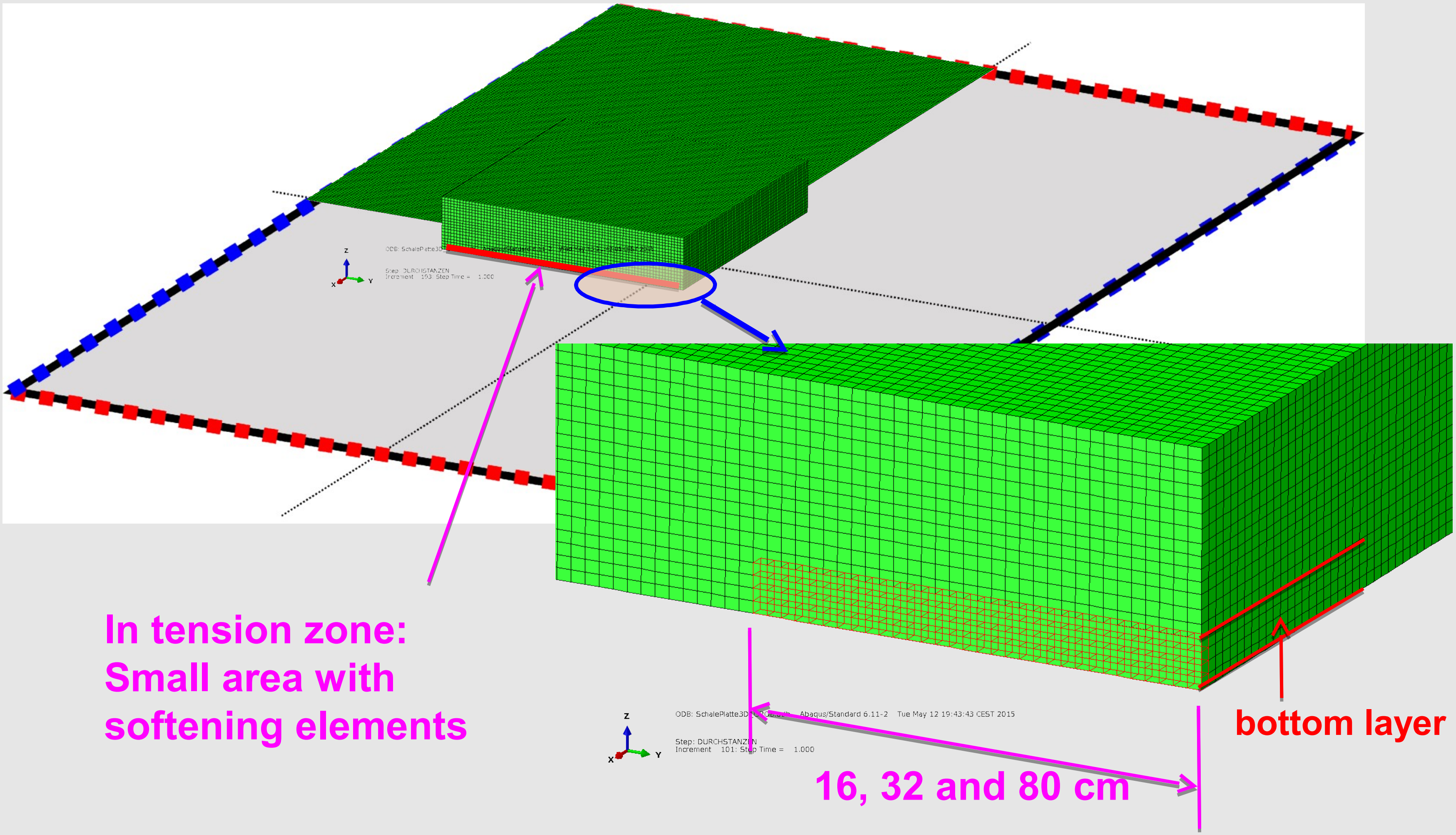


FEM Model: shell-solid elements
CLT 5s (two side support)



In tension zone:
one row of elements with softening material behaviour

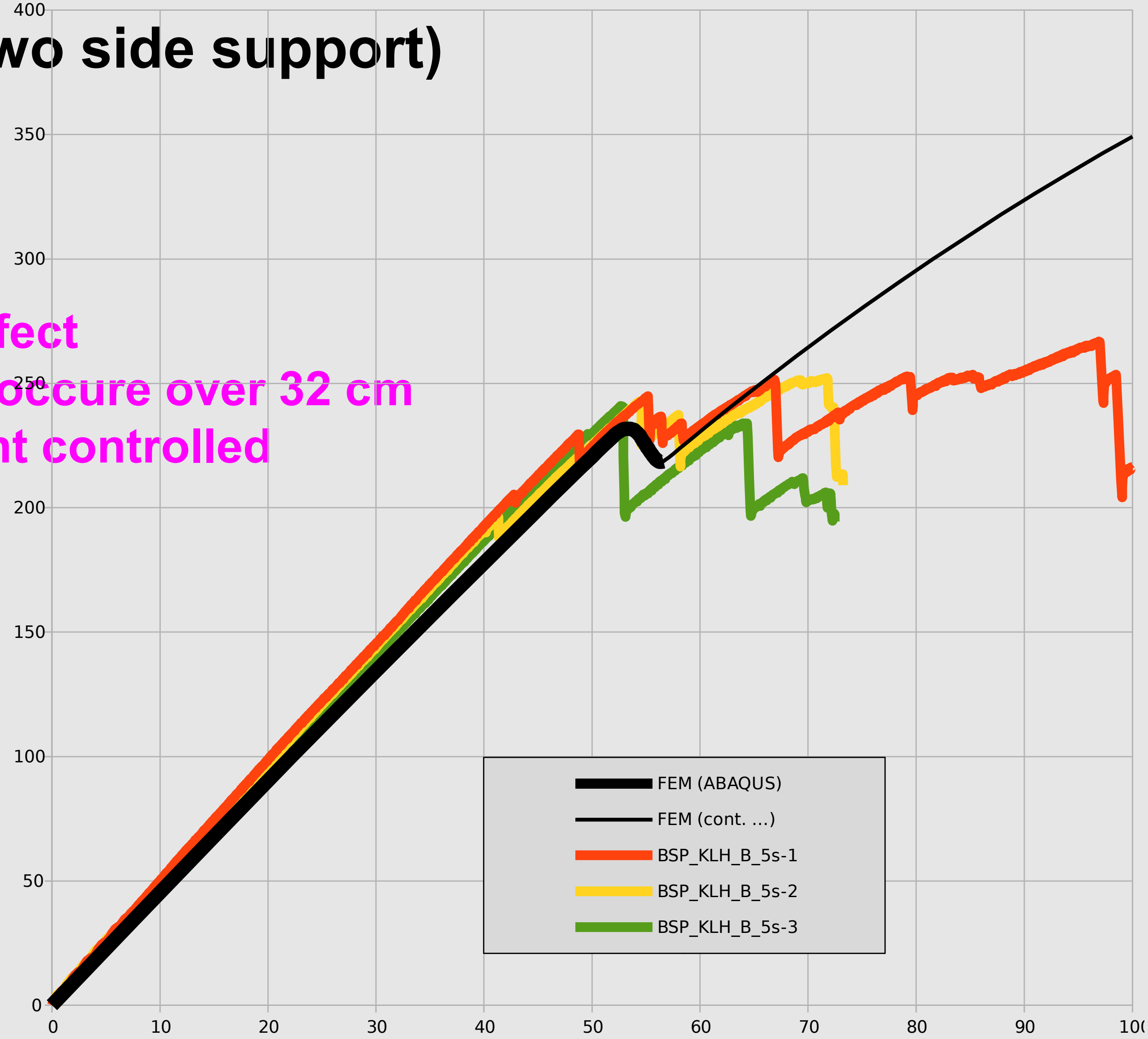
FEM Model: shell-solid elements
CLT 5s (two side support)



CLT5s (two side support)

Model 1:

No length effect
Failure may occure over 32 cm
Displacement controlled



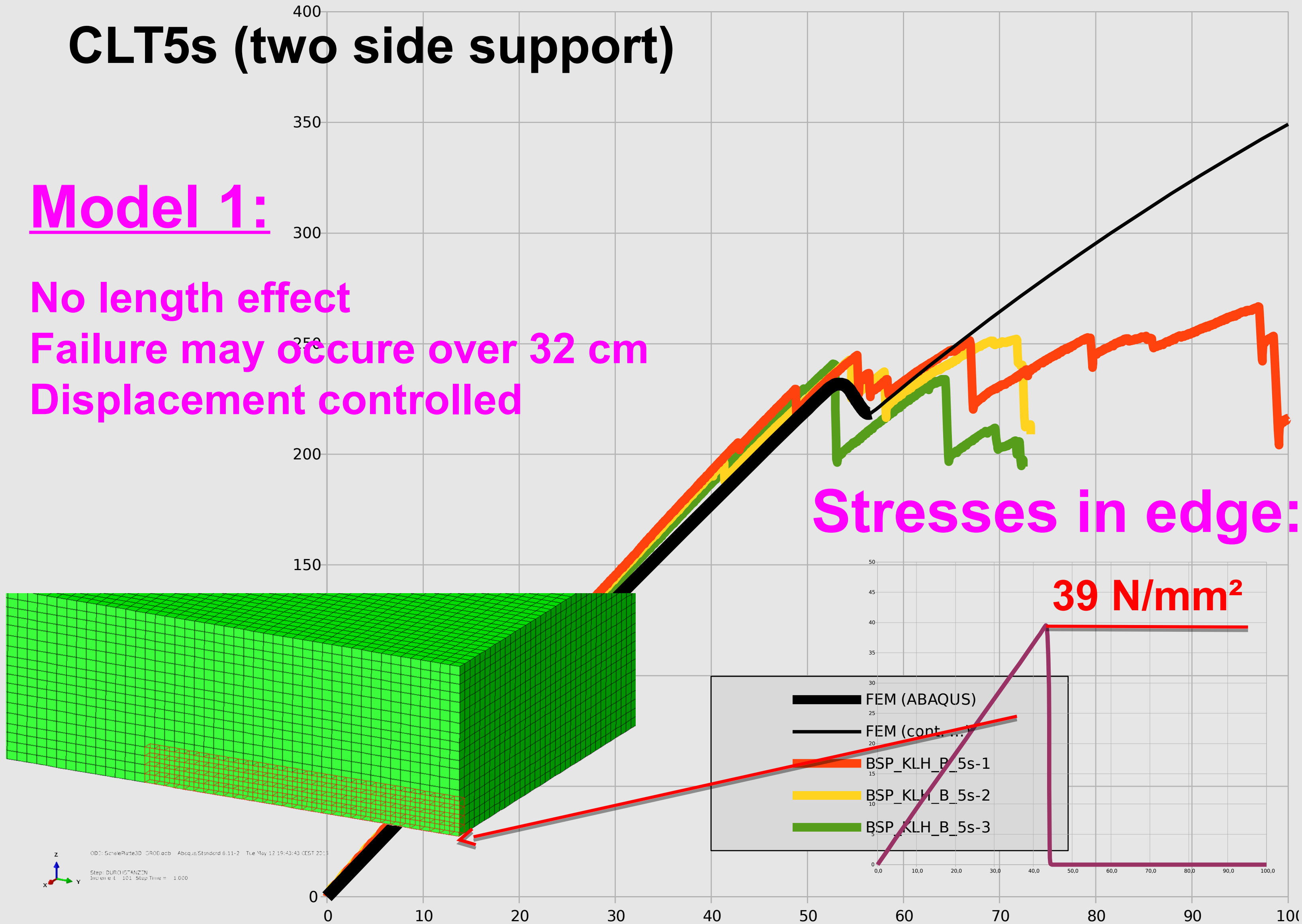
CLT5s (two side support)

Model 1:

No length effect
Failure may occure over 32 cm
Displacement controlled

Stresses in edge:

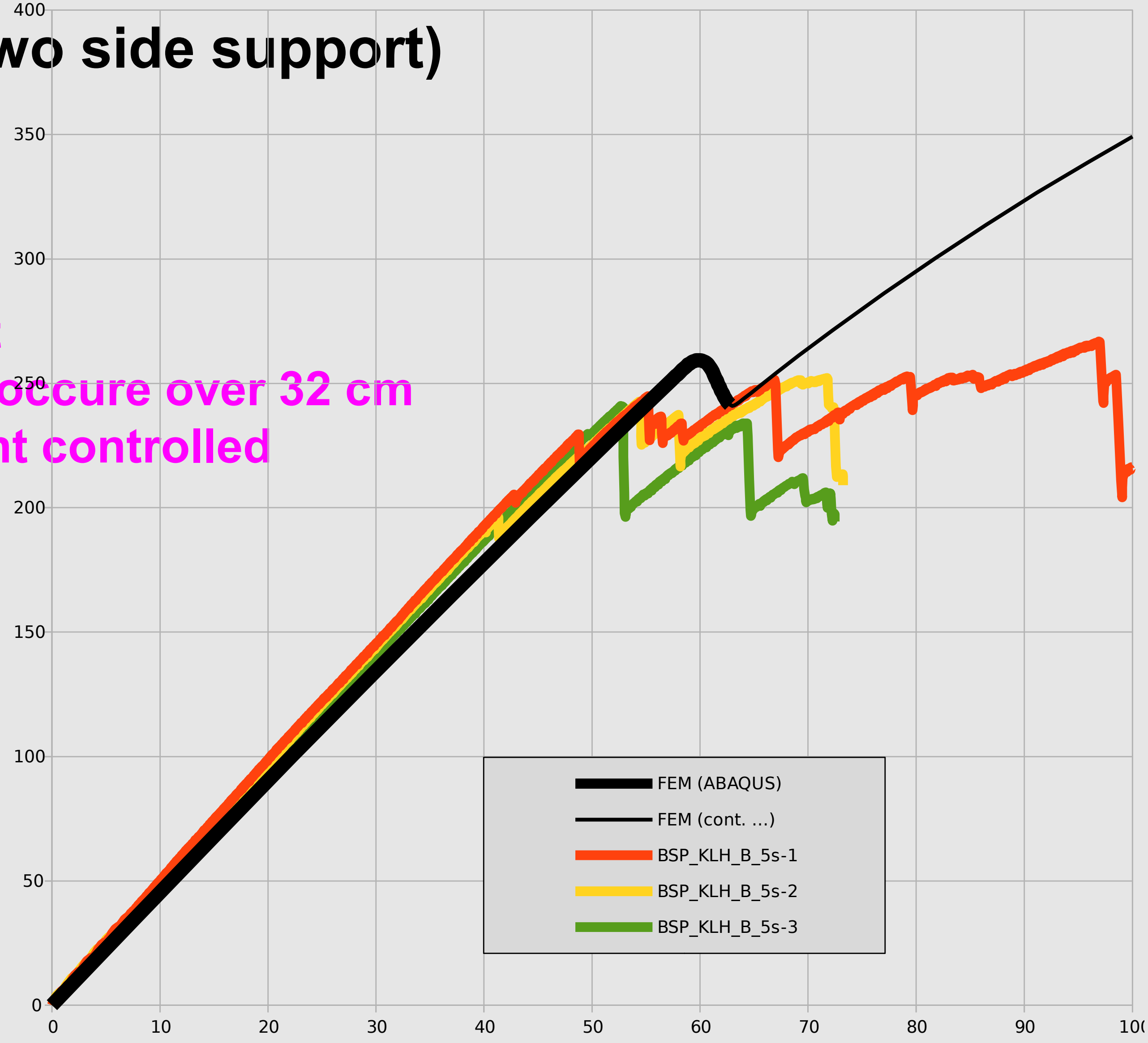
39 N/mm²



CLT5s (two side support)

Model 2:

length effect
Failure may occure over 32 cm
Displacement controlled

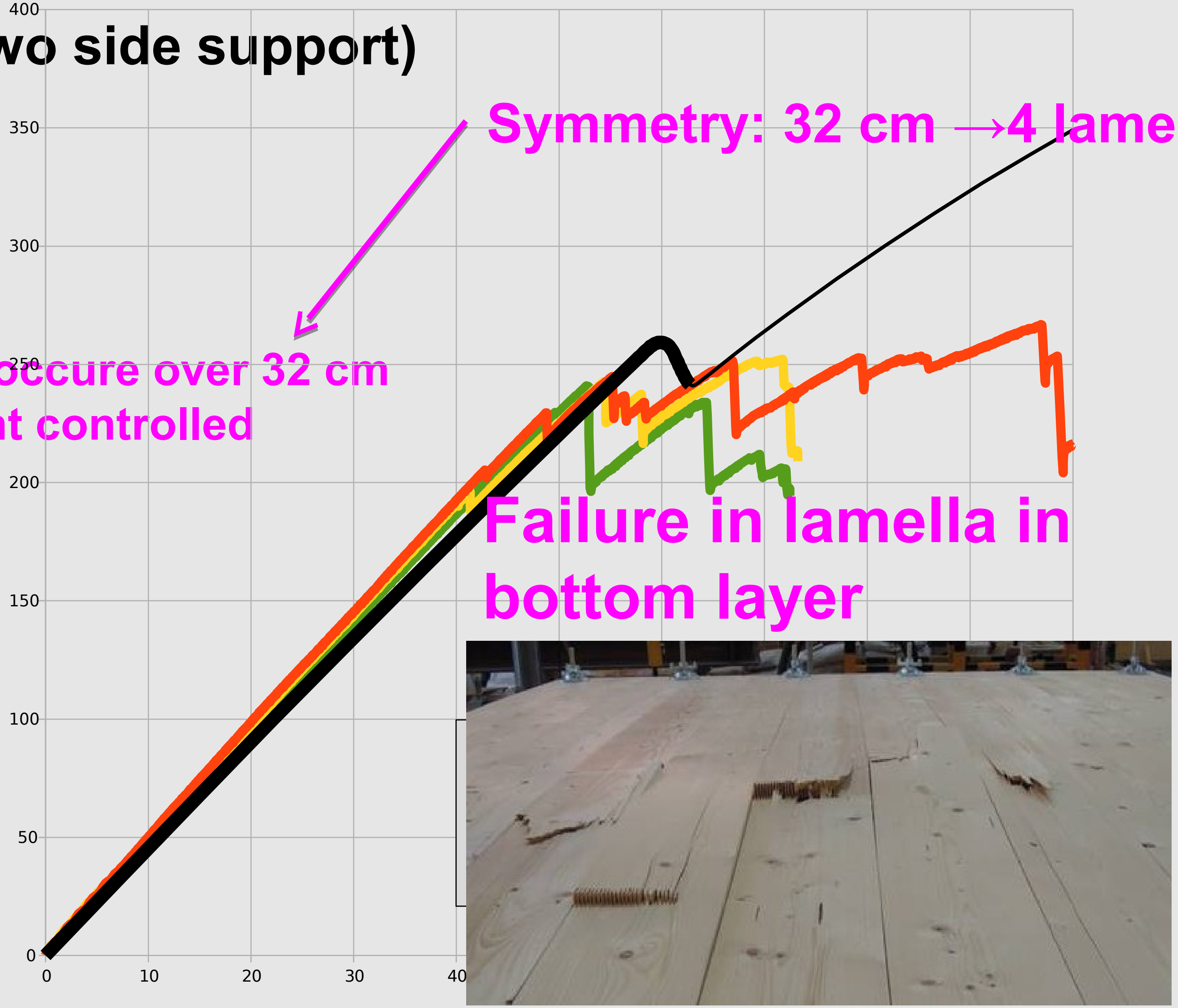


CLT5s (two side support)

Symmetry: 32 cm →4 lamella

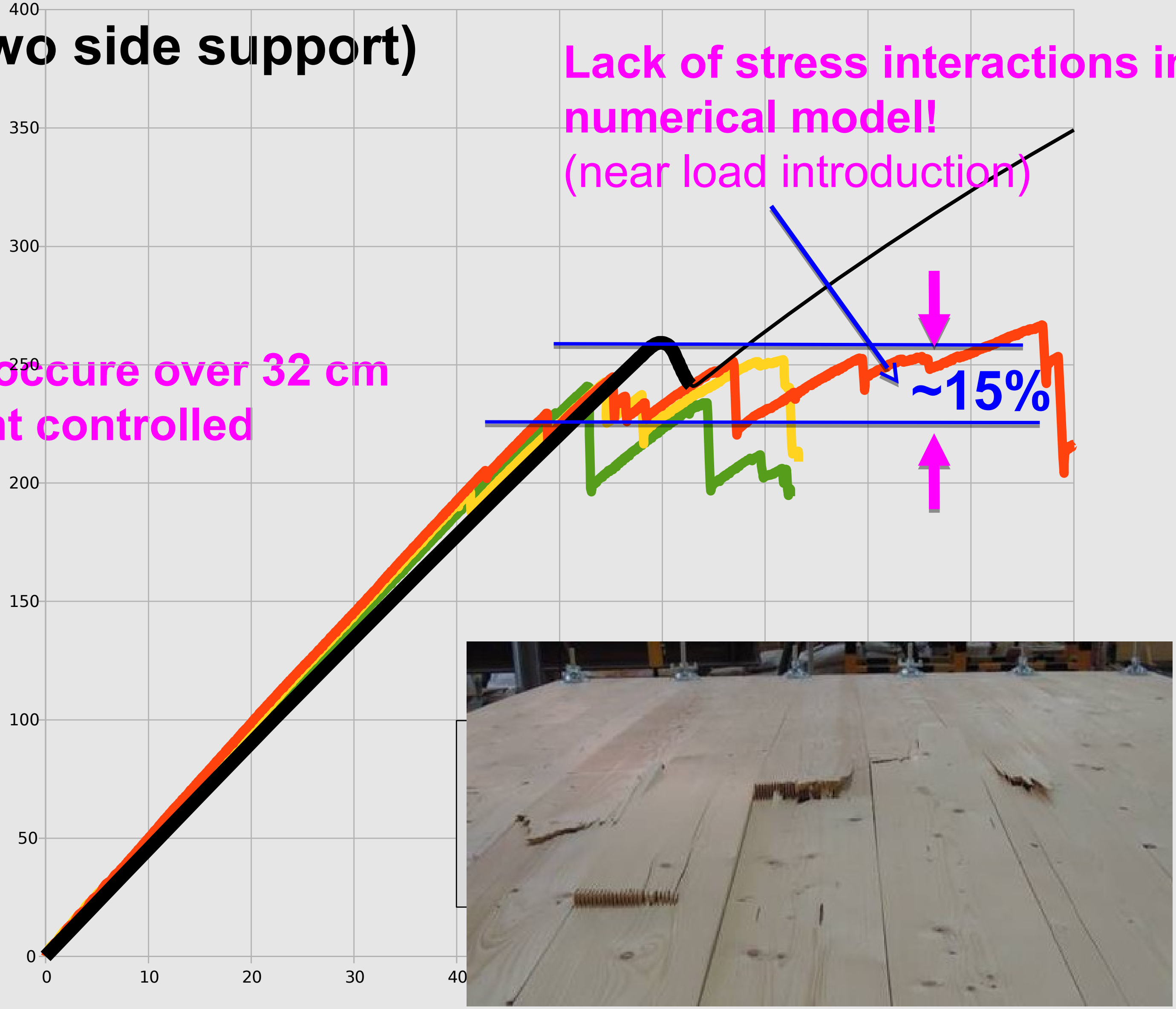
Model 2:

length effect
Failure may occure over 32 cm
Displacement controlled



Failure in lamella in bottom layer

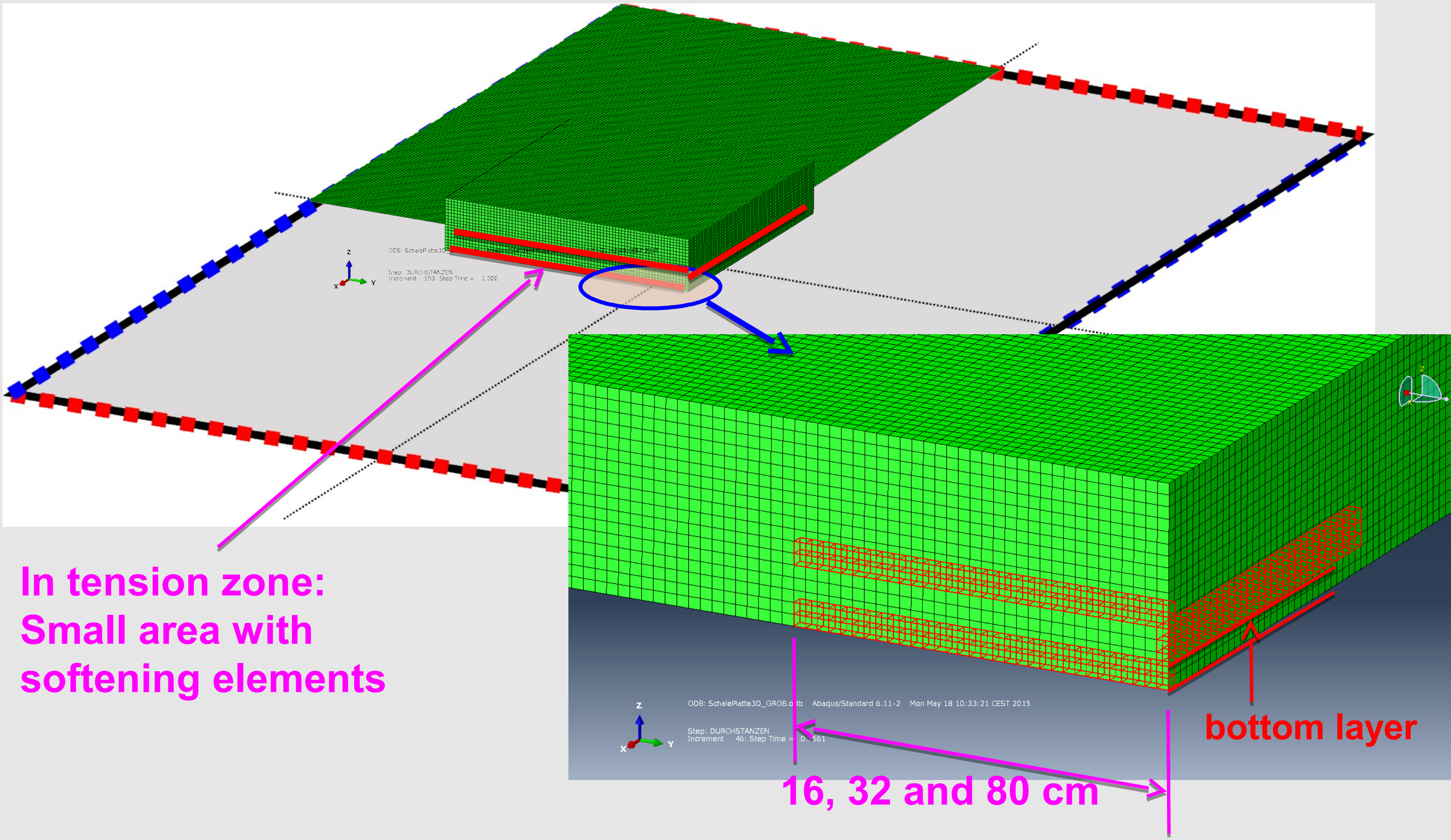
CLT5s (two side support)



Model 2:

length effect
Failure may occure over 32 cm
Displacement controlled

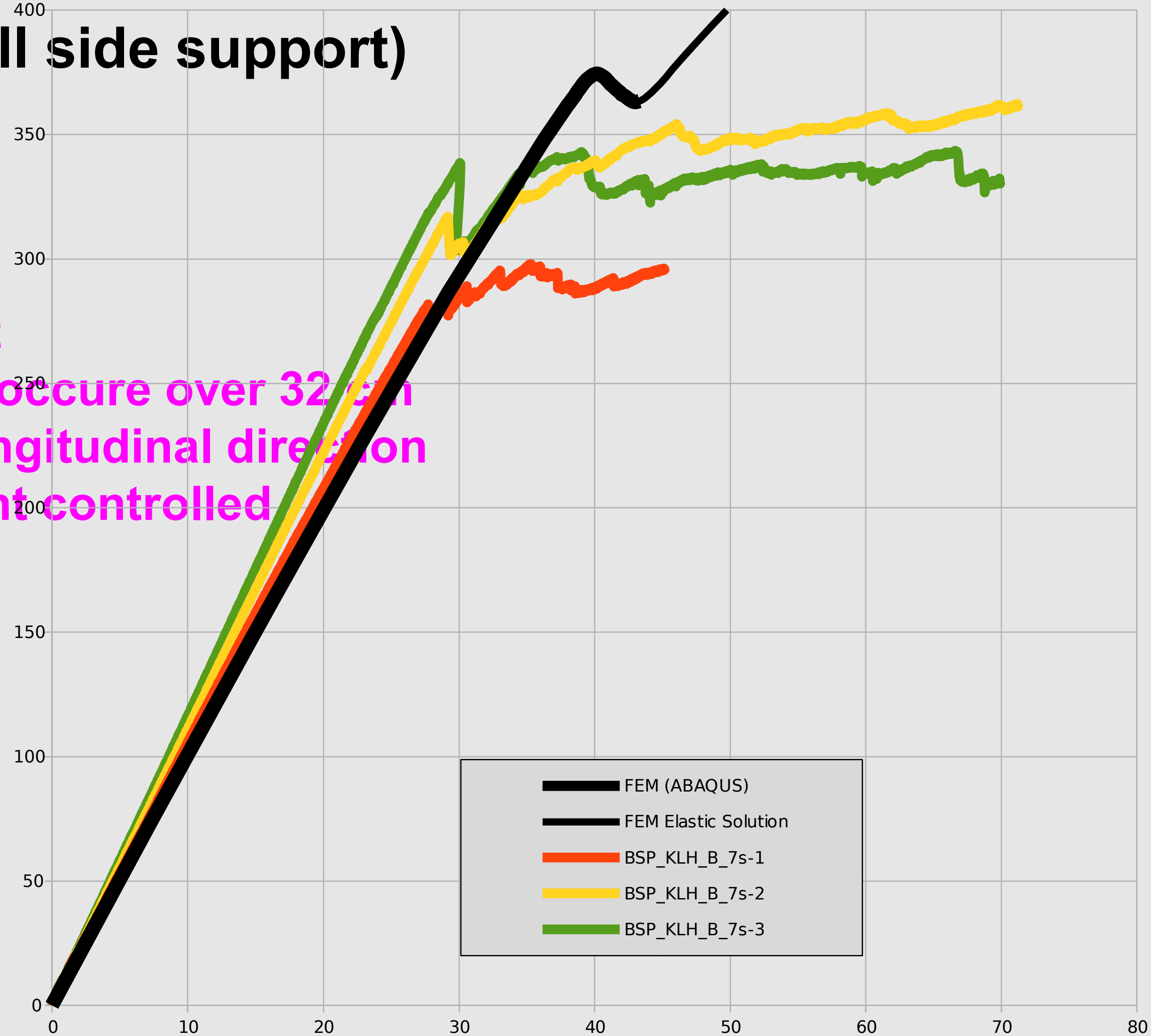
FEM Model: shell-solid elements
CLT 7s (all side support)



CLT7s (all side support)

Model 2:

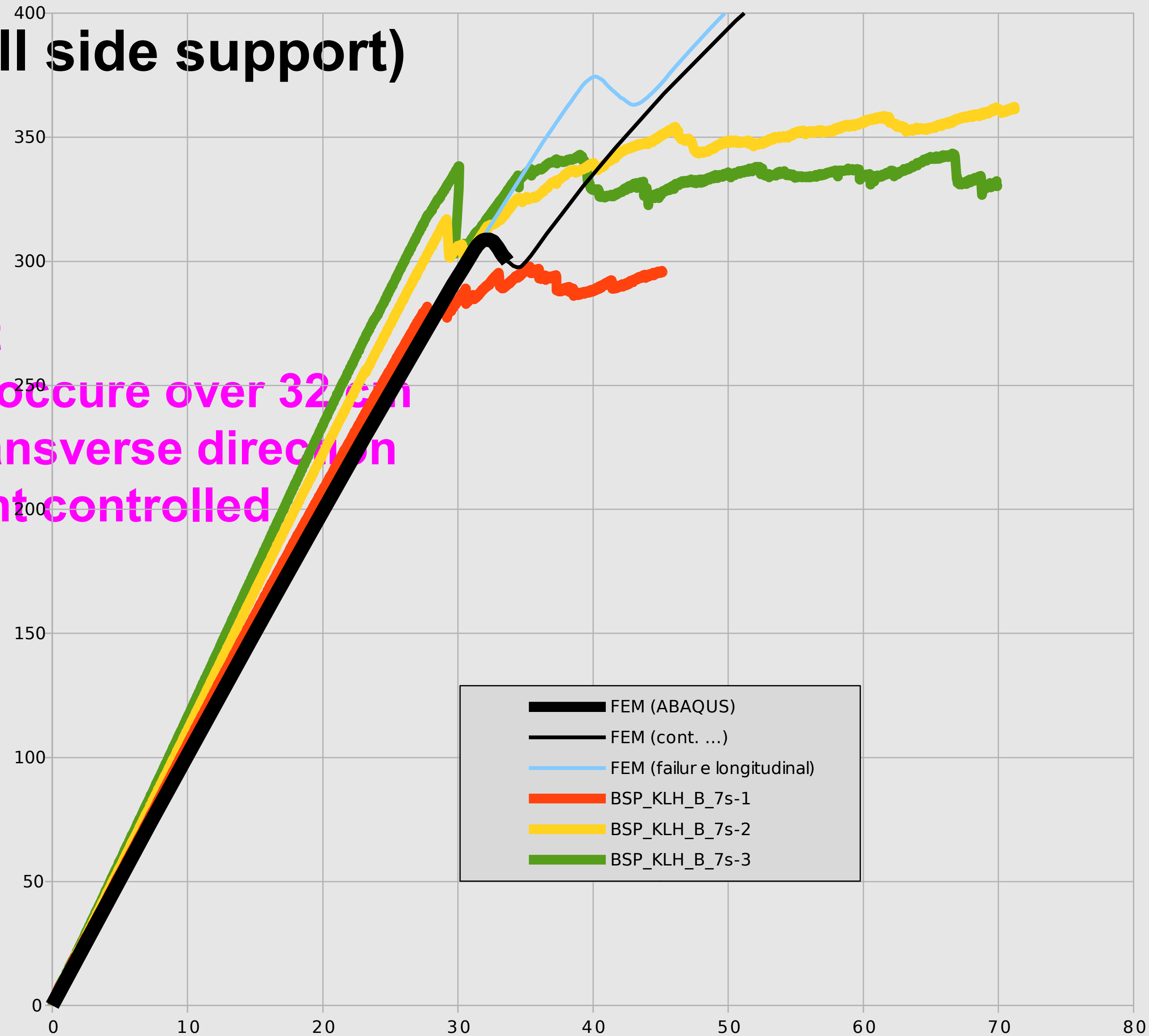
length effect
Failure may occure over 32 cm
Failure in longitudinal direction
Displacement controlled



CLT7s (all side support)

Model 2:

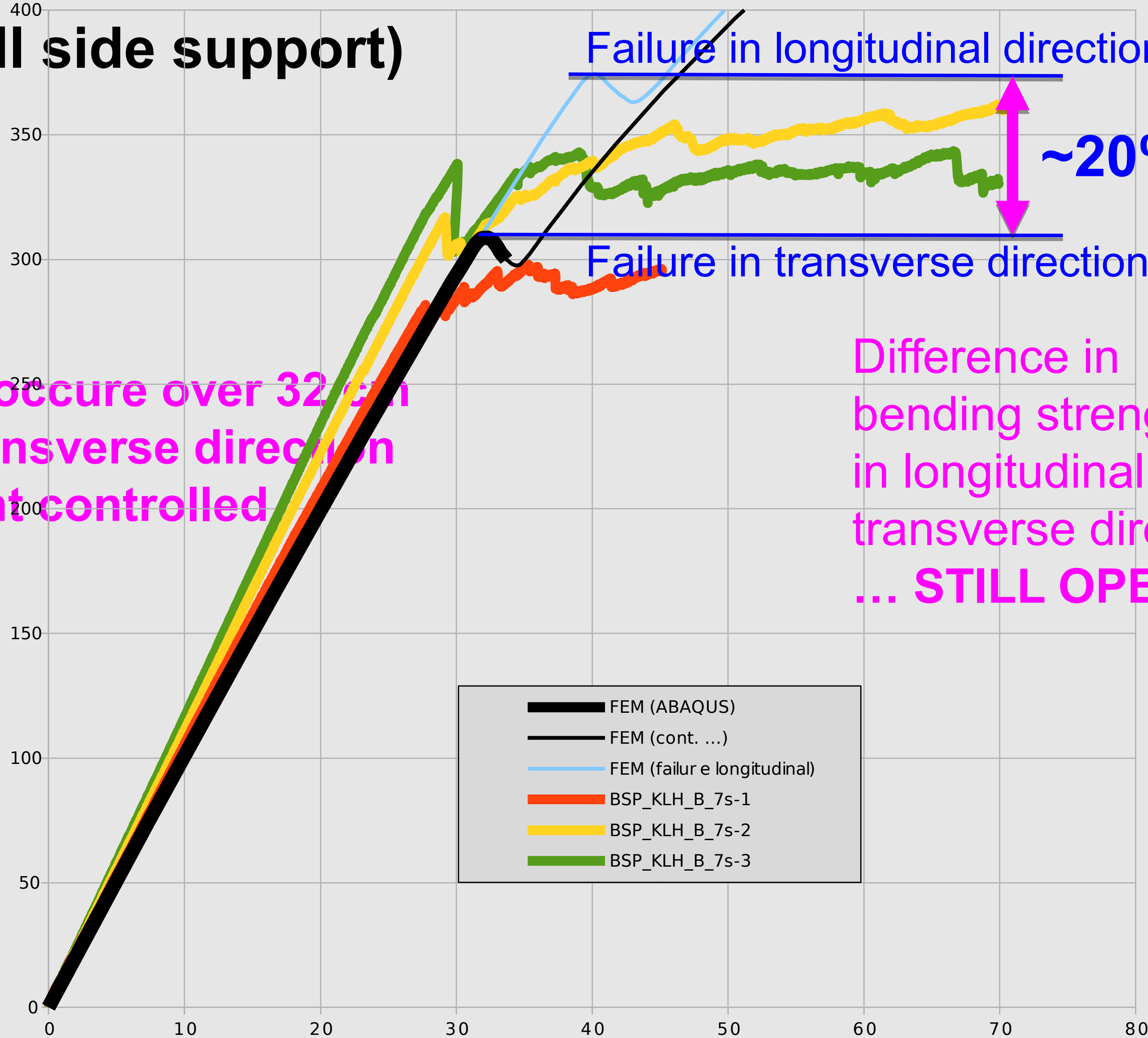
length effect
Failure may occure over 32 cm
Failure in transverse direction
Displacement controlled



CLT7s (all side support)

Model 2:

length effect
Failure may occure over 32 cm
Failure in transverse direction
Displacement controlled



Difference in bending strength in longitudinal and transverse direction
... STILL OPEN!

- **Introduction Cross Laminated Timber (CLT)**
  - Short introduction/motivation
  - Verifications (ULS) of CLT plates under bending/shear (engineering level)
  - Research of Mestek (PhD at Munich University of Technology, 2011)
- **Test configuration**
  - bending configuration geometry, typ of CLT plate, chosen cross sections
  - linear elastic analysis
  - ULS verifications (bending, shear), expected failure modes
  - Outlook: shear configuration
- **Test results**
  - overview of test programm,
  - load displacement curves & statistical evaluation of results
  - observed failure mechanisms
- **Mechanical model**
  - Material parameters/length-effect of brittle material (timber tension members)
  - Numerical model and comparison to test results
- **Summary and outlook**

Summary

- Developed test configurations and test results of local concentrated load introduction into CLT plates were shown. An observed apparently ducilitiy can be explained with the ductility of compression perpendicular to grain.
- Expected and observed failures and load capacities were presented.
- Bending tests were computed with a numerical FE - model. All implemented strength values are deducted from a pool of test results (various research programs, master and diploma thesis).
- Well known length effect is applied to brittle tension strength.
- Good congruence between test tesults and numerical results can be achieved.
- Numerical results are about 15% higher than results from experimental

… and outlook

- This disagreement between numerical model and test results (~15%) can be explained with lack of interaction conditions in strenth model.
  → **IMPLEMENTATION** of MATERIAL with **full coupled stress interactions**
- **Transverse bending strength** seems to be higher than well known bending strength in main direction
  → stress redistribution possible at both sides of layer
  → can be expected up to 20%
  → OPEN field for scientists:
  experimental and/or theoretical based proof is still missing

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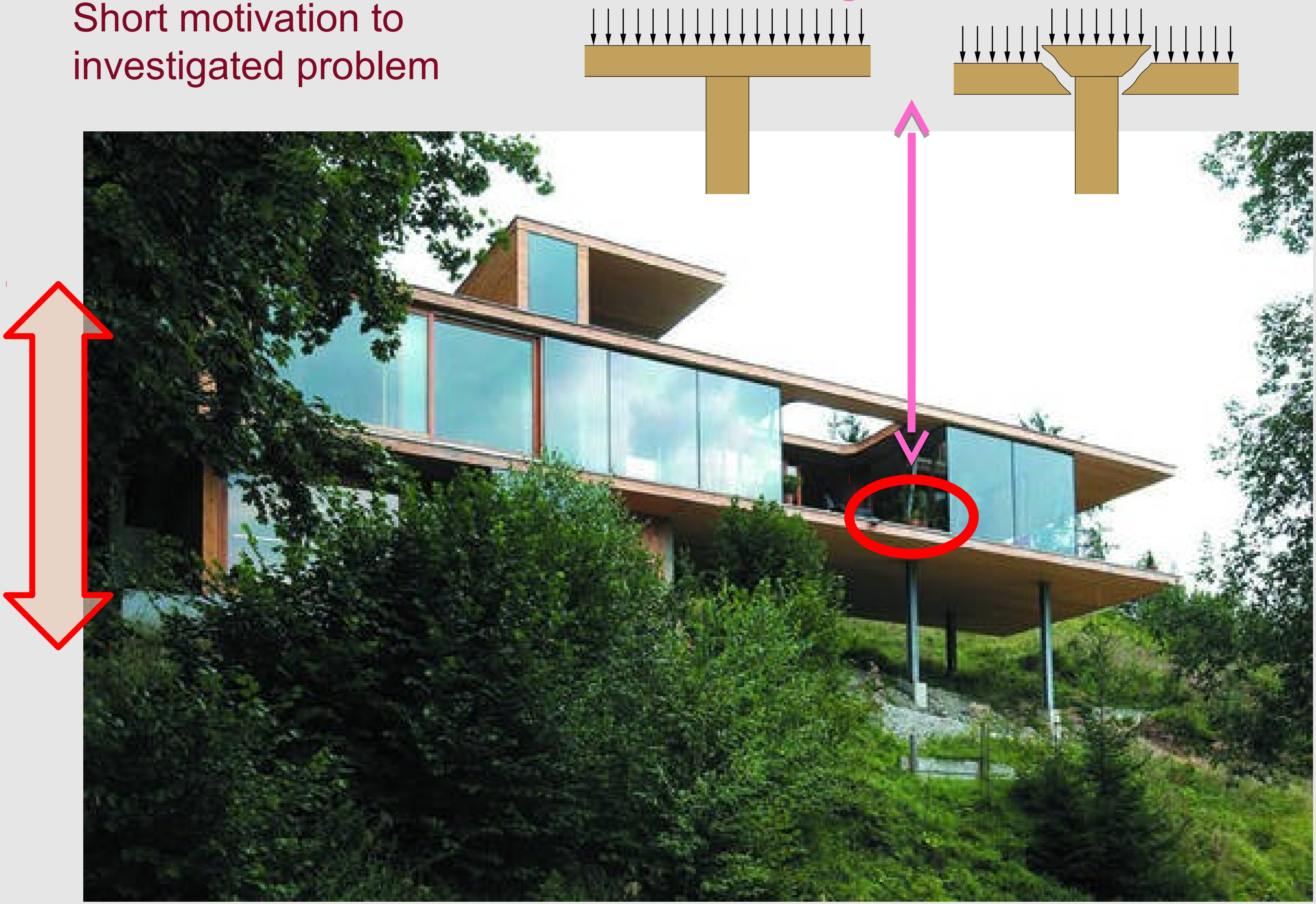
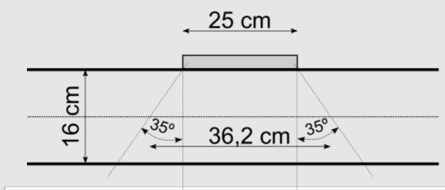
**Das Kompetenzzentrum
für Holzbau und Holztechnologie**
im Bautechnikzentrum
der Technischen Universität Graz

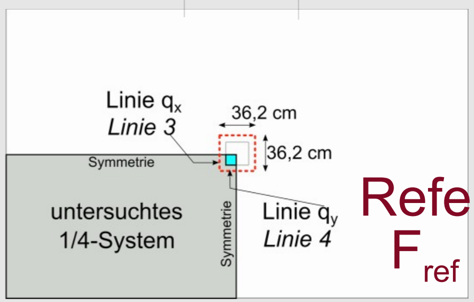
Short motivation to investigated problem

Punching of CLT elements

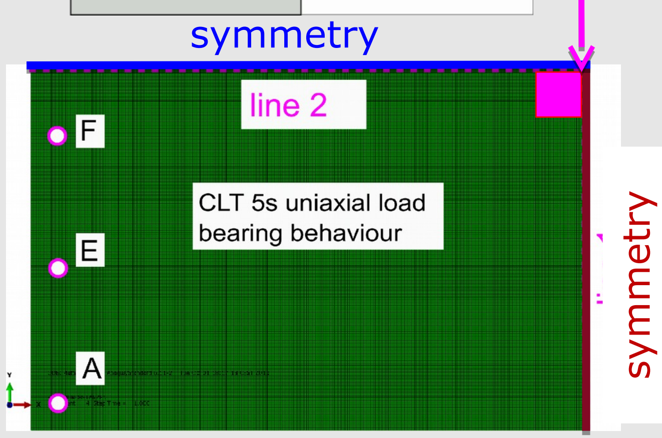


linear elastic analysis

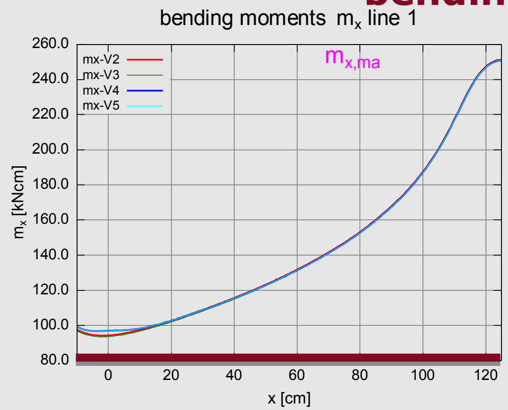


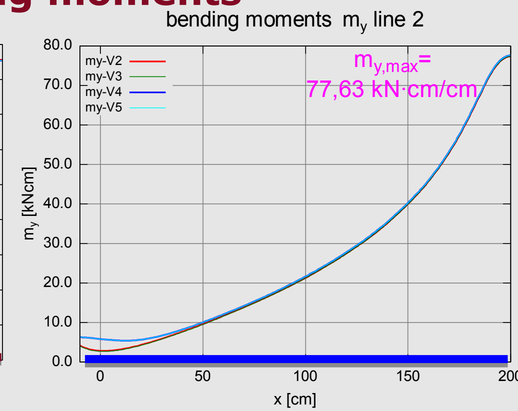


Reference force:
F_{ref} = 400/4 kN

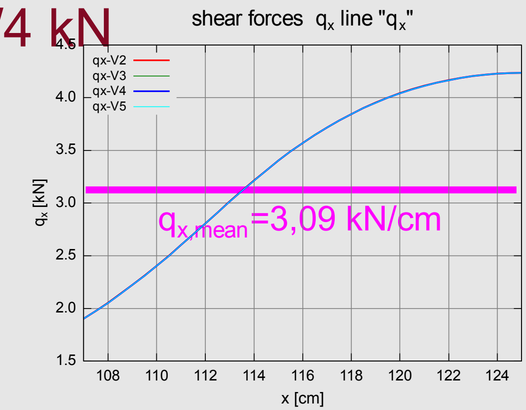


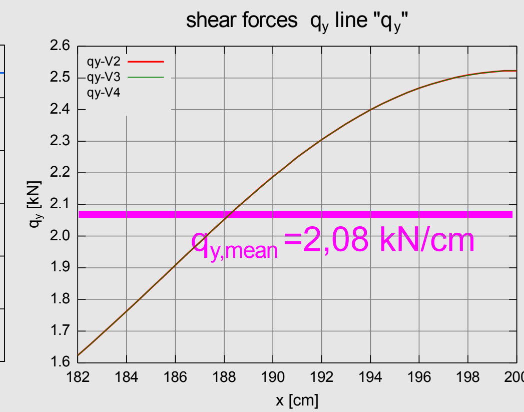
bending moments





shear forces

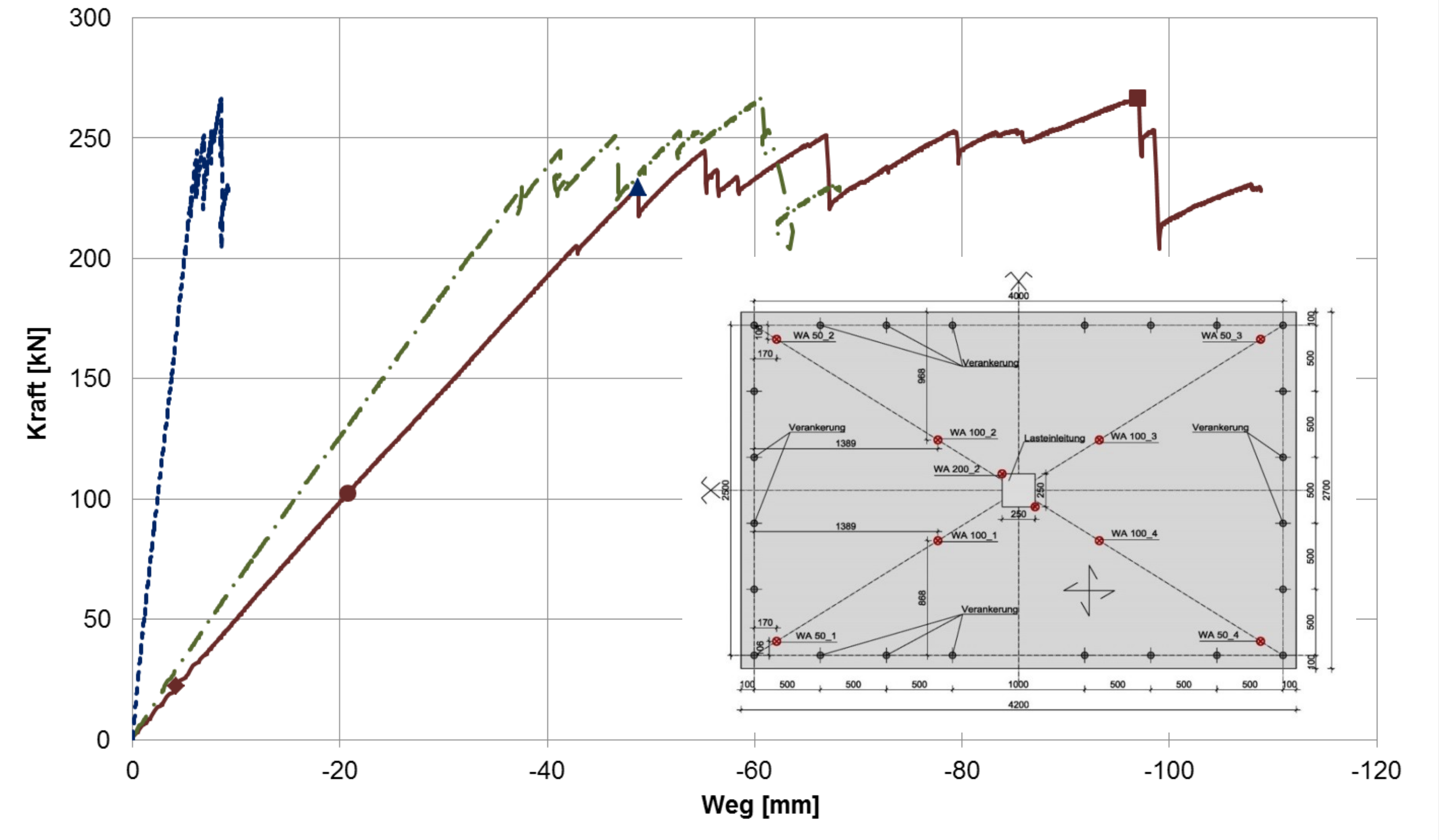




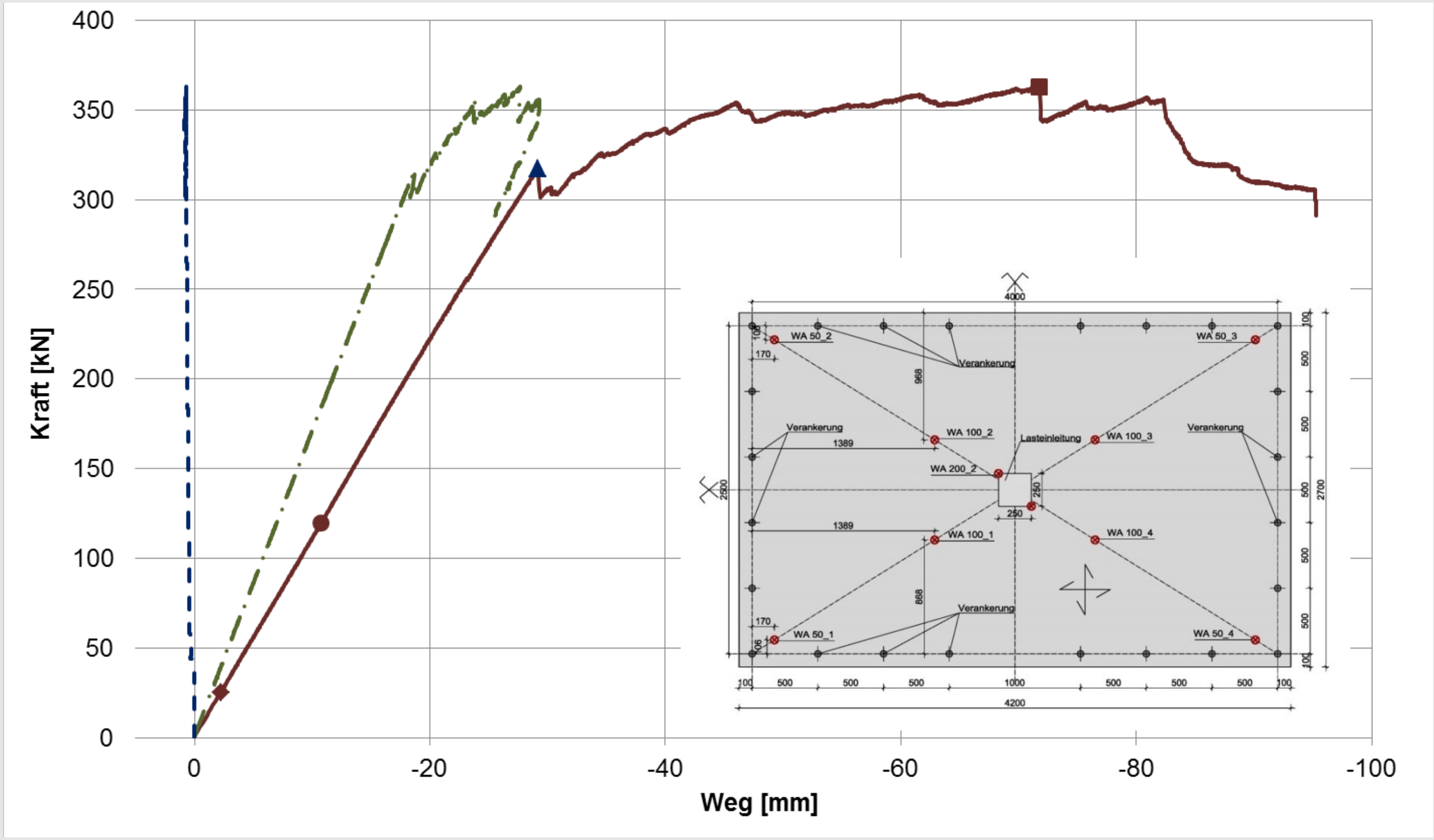
Properties of elected CLT sections

element	E_0	E_{90}	G_0	G_{90}	#	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_{ges}
	N/mm²	N/mm²	N/mm²	N/mm²		mm	mm	mm	mm	mm	mm	mm	**mm**
CLT-5s	11.600	300	690	50	5	34	30	34	30	34	-	-	**162**
CLT-7s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Experimental load displacement curves for CLT 5s



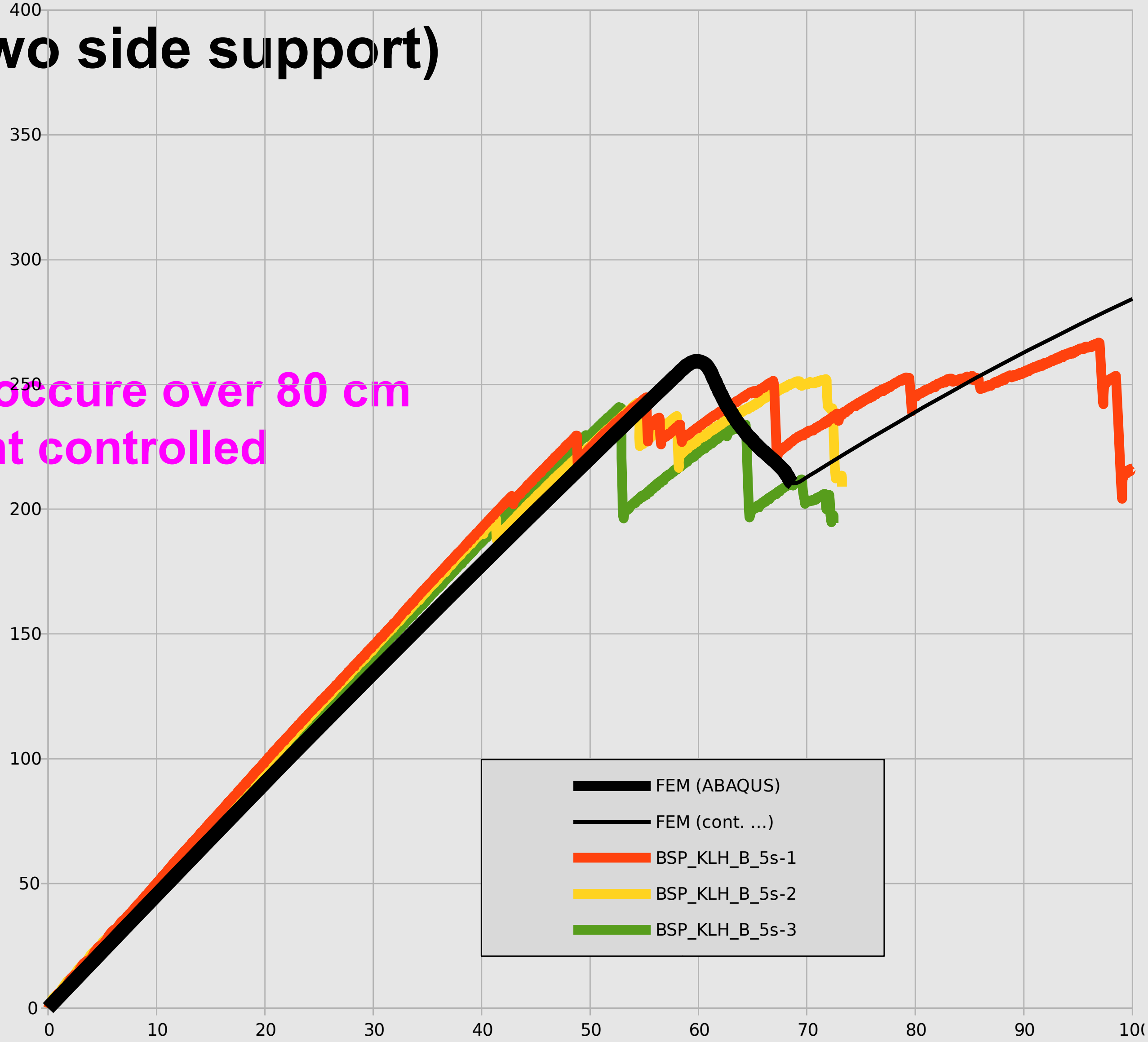
Experimental load displacement curves for CLT 7s



CLT5s (two side support)

Model 3:

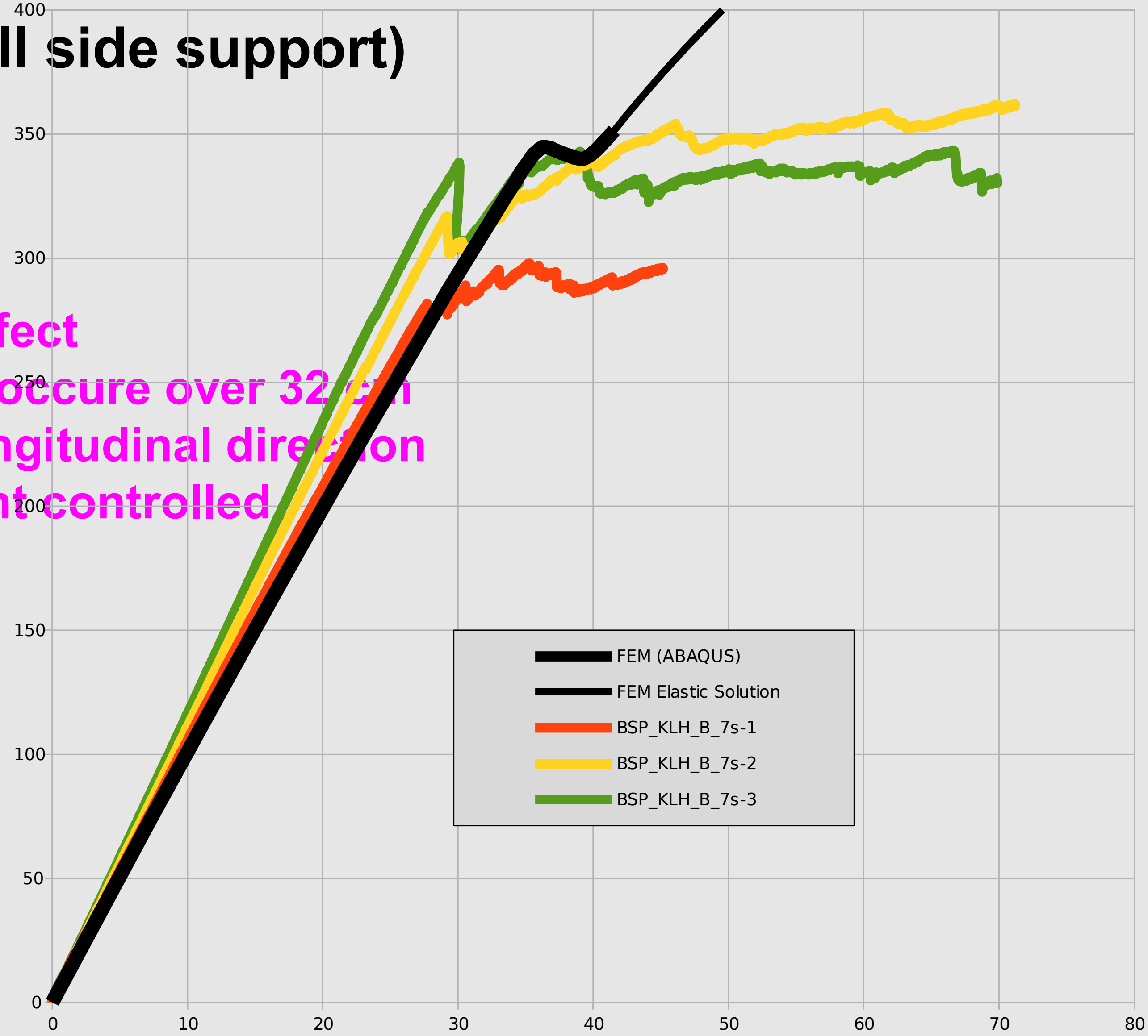
length effect
Failure may occure over 80 cm
Displacement controlled



CLT7s (all side support)

Model 1:

No length effect
Failure may occure over 32 cm
Failure in longitudinal direction
Displacement controlled



CLT7s (all side support)

Model 1:

No length effect
Failure may occure over 32 cm
Failure in transverse direction
Displacement controlled