Empa

Materials Science and Technology

Flexural strengthening of reinforced concrete according to Swiss Code 166 (2024)

ETH Lecture 101-0167-01L

Fibre Composite Materials in Structural Engineering

Christoph Czaderski

23. October 2024

Program overview of the lectures and laboratory work

- Wednesday 23.10.2024, 15:45-17:30 (ETH Hönggerberg, HIL E10.1)
  - Lecture on Flexural Strengthening
  - Preparations for laboratory competition (Beam) and second written intermediate exam

- Wednesday 13.11.2024, 15:45-17:30 (Empa Dübendorf)
  - Meeting point at ETH Hönggerberg 15:30!! Transport organized by Empa.
  - Application of Externally Bonded FRP Reinforcement (Confinement) for laboratory competition
  - Video of the beam failure test
  - Empa structural laboratory tour (if time available)

- Wednesday 11.12.2024, 15:45 – ca. **18:00** (Empa Dübendorf)
  - Meeting point at ETH Hönggerberg 15:30!! Transport organized by Empa.
  - Laboratory experiments and awarding of lab competition
  - Second written interim exam

Overview of the lecture

- Information about the second written intermediate exam
- Introduction
- Bond between CFRP strip and concrete
    - Lap-shear test
    - Slip, Bond shear stress and Bond shear stress-Slip-Relation
    - Simplified modeling
- Debonding failure modes according to the old and the new SIA 166
- Summary, debonding failure modes treated in SIA 166
- Example
- Video of CFRP strip application on a beam, competition on prediction of failure load
- Several additional topics according to SIA 166

Content of the second exam on 11.12.2024, 15:45 - ca. 18:00!!! at Empa Dübendorf

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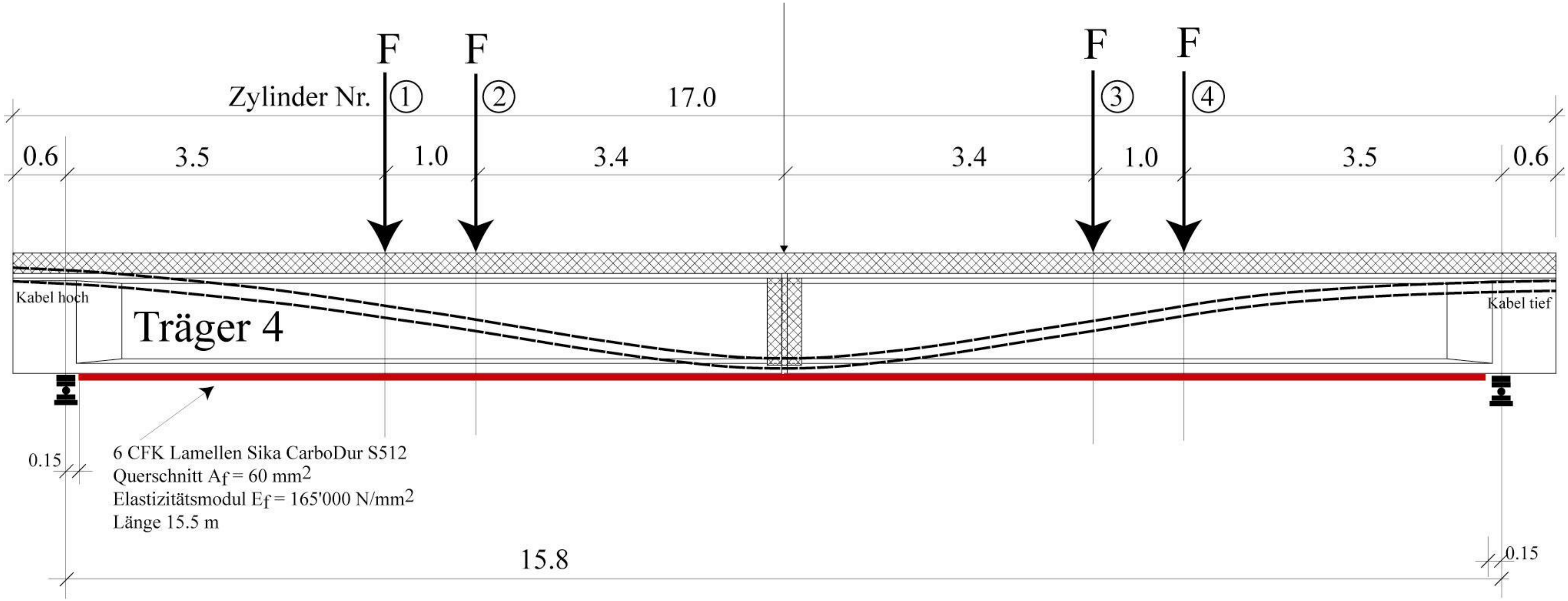
Topics:

- Flexural strengthening of RC according to SIA166
  Lecture from 23.10.2024, Lecturer Dr. C. Czaderski
- Column confinement of RC
  Lecture from 30.10.2024, Lecturer Prof. Dr. M. Motavalli
- Externally bonded FRP reinforcement for metallic structures
  Lecture from 06.11.2024, Lecturer Dr. H. Heydarinouri
- Design of FRP profiles and all FRP structures
  Lecture from 04.12.2024, Lecturer Prof. Dr. M. Shahverdi
- Conceptual questions on the topics which were presented in the mentioned lectures. Furthermore, some calculations have to be performed.

- Time: 60 Minutes
- No laptops, tablets, smart phones etc.
- Only a calculator
- One A4 – Summary (both sides or two pages one side)

Introduction

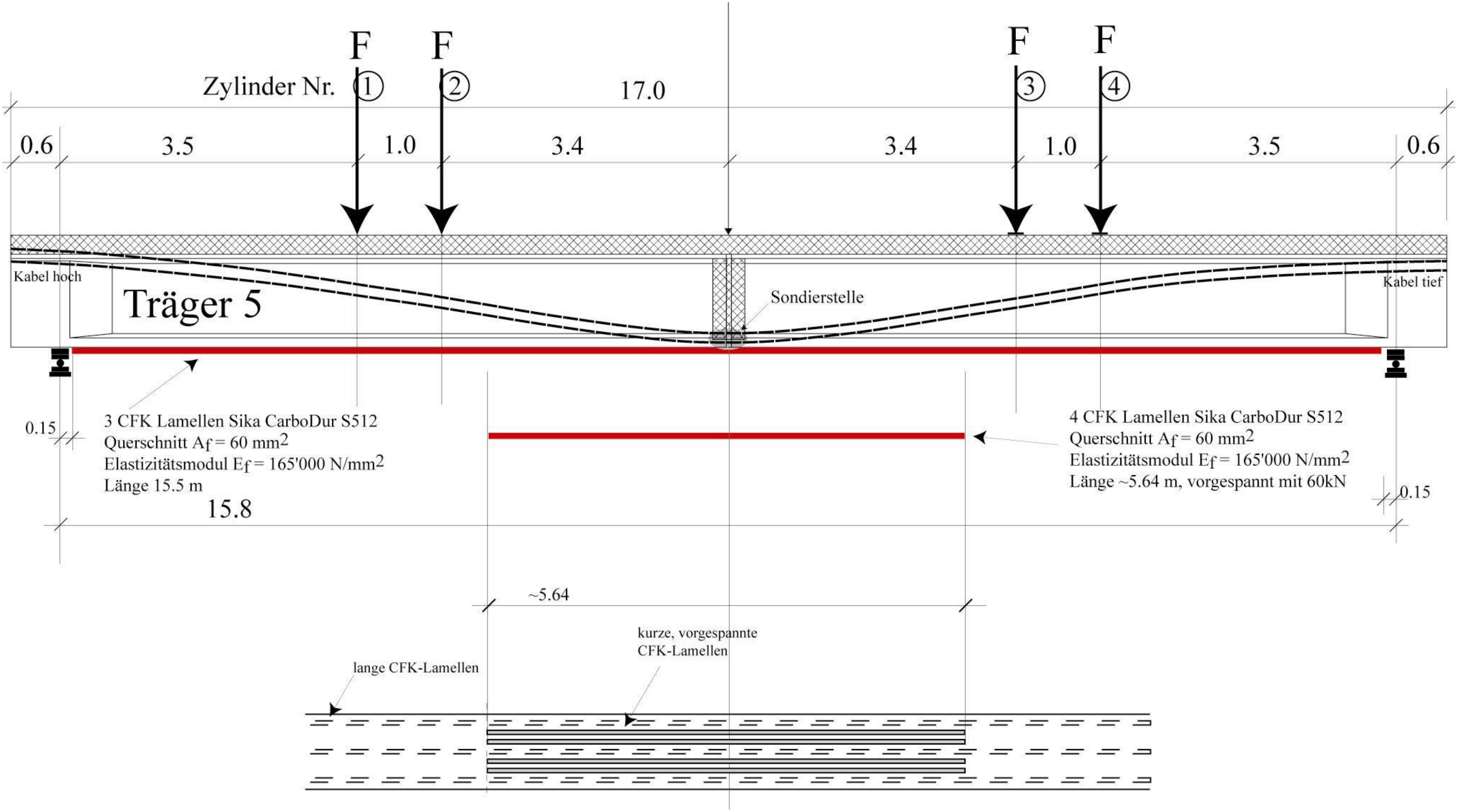

EMPA
4
F = 421 KN



6 CFK Lamellen Sika CarboDur S512
Querschnitt $A_f = 60\ \mathrm{mm}^2$
Elastizitätsmodul $E_f = 165'000\ \mathrm{N/mm}^2$
Länge 15.5 m


F = 421 KN


2 (4/11)
EMPA



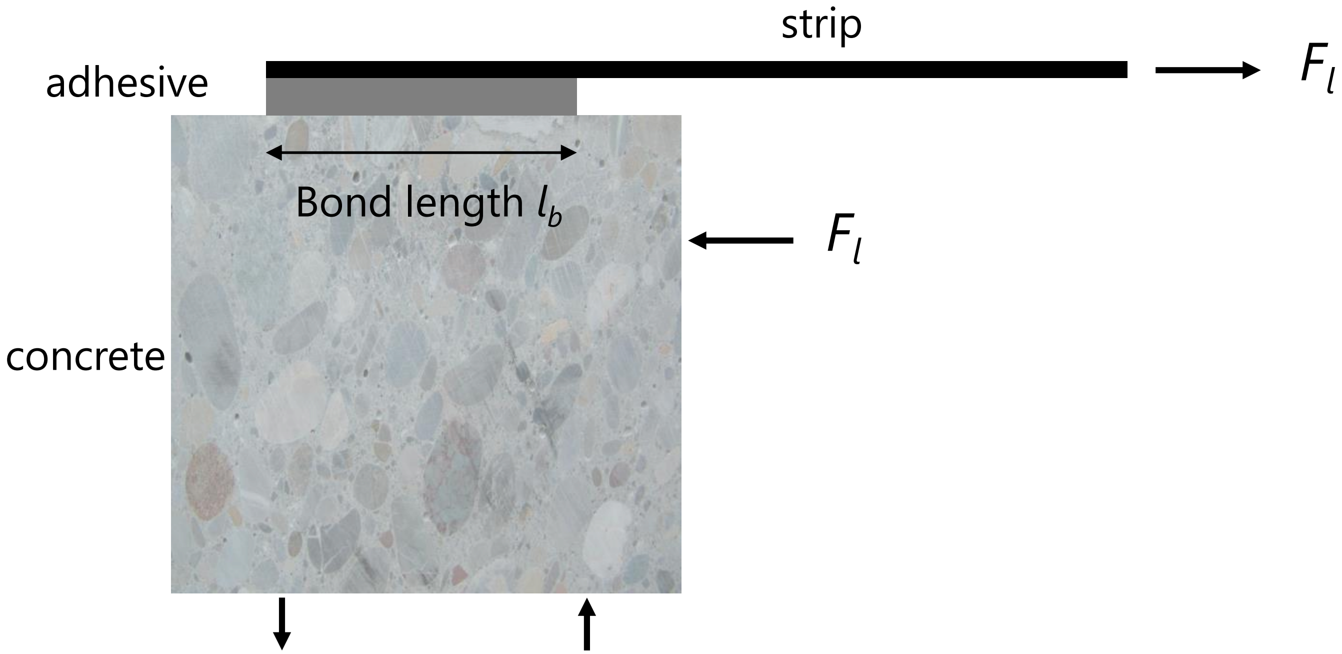
3 CFK Lamellen Sika CarboDur S512
Querschnitt $A_f = 60\ \text{mm}^2$
Elastizitätsmodul $E_f = 165'000\ \text{N/mm}^2$
Länge 15.5 m

4 CFK Lamellen Sika CarboDur S512
Querschnitt $A_f = 60\ \text{mm}^2$
Elastizitätsmodul $E_f = 165'000\ \text{N/mm}^2$
Länge ~5.64 m, vorgespannt mit 60kN

EMPA

Bond between CFRP strip and concrete

Lap-shear test



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EMPA

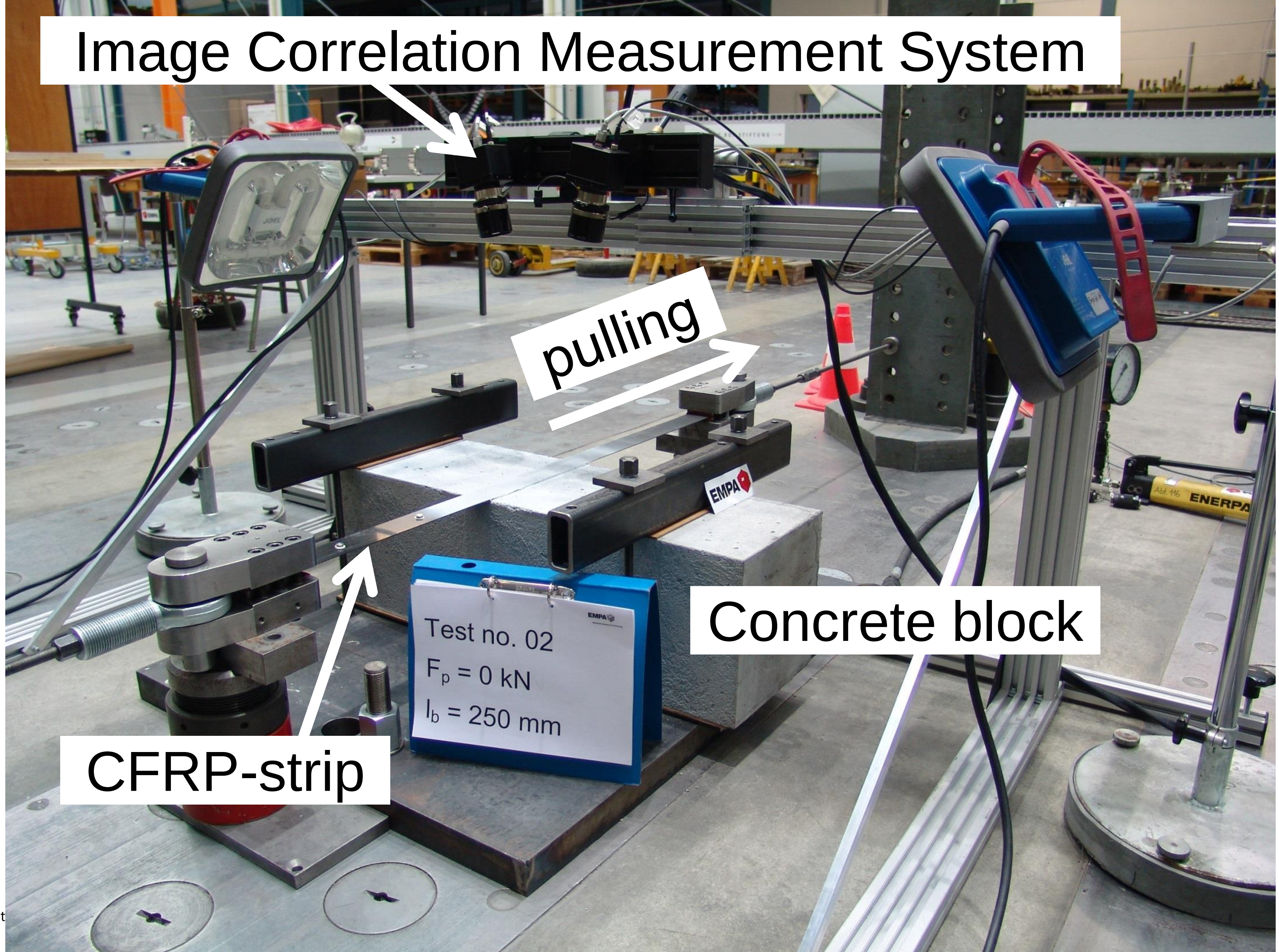
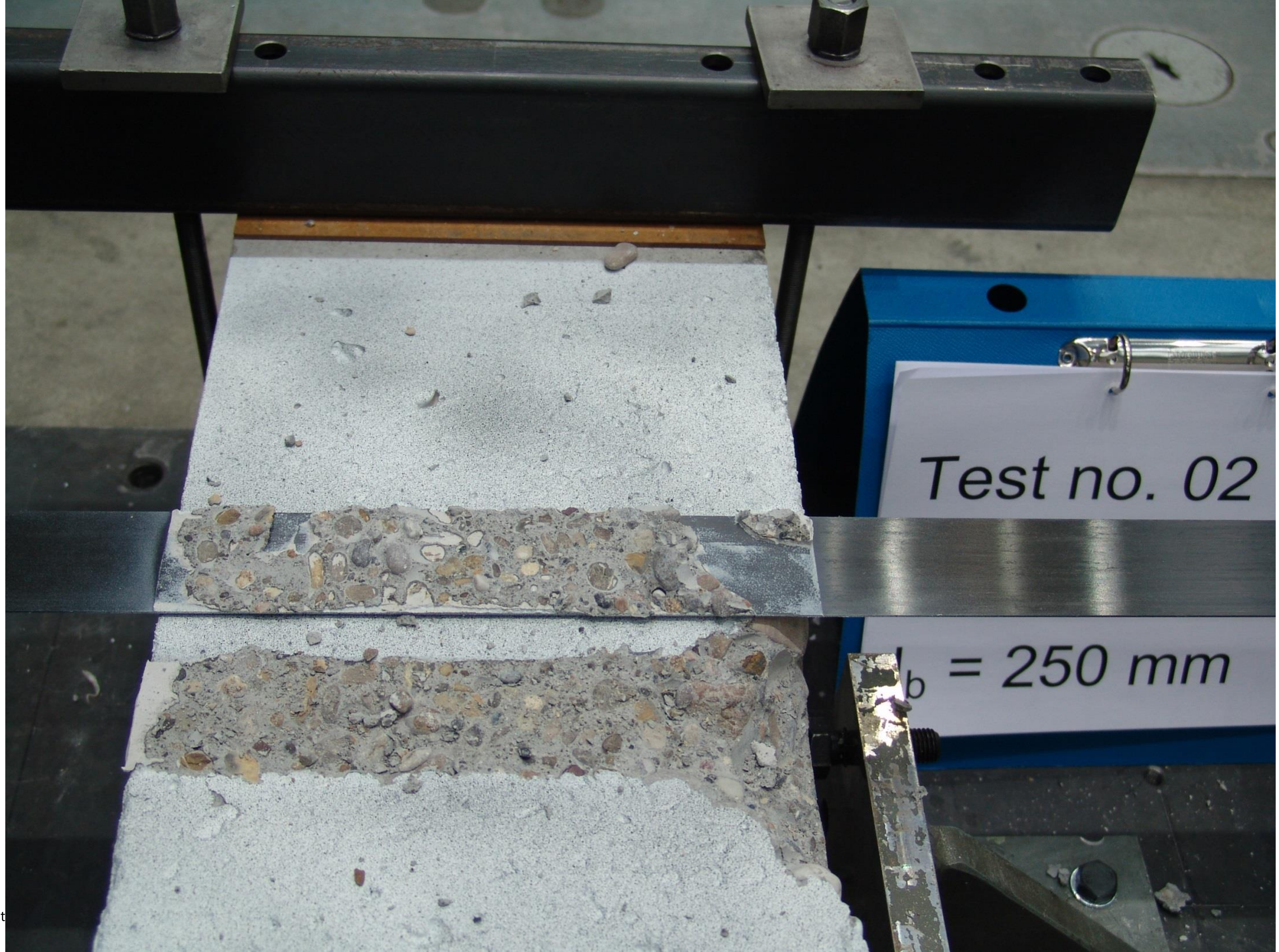


Image Correlation Measurement System
pulling
Concrete block
CFRP-strip
EMPA
Test no. 02
F_p = 0 kN
l_b = 250 mm
ENERPAC


Test no. 02
l_b = 250 mm

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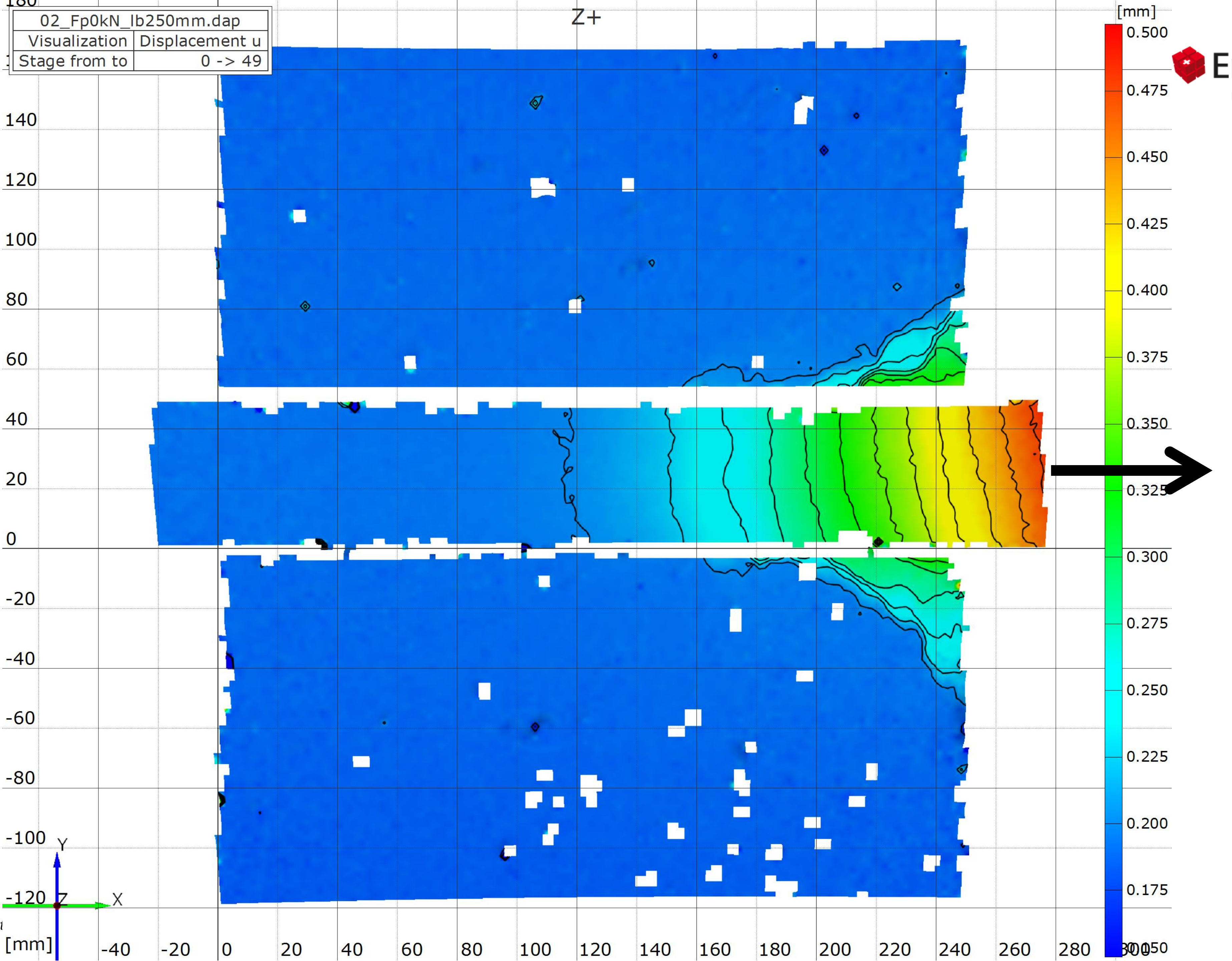
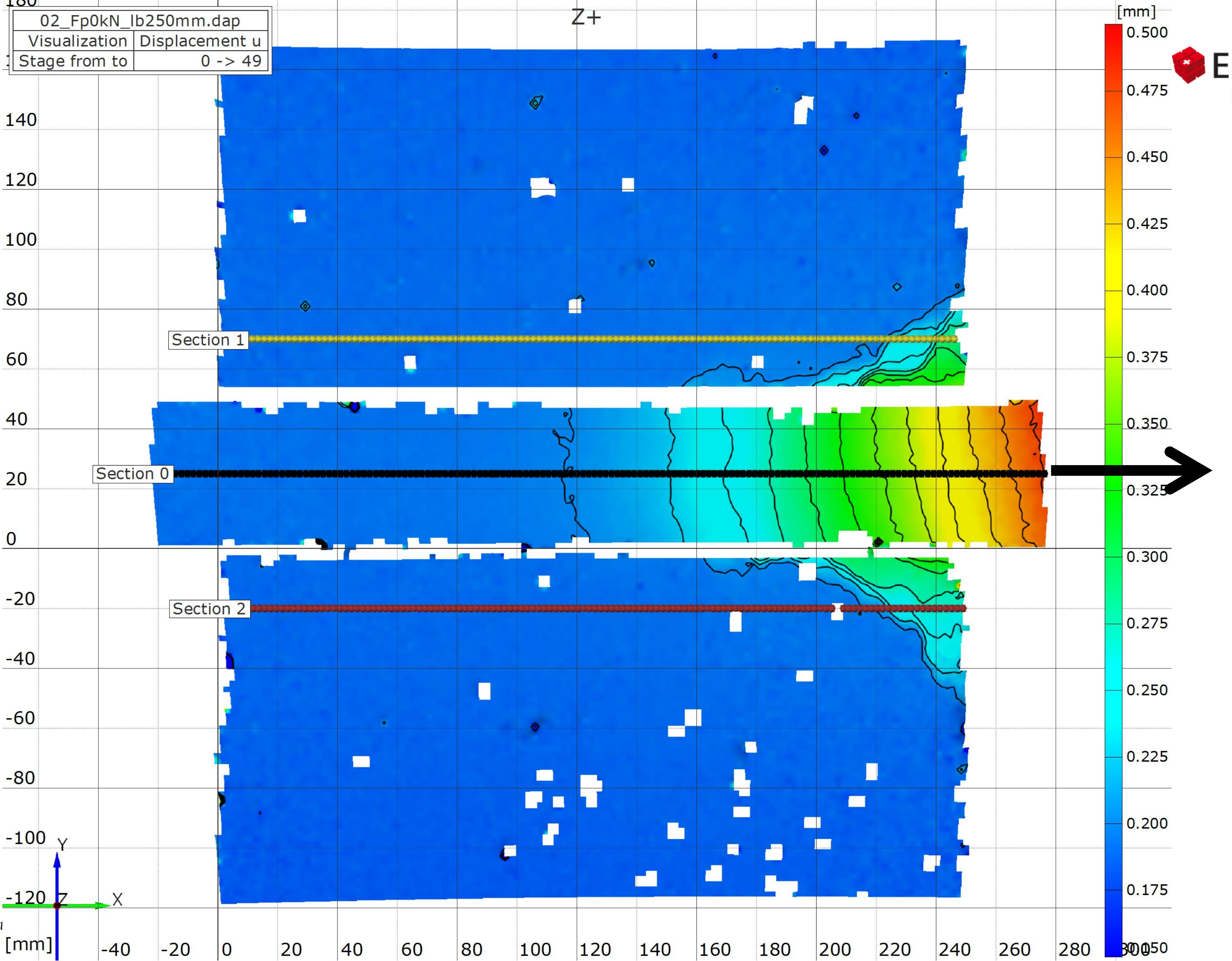
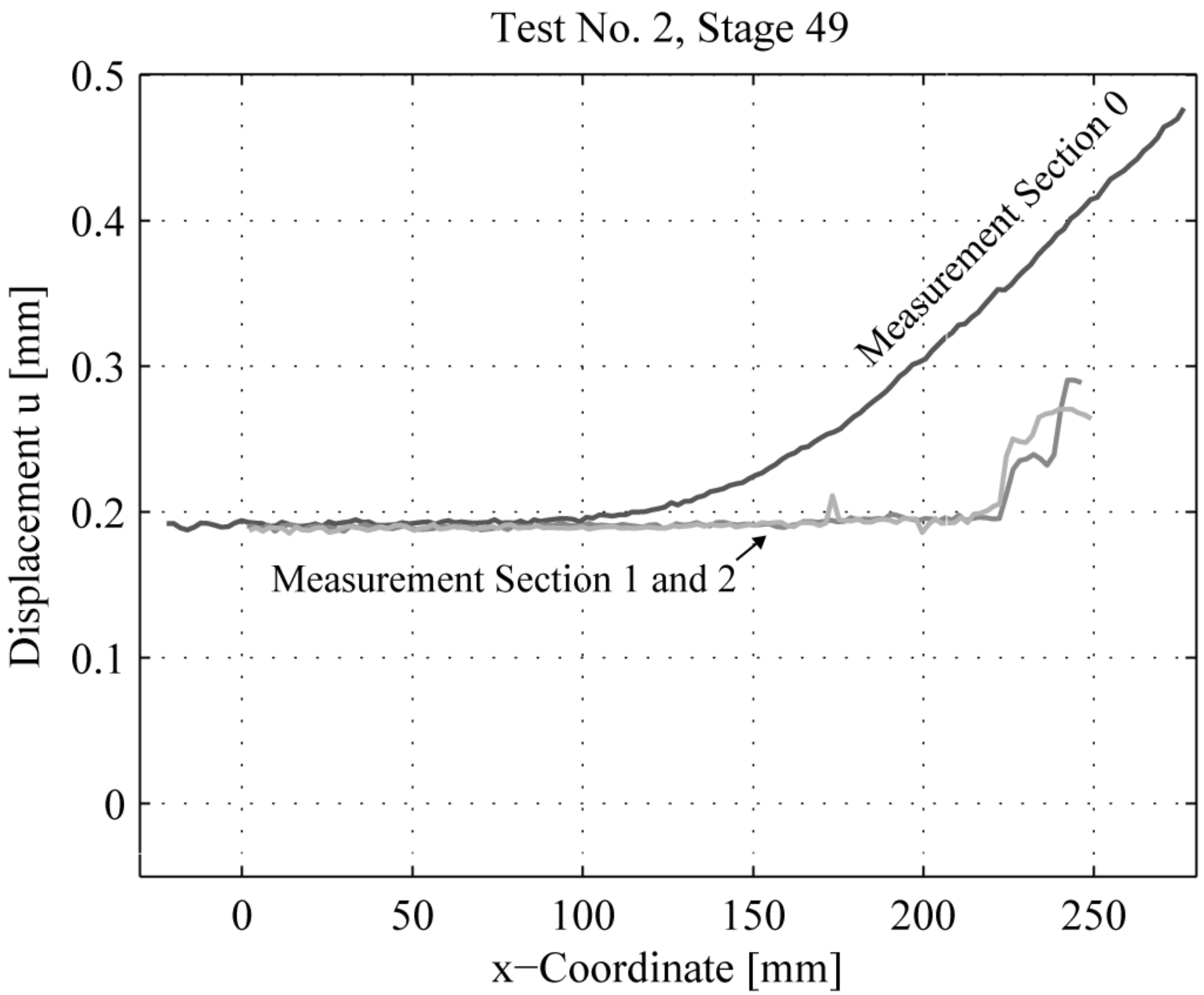
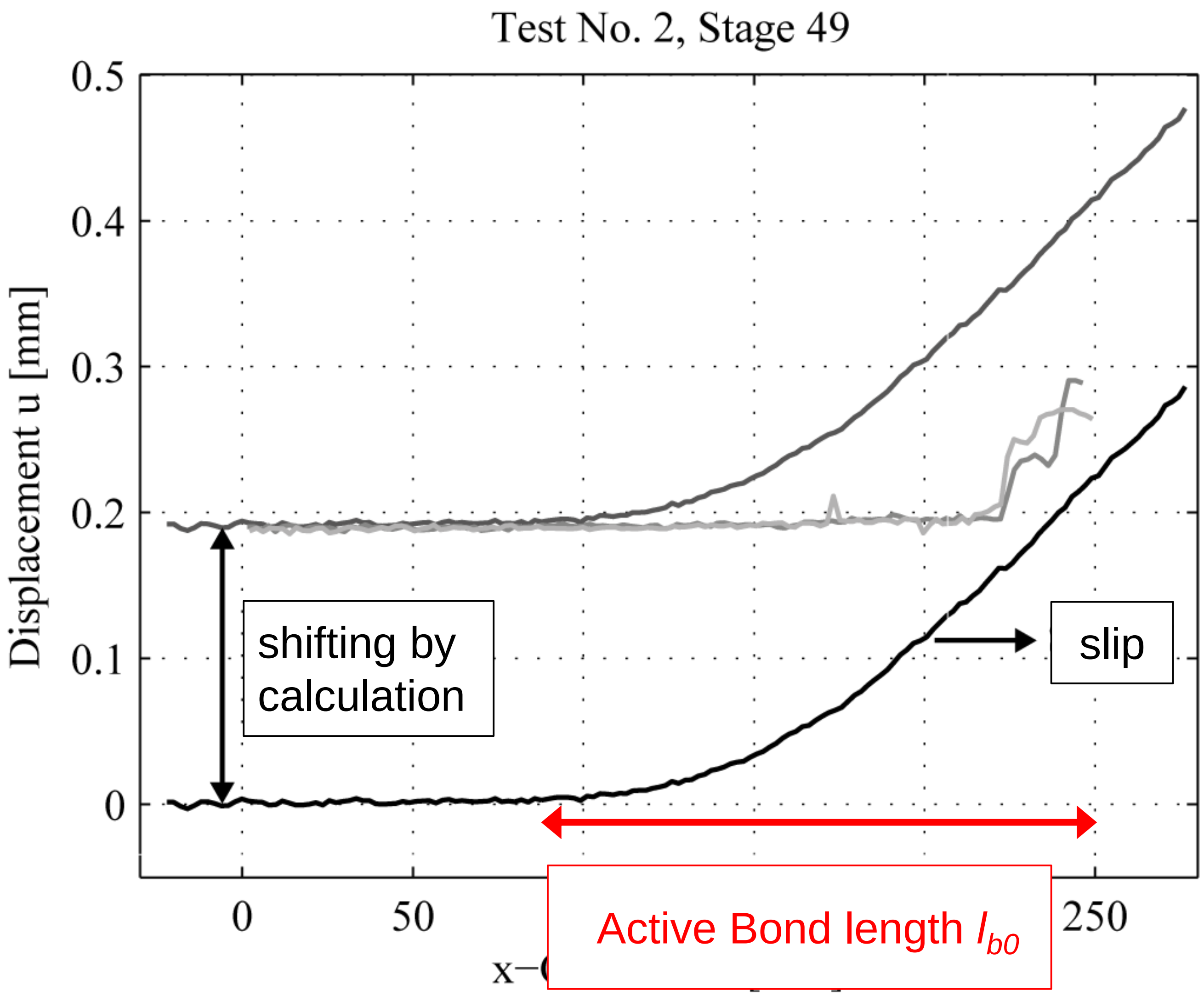



02_Fp0kN_lb250mm.dap
Visualization | Displacement u
Stage from to | 0 -> 49
Z+
[mm]
0.500
0.475
0.450
0.425
0.400
0.375
0.350
0.325
0.300
0.275
0.250
0.225
0.200
0.175
0.150
Section 1
Section 0
Section 2
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
Y
Z
X
[mm]
-40
-20
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300


Test No. 2, Stage 49
0.5
0.4
0.3
0.2
0.1
0
Displacement u [mm]
0
50
100
150
200
250
x−Coordinate [mm]
Measurement Section 0
Measurement Section 1 and 2



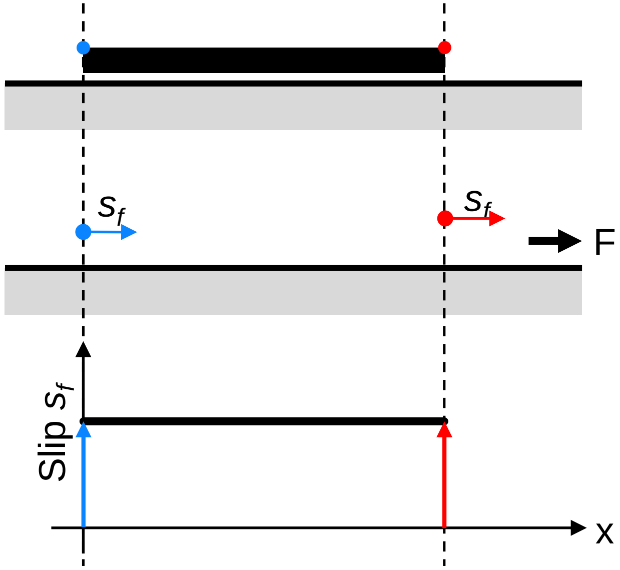
shifting by calculation

slip

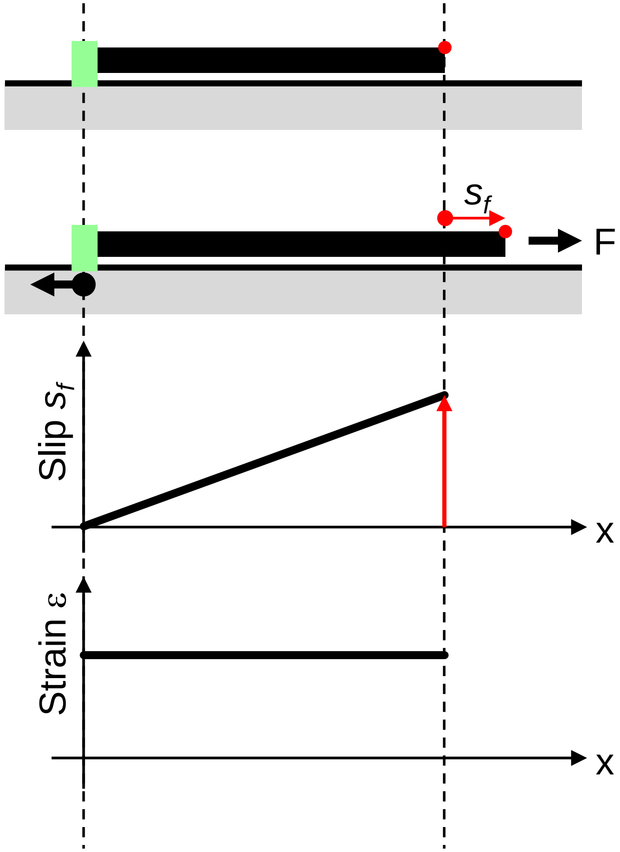
Active Bond length l_{b0}

Active bond length: the length which is actively involved in the force transfer from the strip to the concrete.

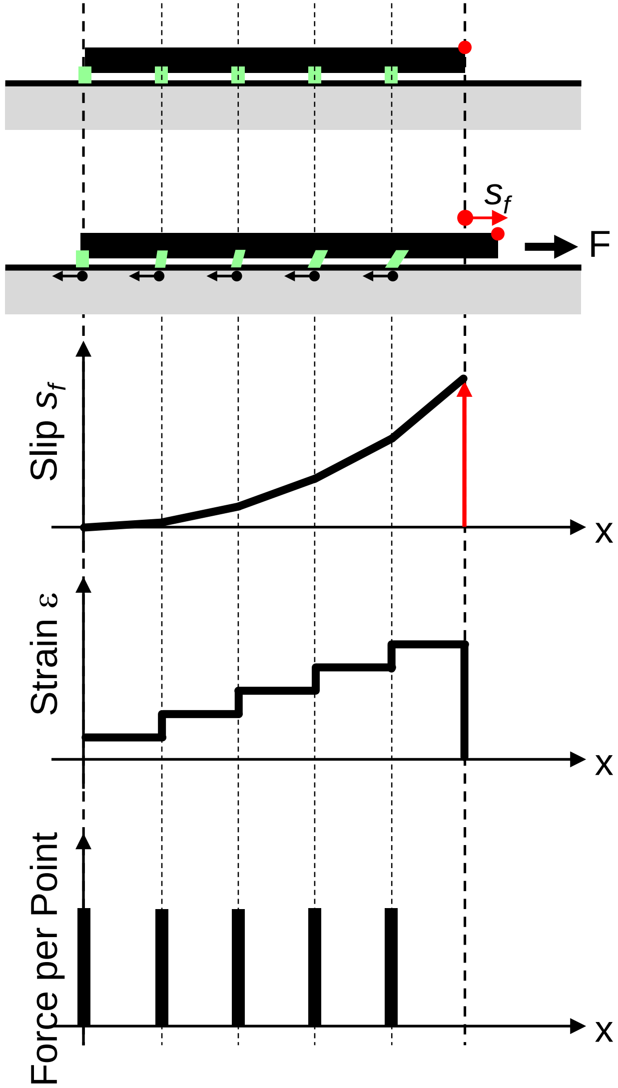
without connection

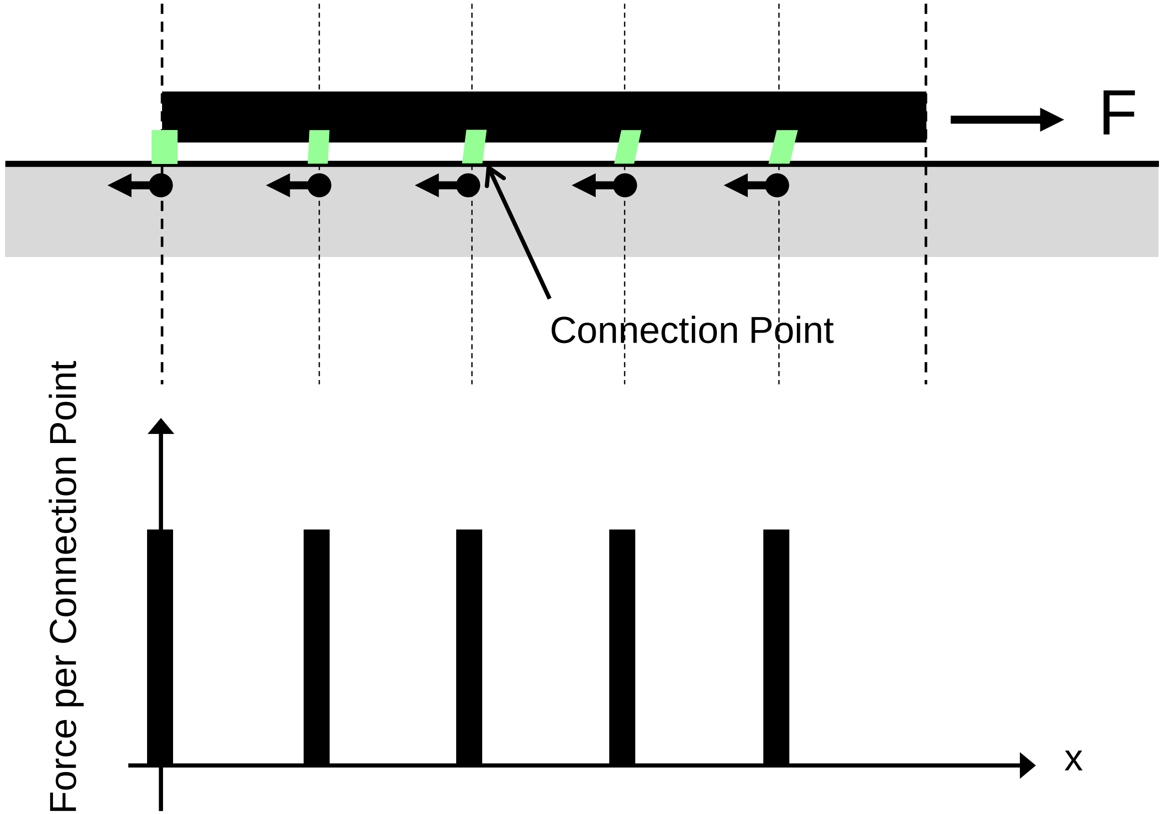


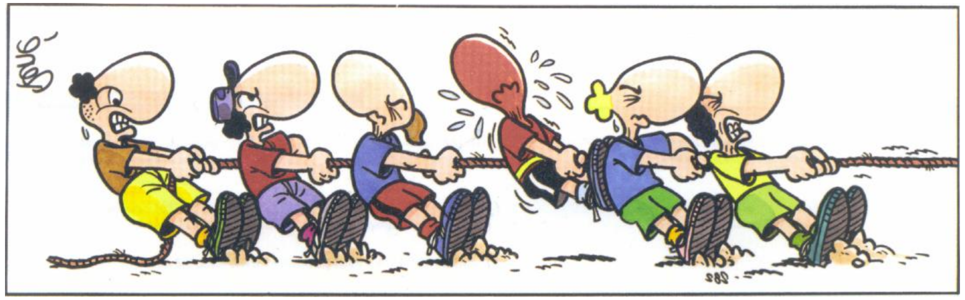
connection in one point



Connection in several points

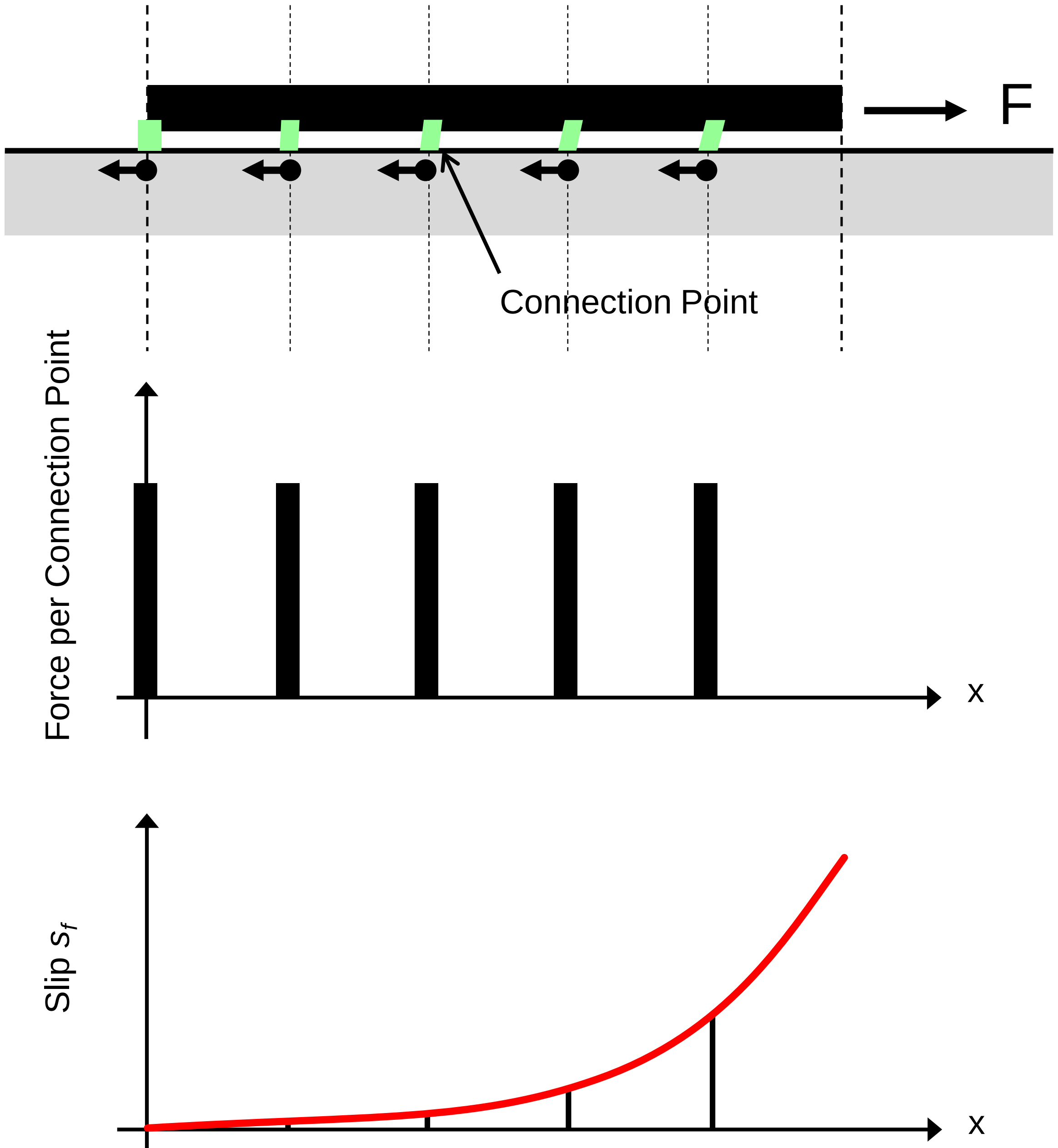




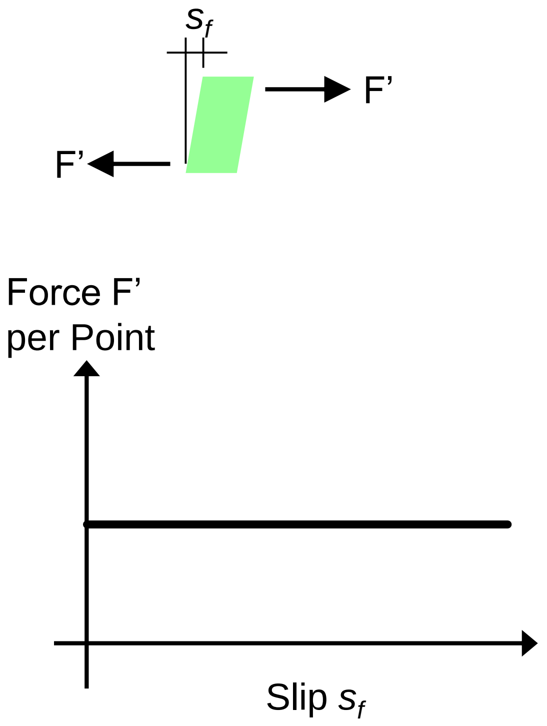


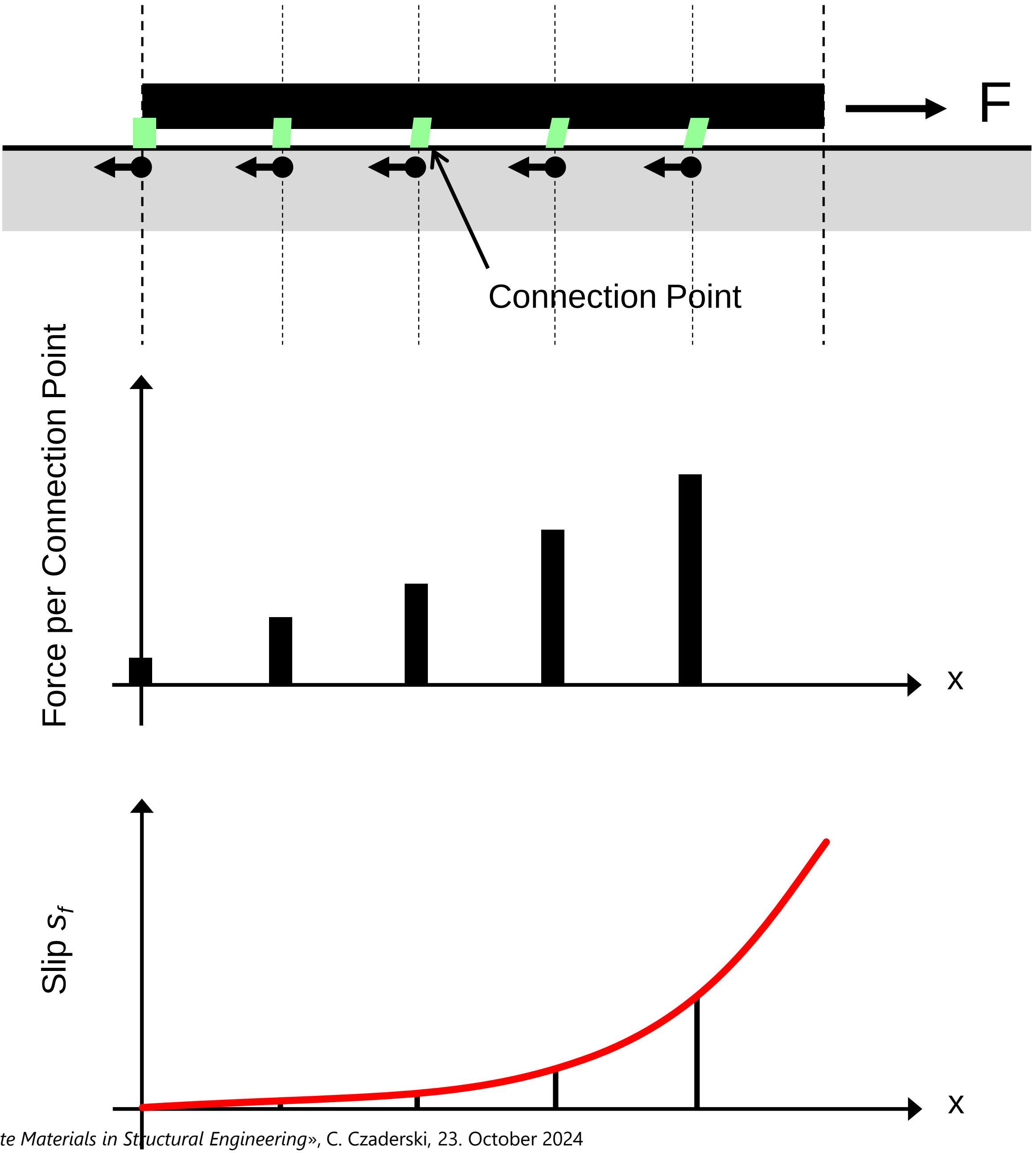
rope pulling

Picture taken from http://www.seilziehclub-gonten.ch/images/diverse/Comic1.JPG (displayed mirrored)

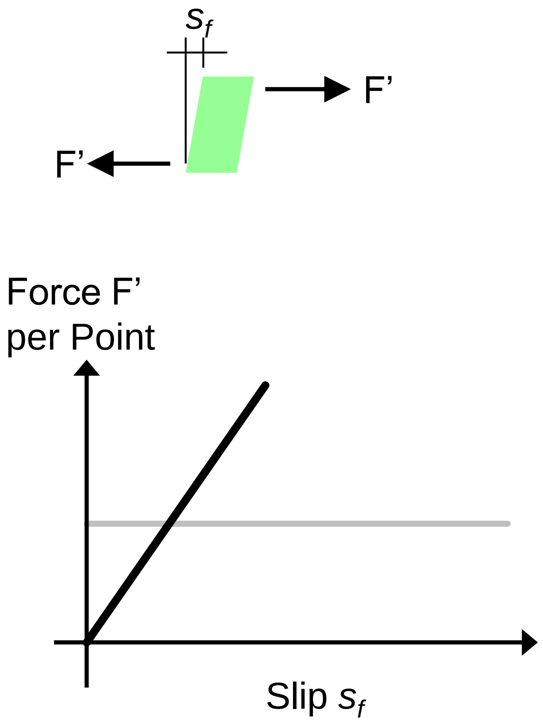


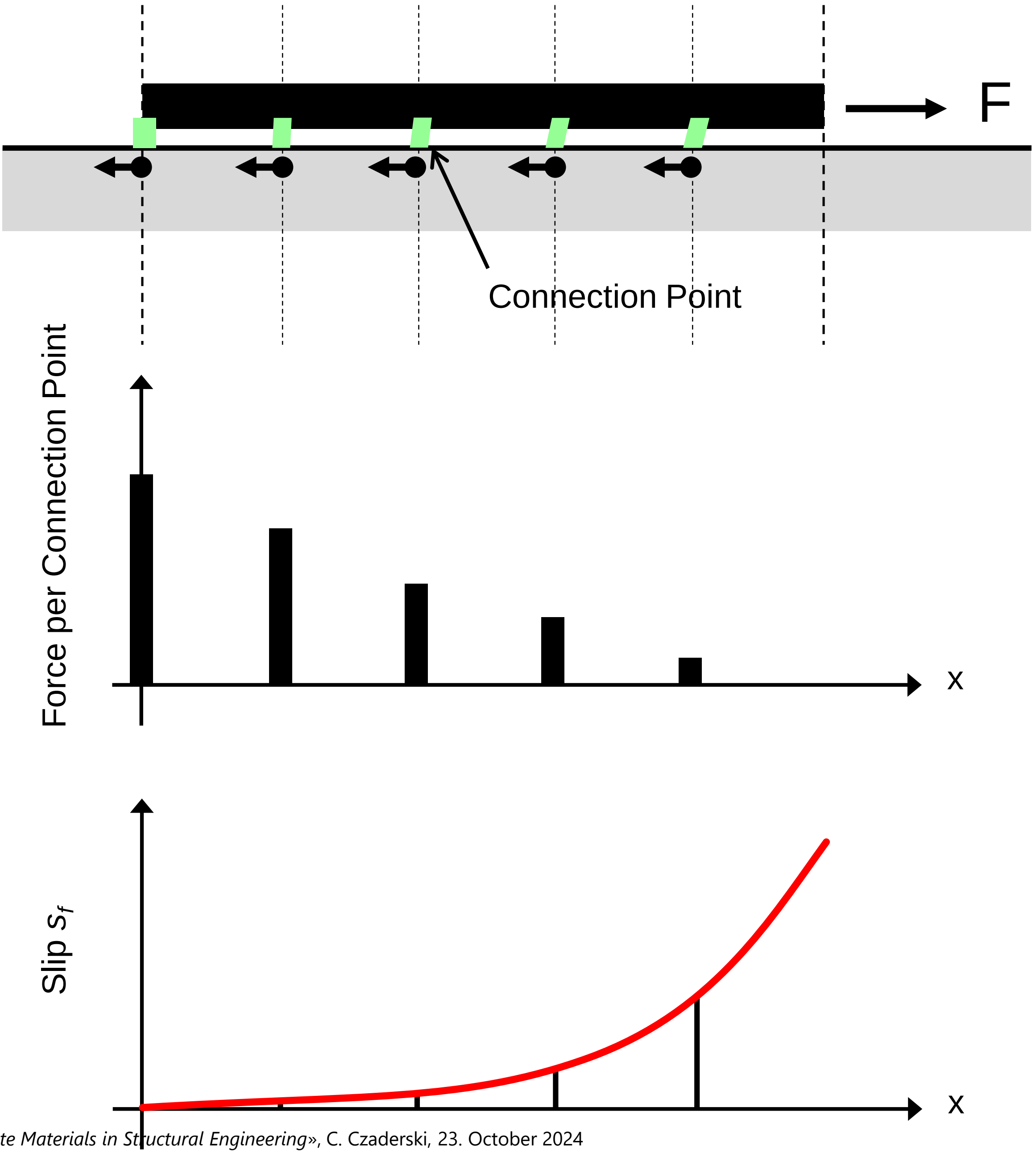
Behavior of the Connection Point:



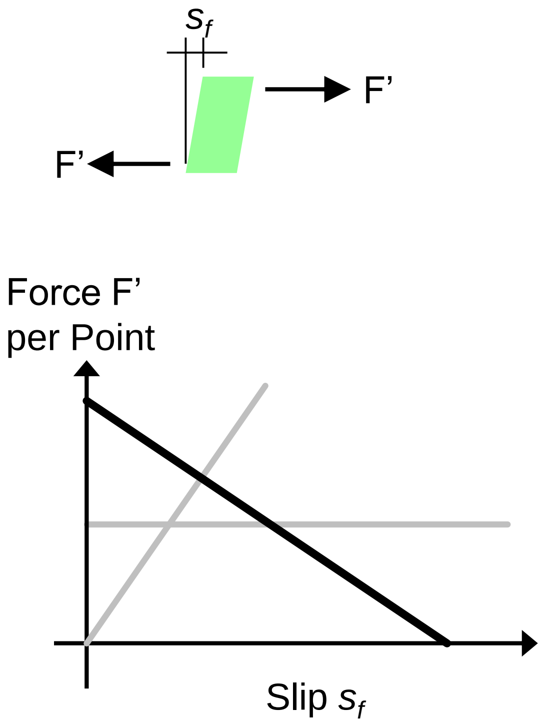


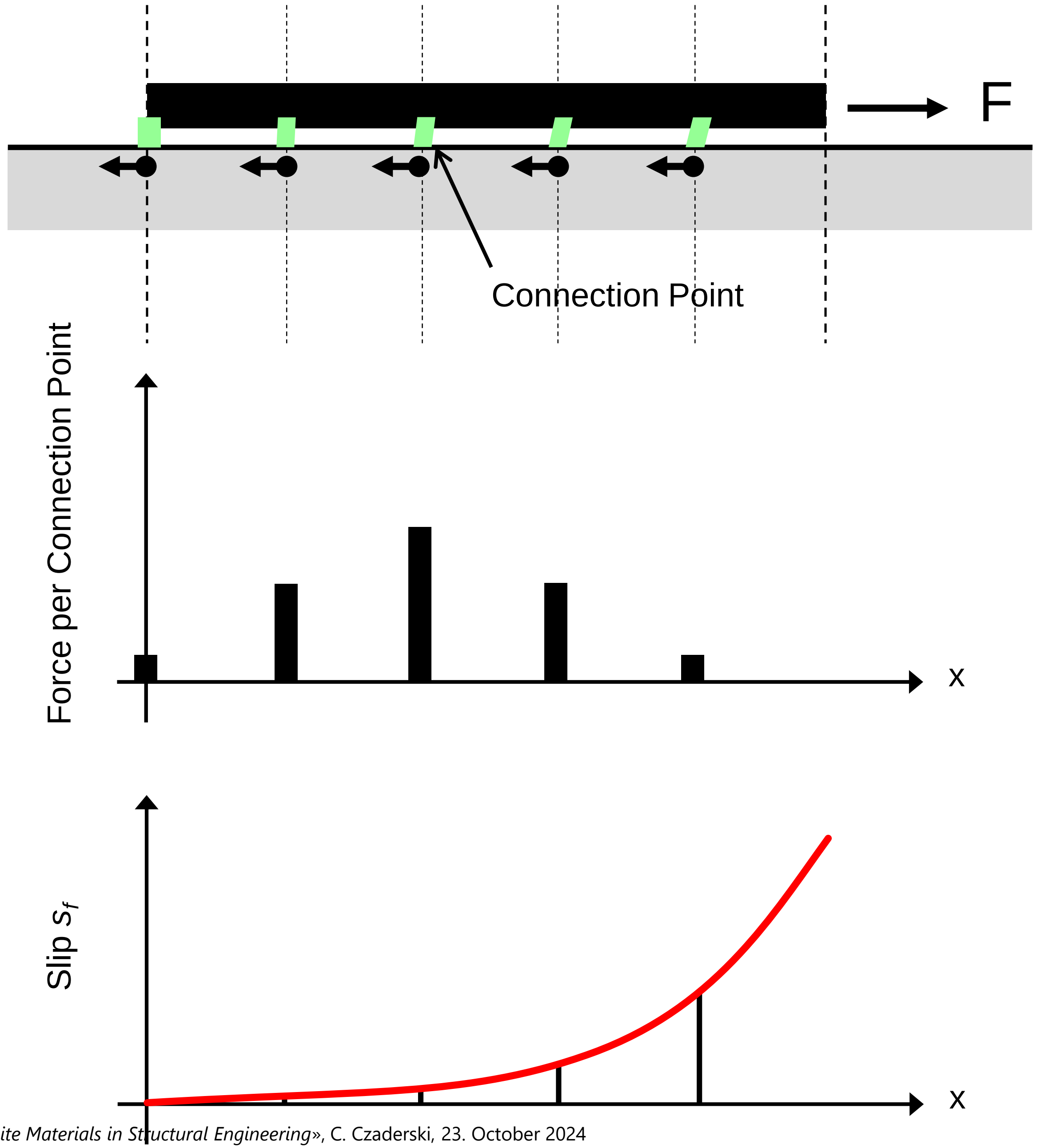
Behavior of the Connection Point:



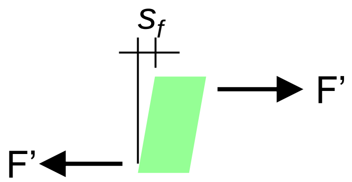


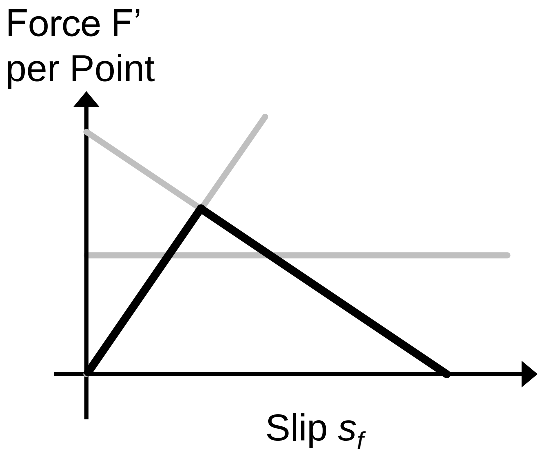
Behavior of the Connection Point:

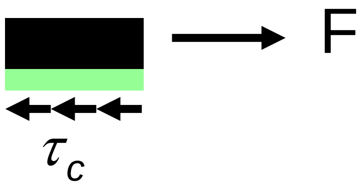




Behavior of the Connection Point:

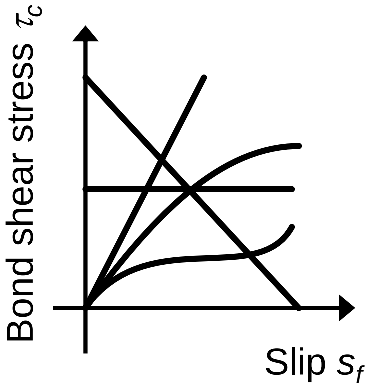






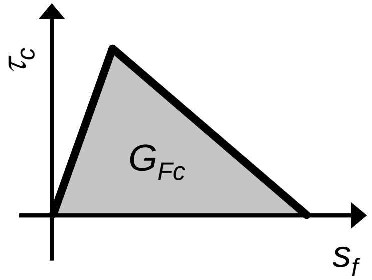
$$\tau_c = \frac{Force}{unit\ area}\ \frac{N}{mm2}$$

$\tau_c =$ bond shear stress



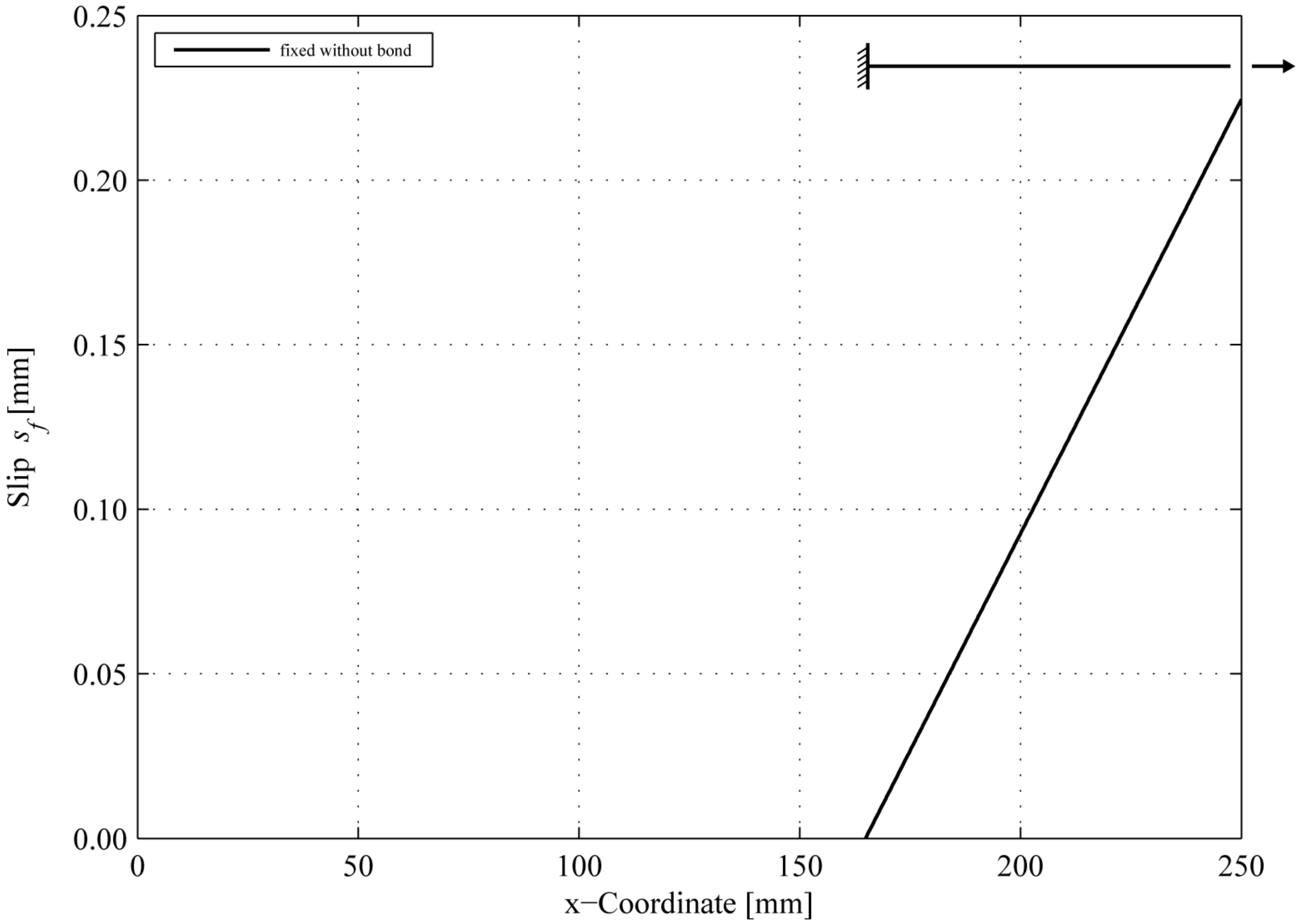
Bond shear stress – Slip – Relation

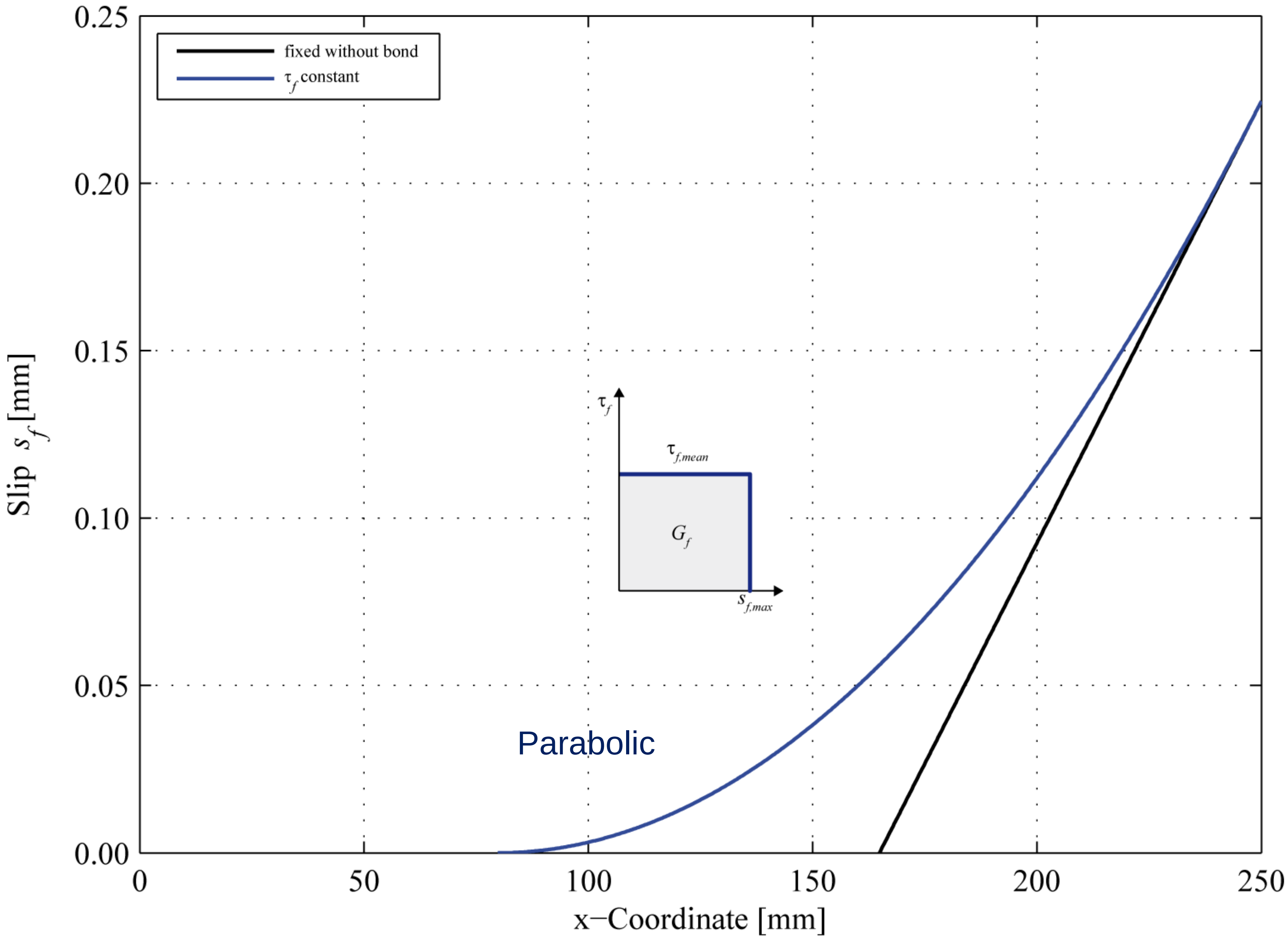
This relation characterizes the bond behavior.

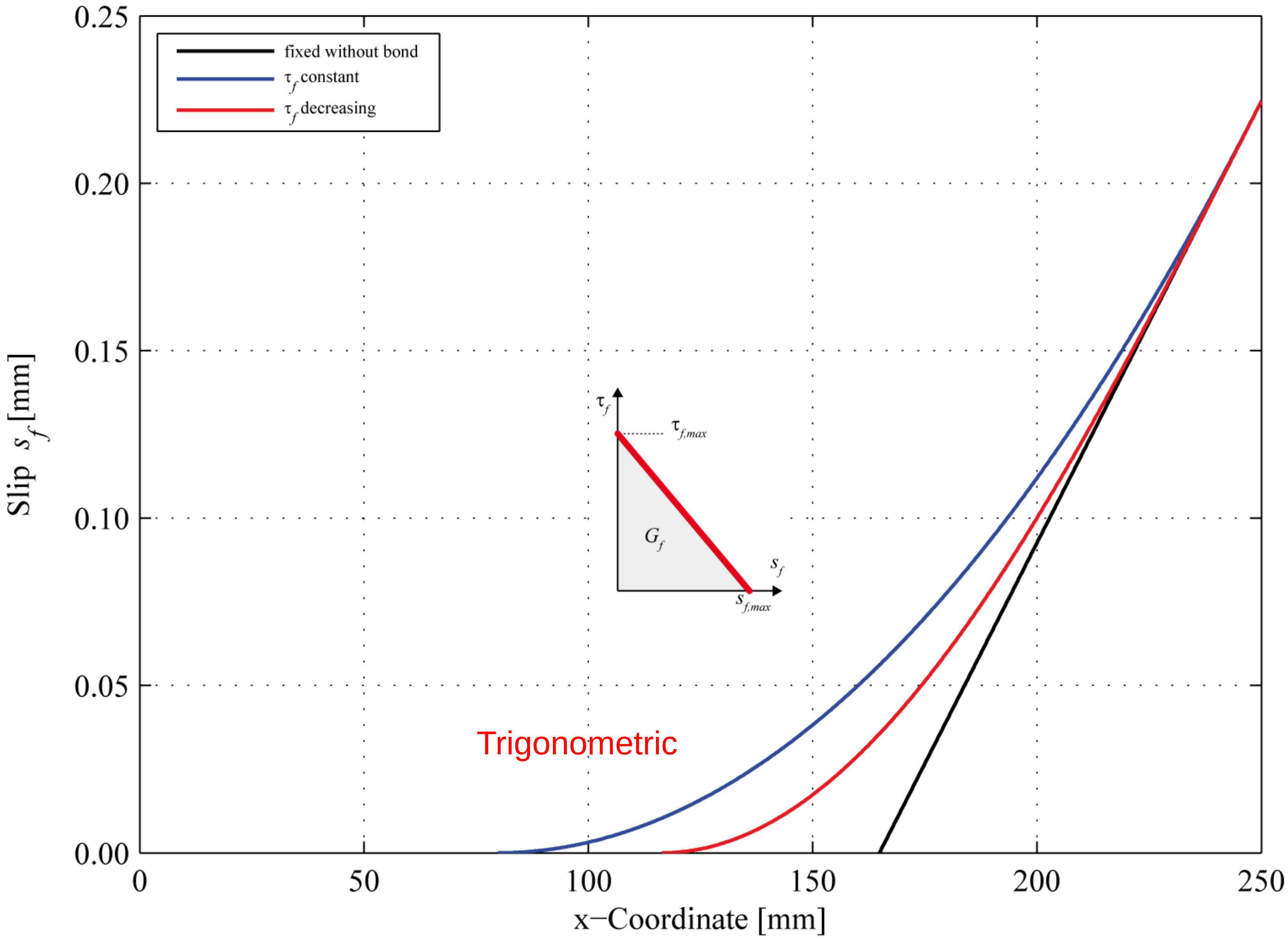


The area under the bond shear stress – slip – relation corresponds to the **specific fracture energy G_{Fc}** of externally bonded reinforcement (EBR) bonded **on concrete**.

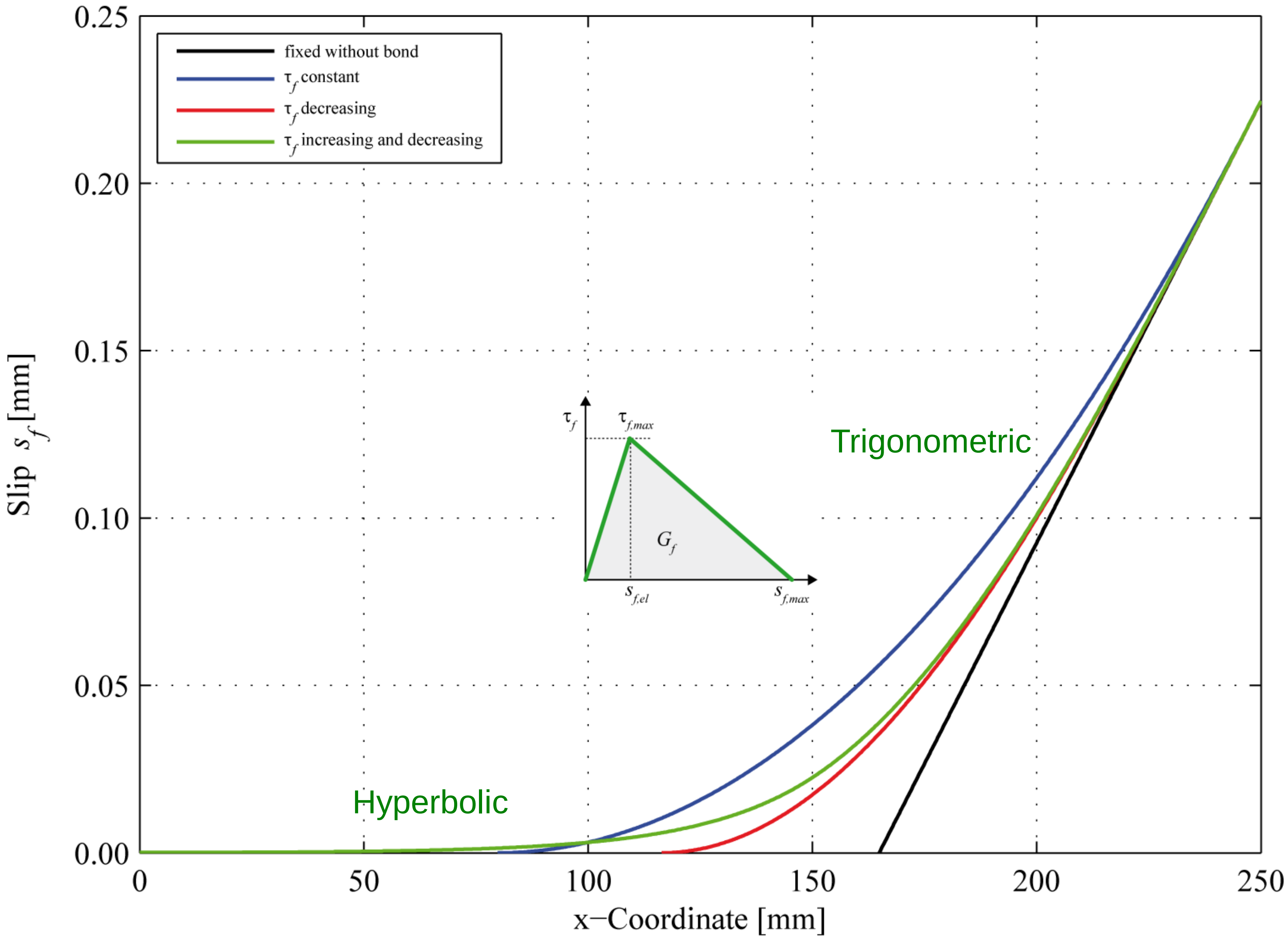
G_{Fa} = specific fracture energy of EBR bonded on steel


fixed without bond
Slip s_f [mm]
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
x−Coordinate [mm]

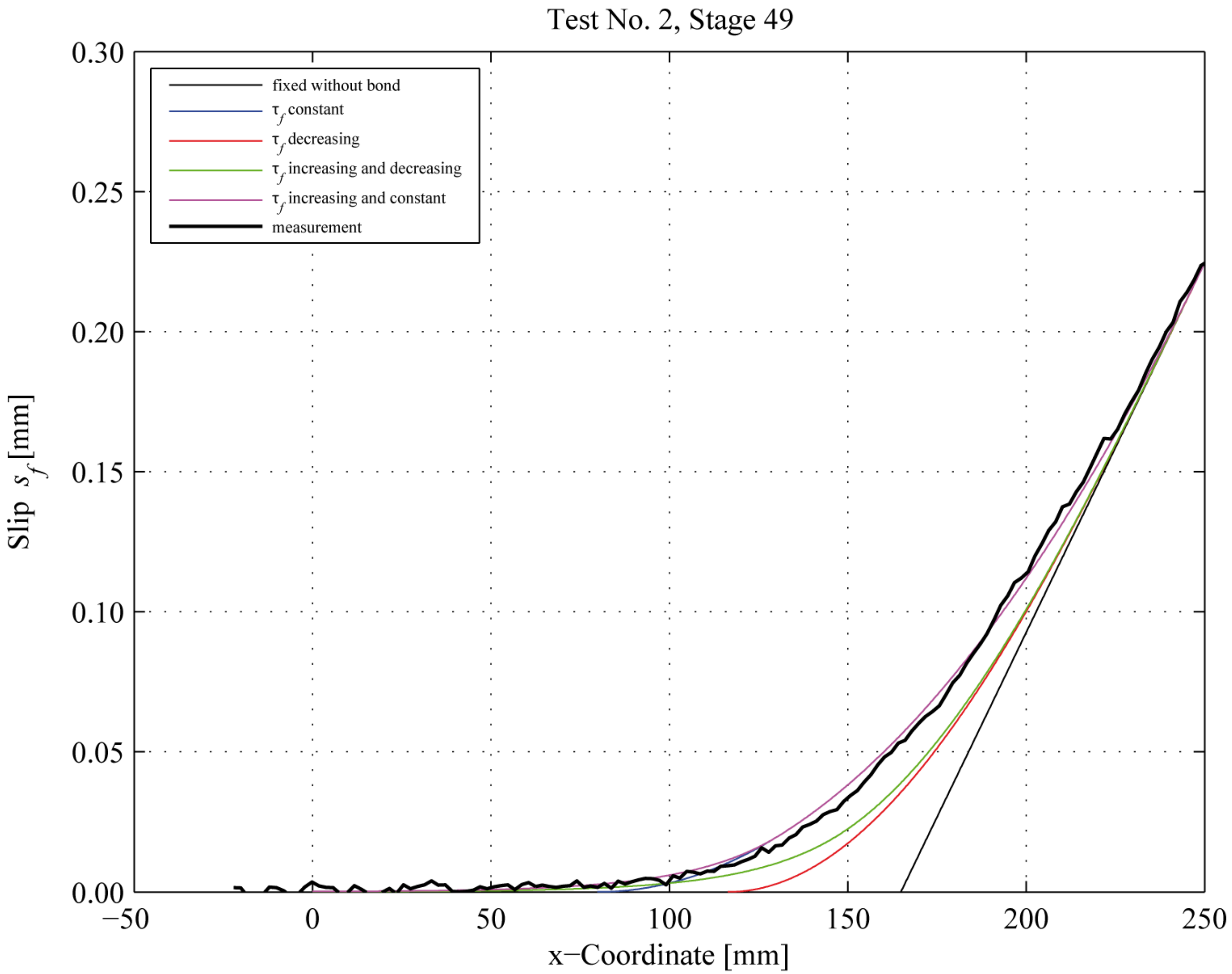

fixed without bond
τ_f constant
Slip s_f [mm]
x−Coordinate [mm]
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
τ_f
$\tau_{f,mean}$
G_f
$s_{f,max}$
Parabolic



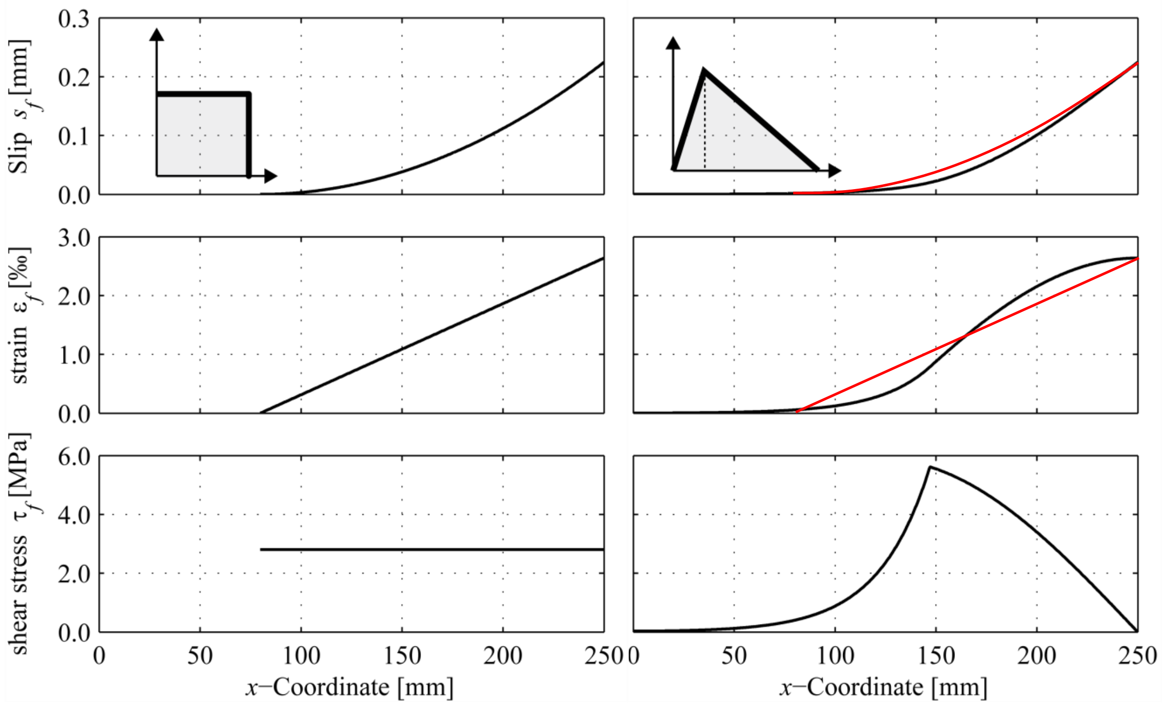
Trigonometric


fixed without bond
τ_f constant
τ_f decreasing
τ_f increasing and decreasing
τ_f
$\tau_{f,max}$
G_f
$s_{f,el}$
$s_{f,max}$
Trigonometric
Hyperbolic
Slip s_f [mm]
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
x−Coordinate [mm]

Comparison Modelling - Measurement

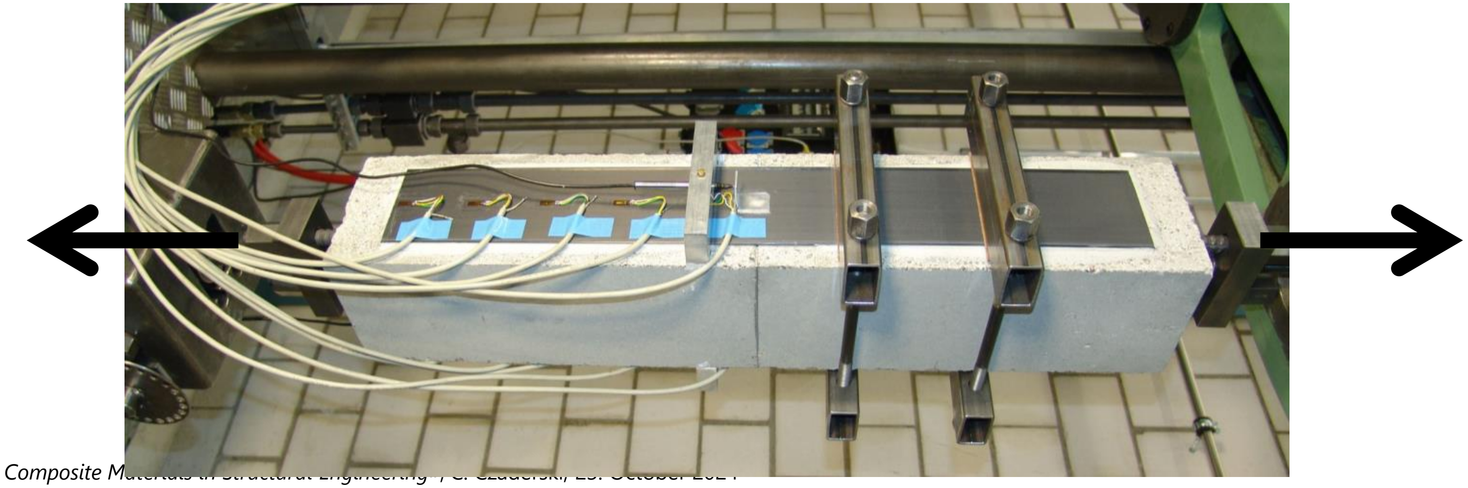


Lap-shear test with strain gauges (SG)

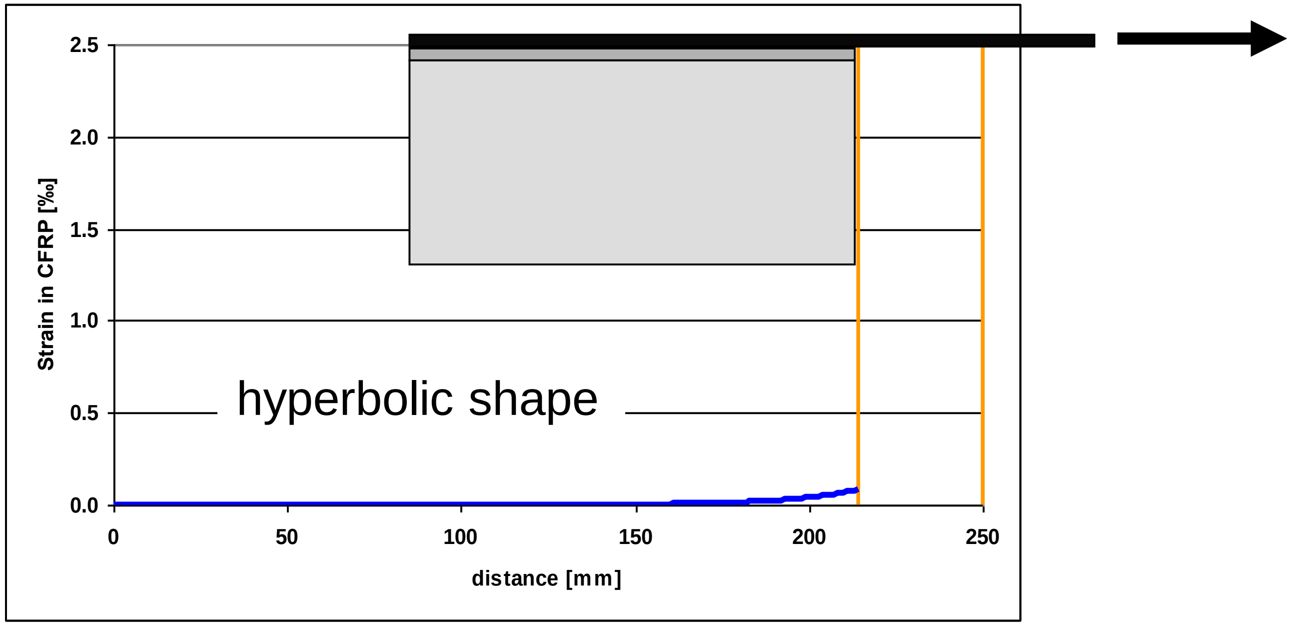


ICS measures slip

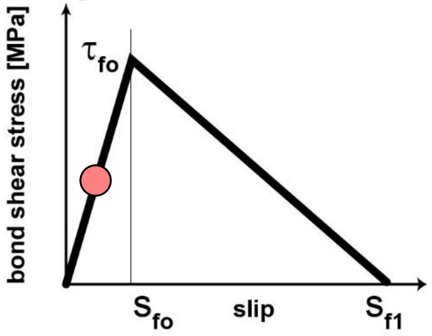
SG's measure strain

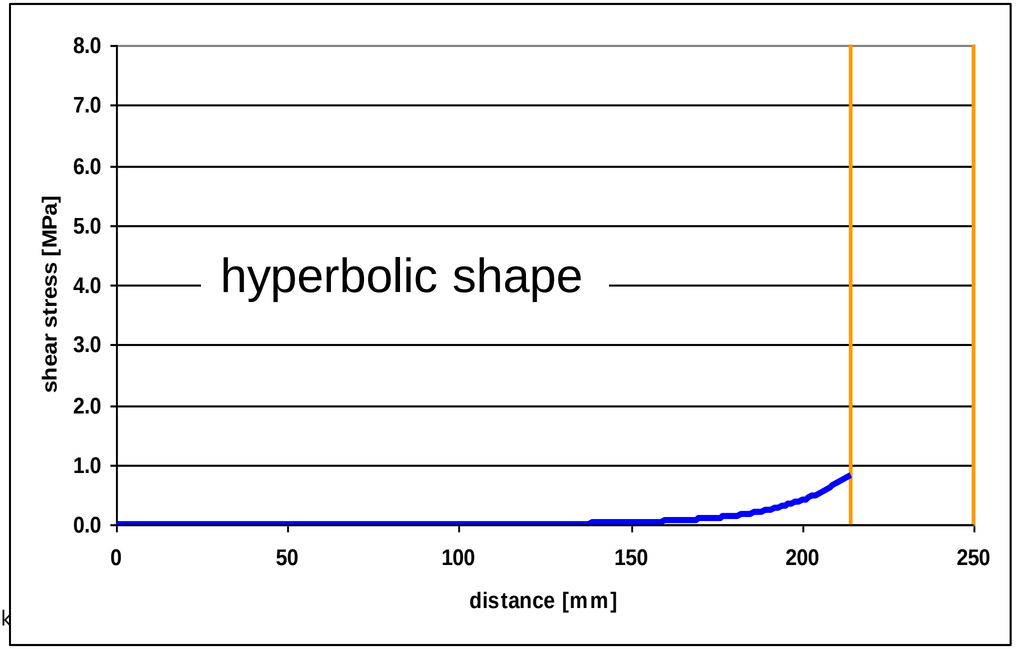


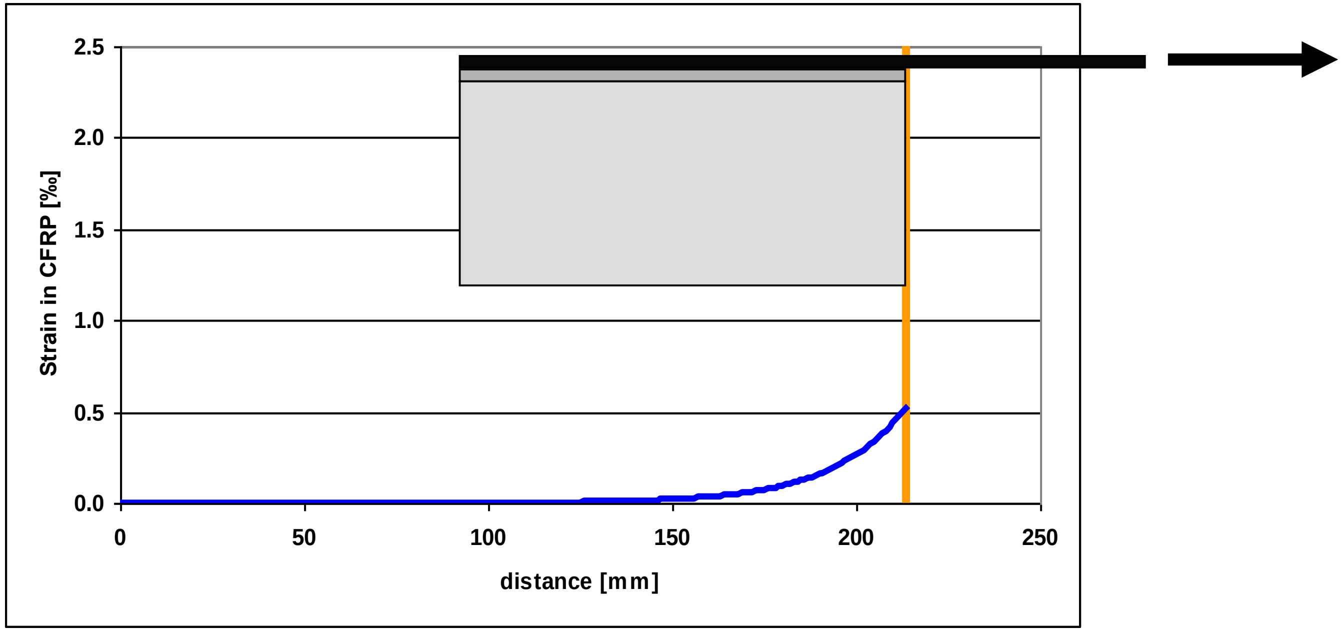
Longitudinal strain

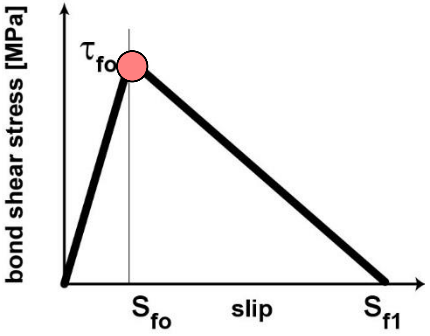


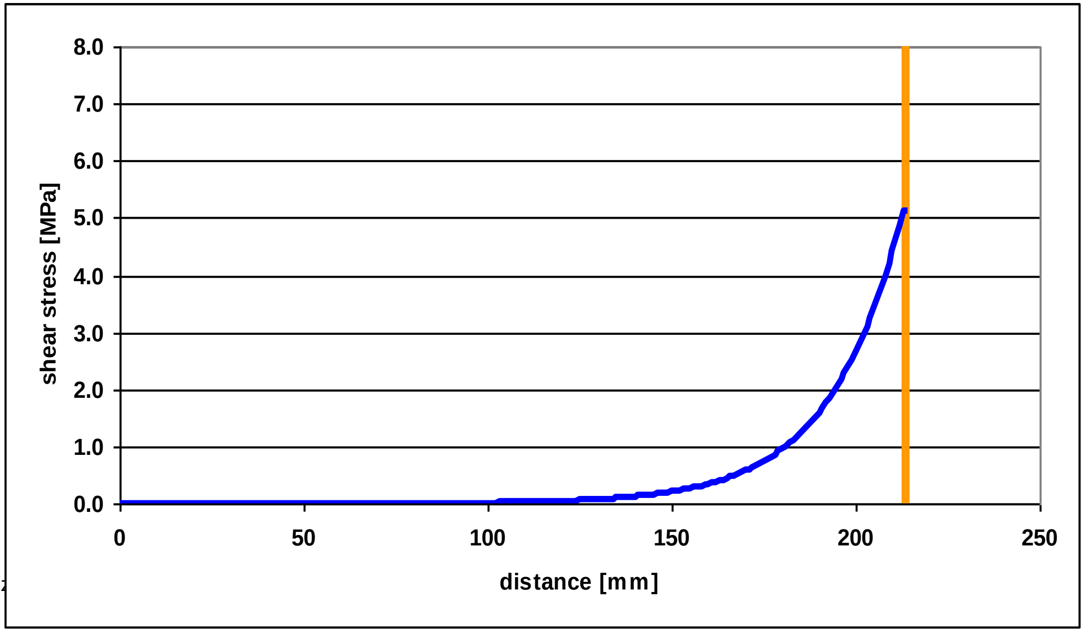
Shear stress between strip and concrete

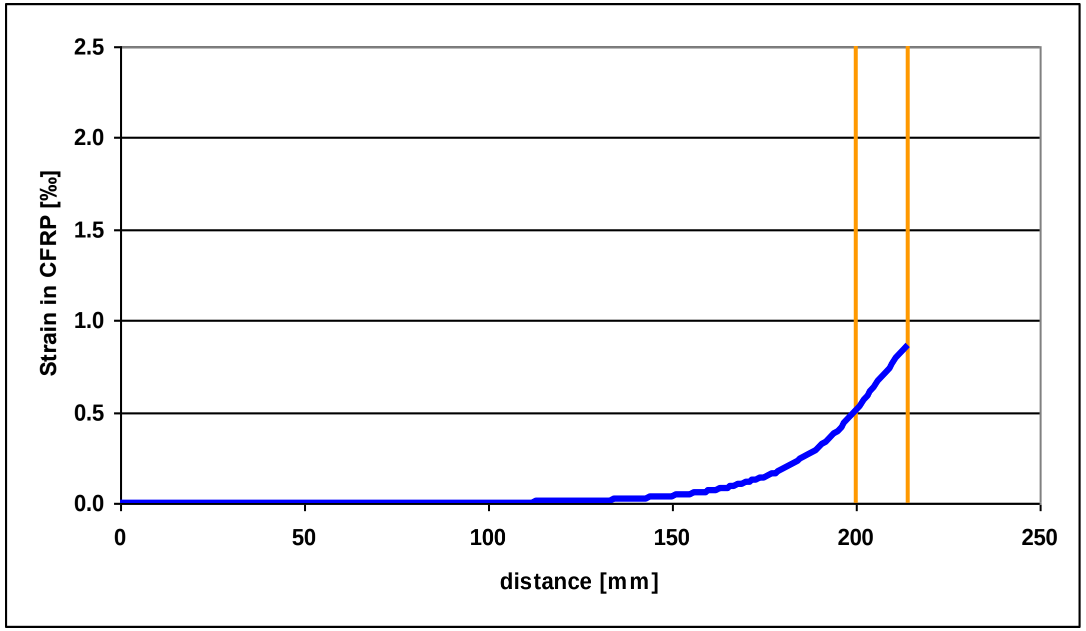


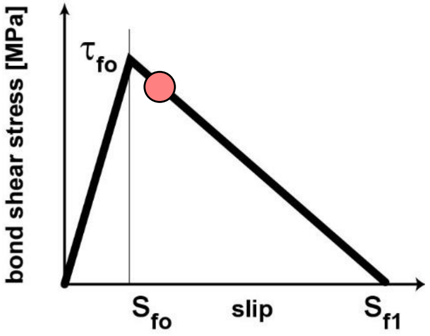


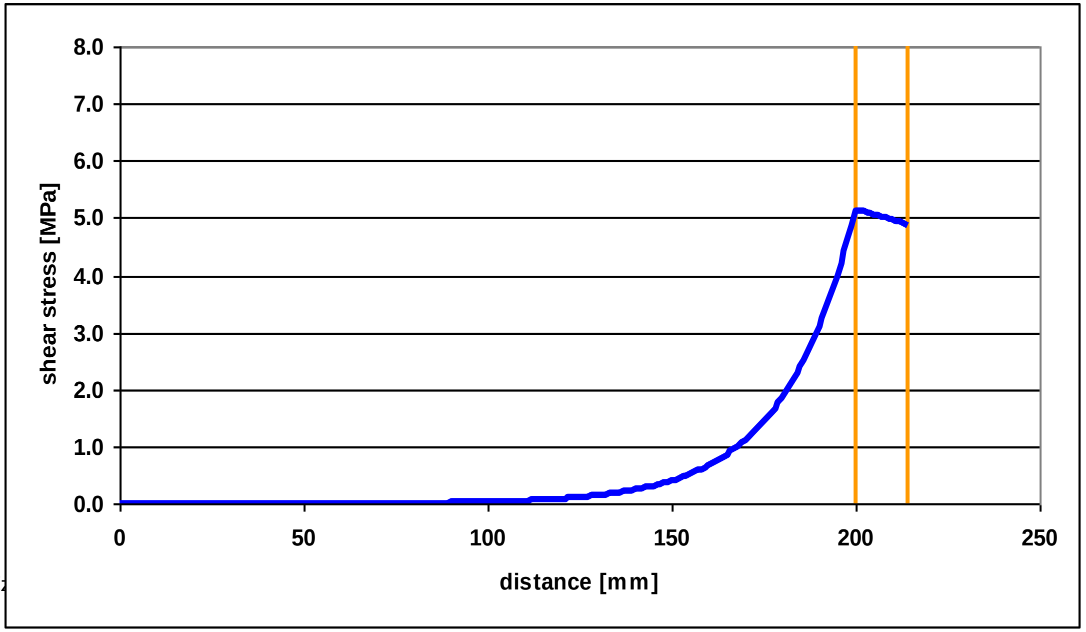

Strain in CFRP [‰]
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
distance [mm]

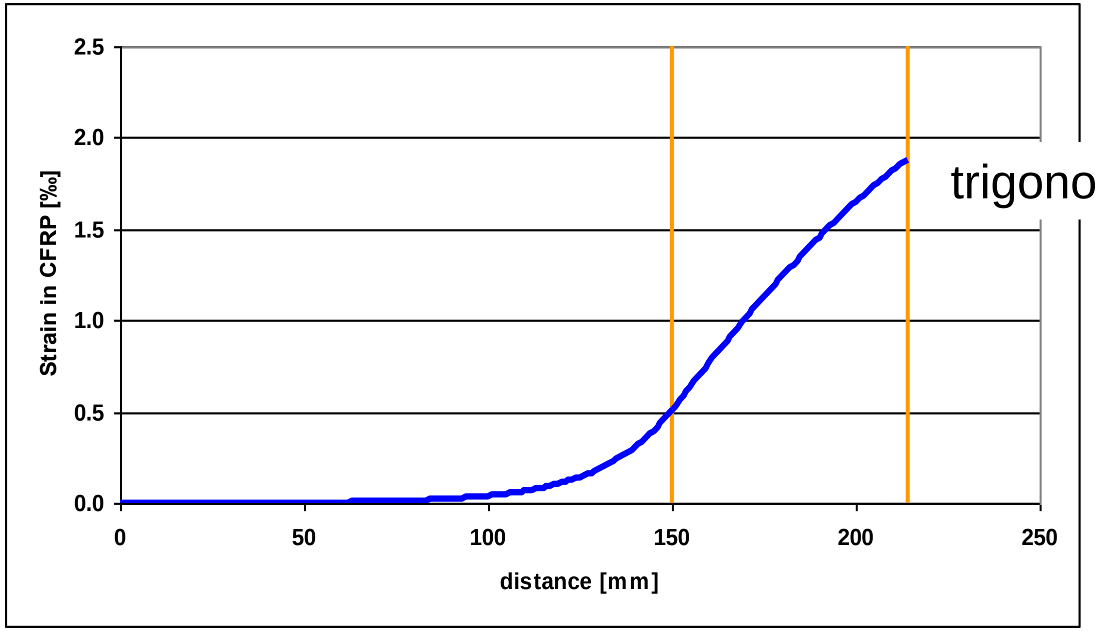

bond shear stress [MPa]
τ_{fo}
S_{fo}
slip
S_{f1}


shear stress [MPa]
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
50
100
150
200
250
distance [mm]

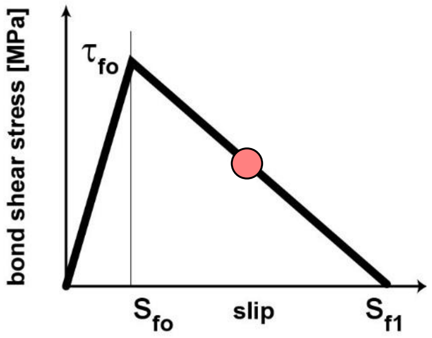

Strain in CFRP [‰]
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
distance [mm]

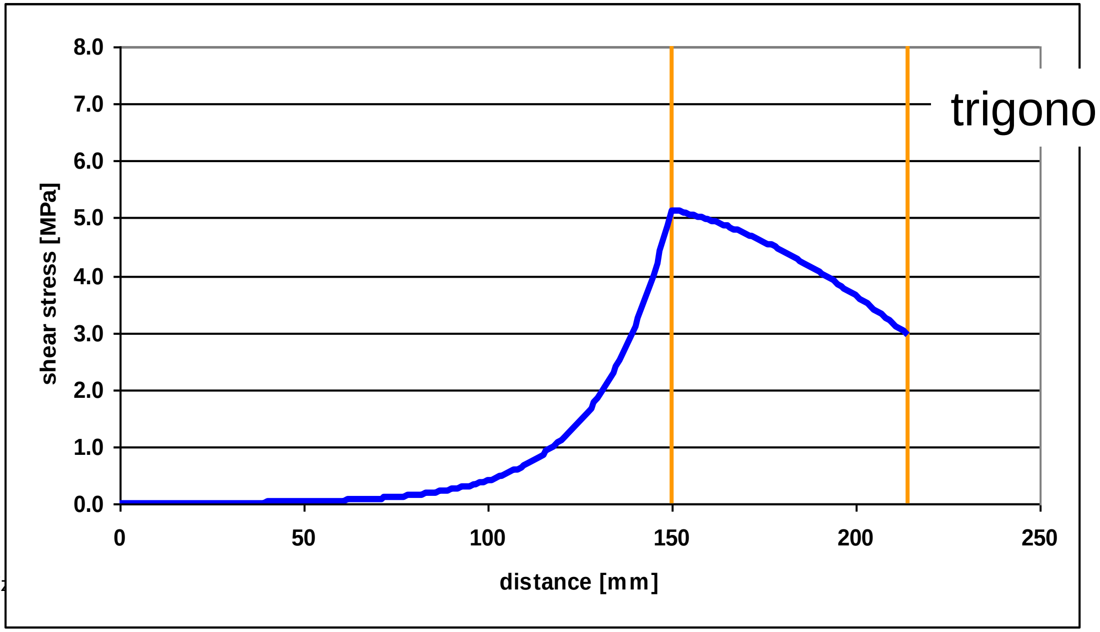

bond shear stress [MPa]
τ_{fo}
S_{fo}
slip
S_{f1}


shear stress [MPa]
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
50
100
150
200
250
distance [mm]

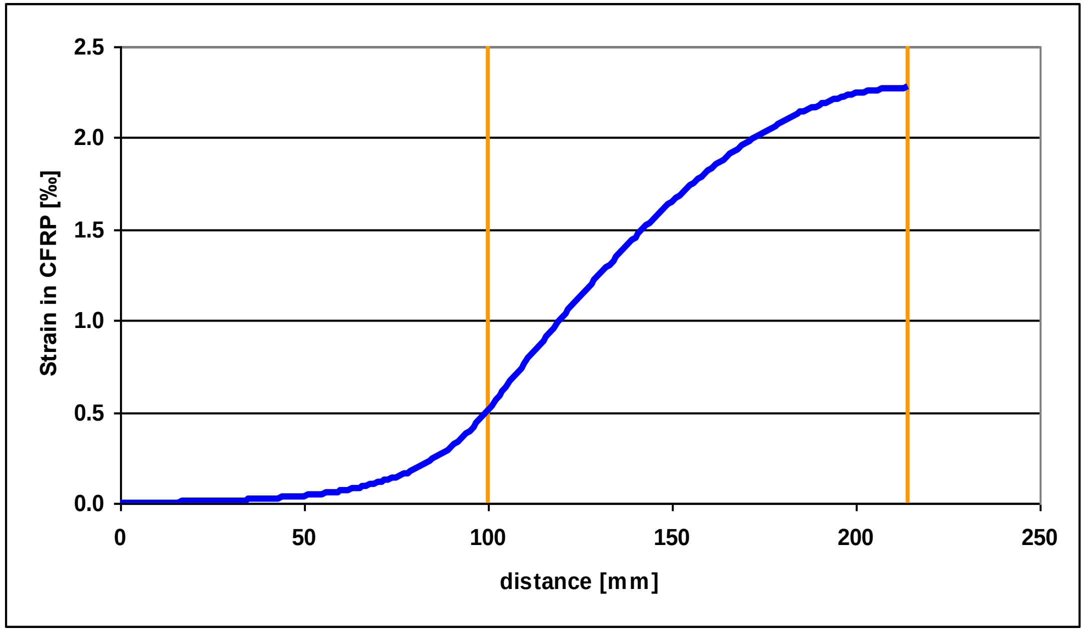


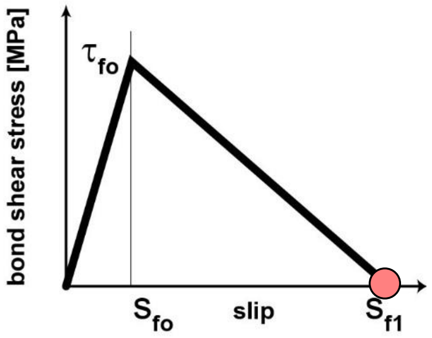
trigonometric shape

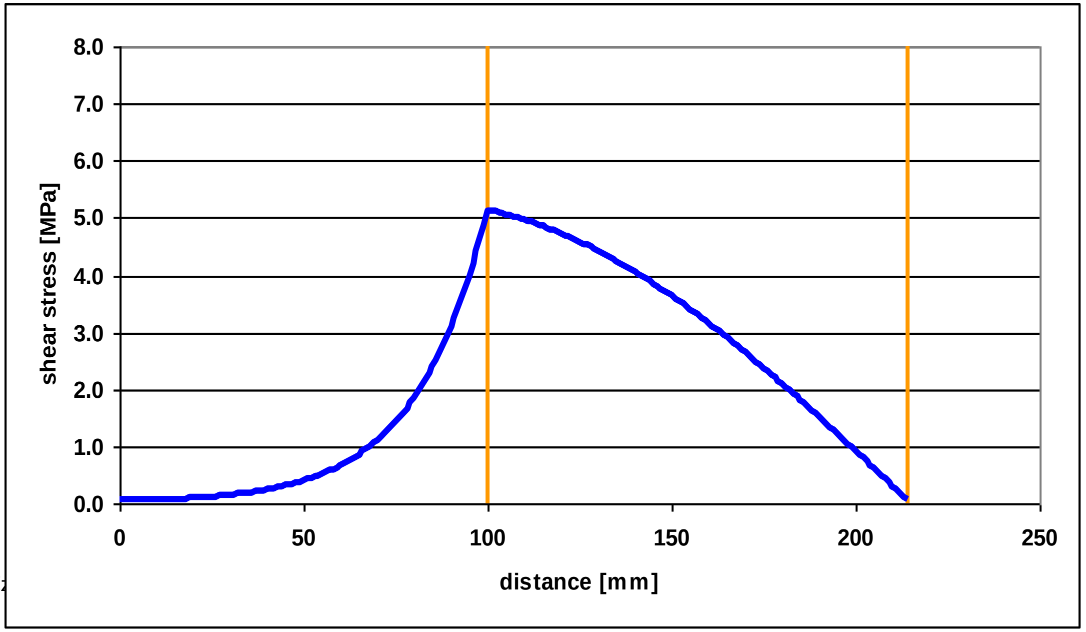




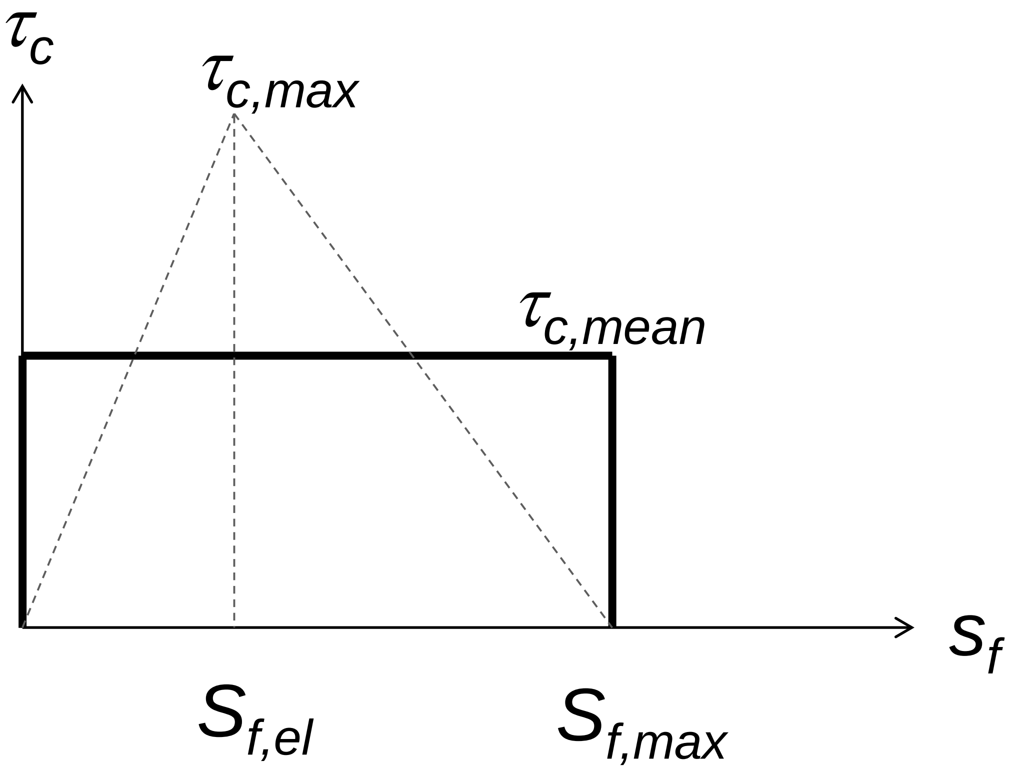
trigonometric shape


Strain in CFRP [‰]
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
distance [mm]


bond shear stress [MPa]
τ_{fo}
S_{fo}
slip
S_{f1}


shear stress [MPa]
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
50
100
150
200
250
distance [mm]

Simplified bond shear stress-slip relation

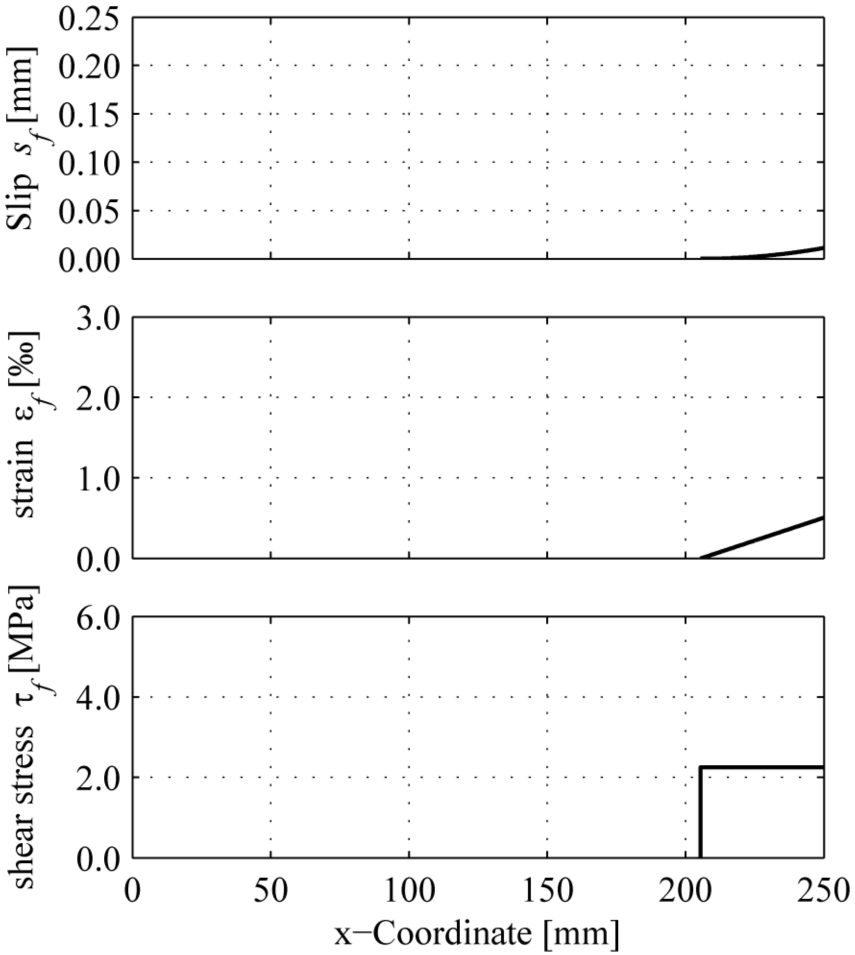


$$G_{Fc} = \frac{\tau_{c,max} s_{f,max}}{2}$$

$$G_{Fc} = \tau_{c,mean} s_{f,max}$$

$\tau_{c,max}$ = maximum bond shear stress on concrete
$\tau_{a,max}$ = maximum bond shear stress on steel

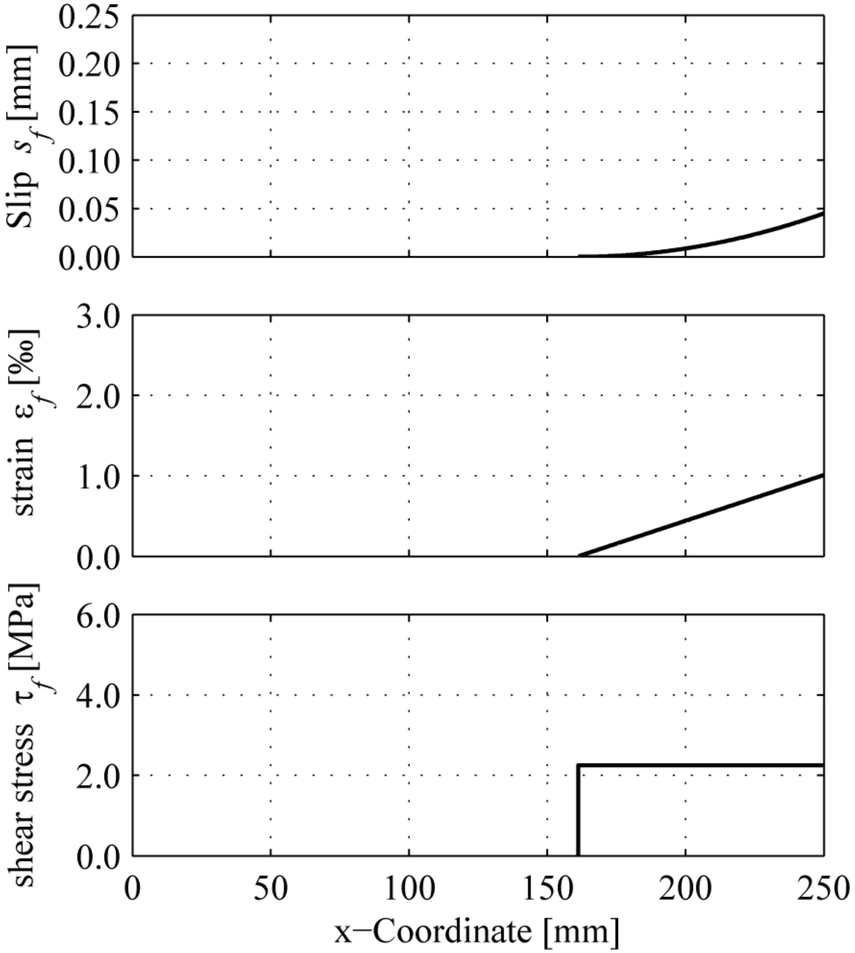
F = 5 kN



parabolic shape of slip

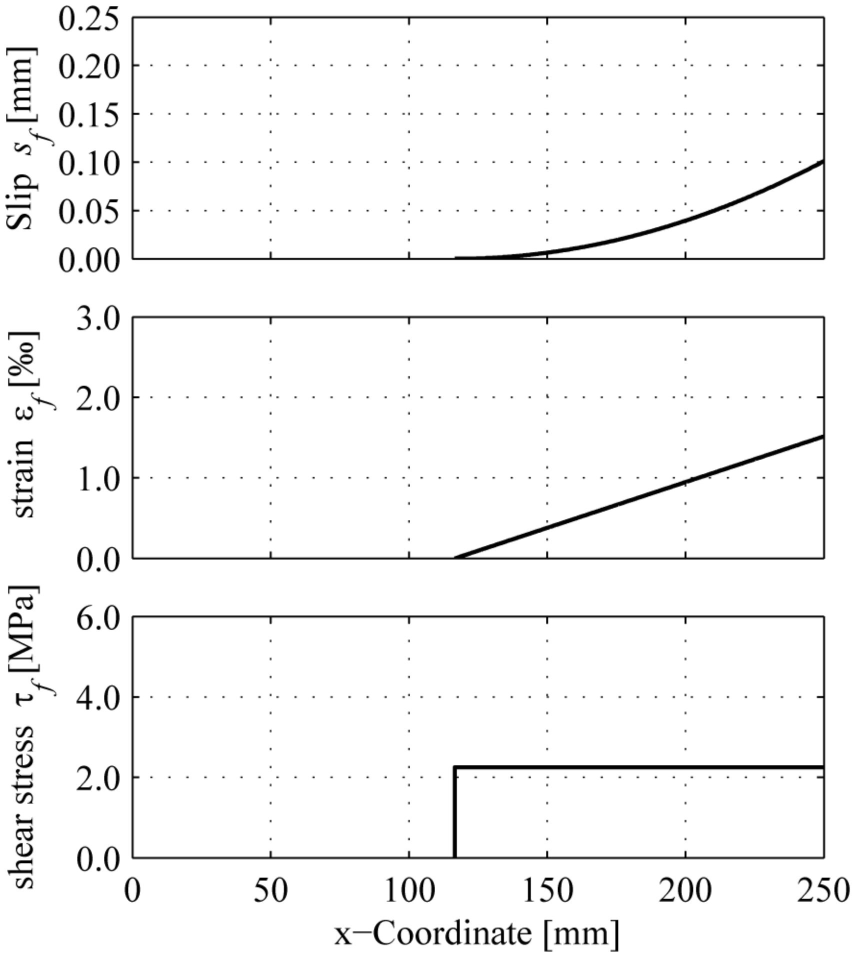
E_f = 165 GPa, b_f = 50mm, t_f = 1.2 mm, $\tau_{c,mean}$ = 2.25 MPa

F = 10 kN



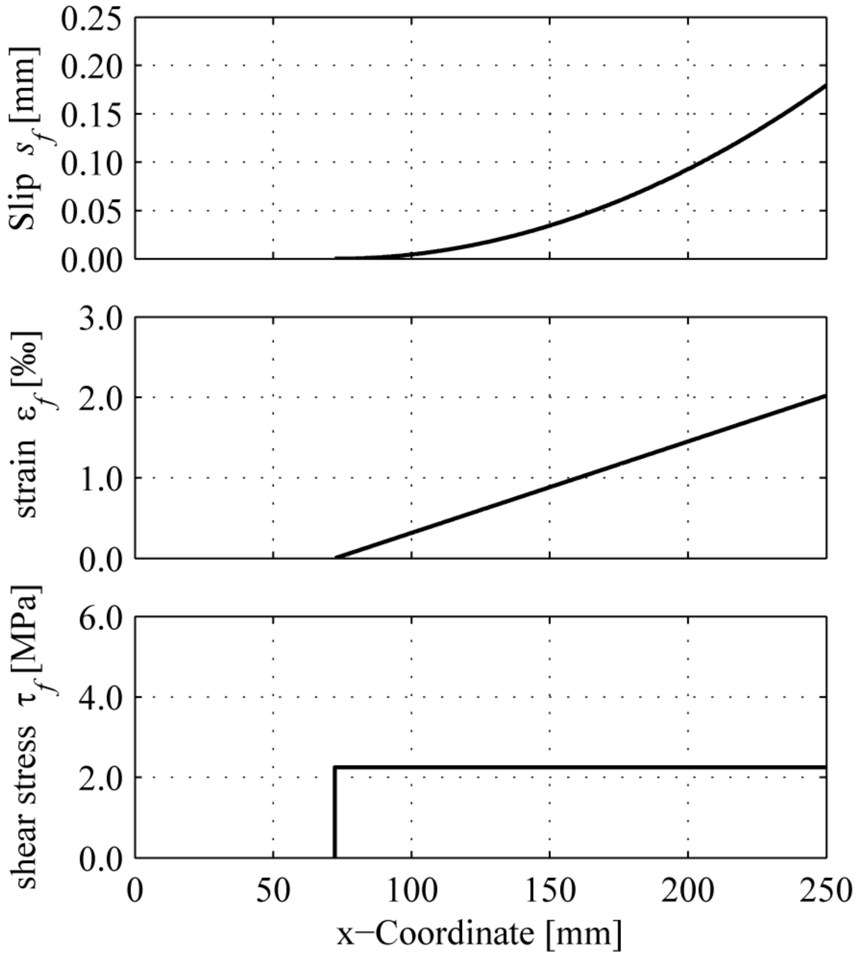
parabolic shape of slip

F = 15 kN

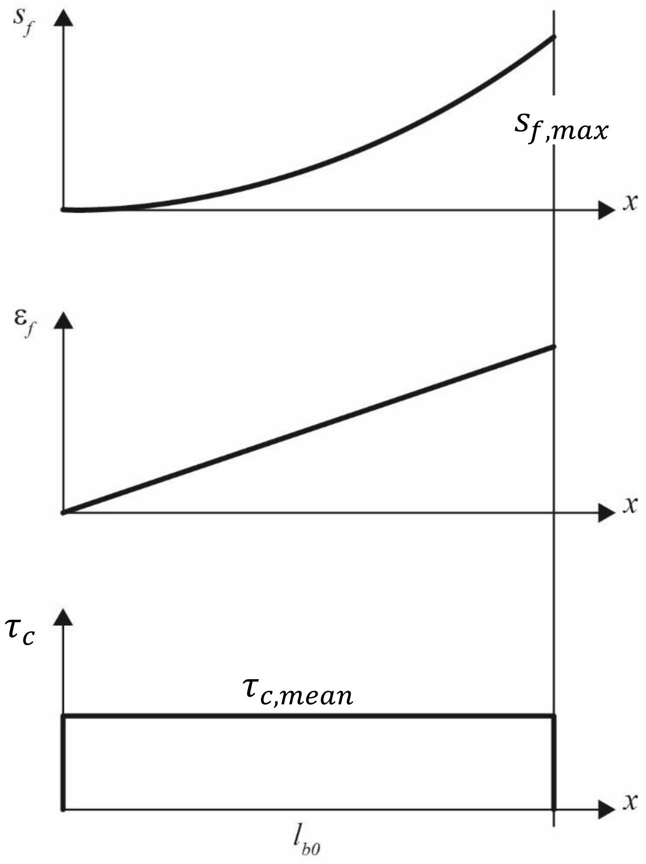


parabolic shape of slip

F = 20 kN



parabolic shape of slip



$$s_f(x) = \frac{\tau_c}{E_f t_f}\frac{x^2}{2} \qquad (1)$$

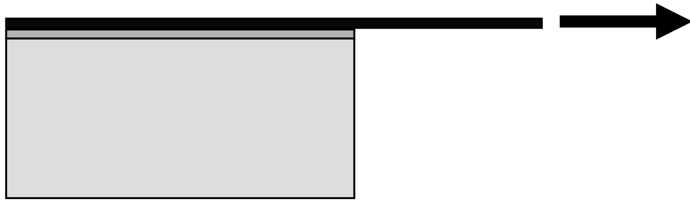
$$\varepsilon_f(x) = \frac{\tau_c}{E_f t_f}x \qquad (2)$$

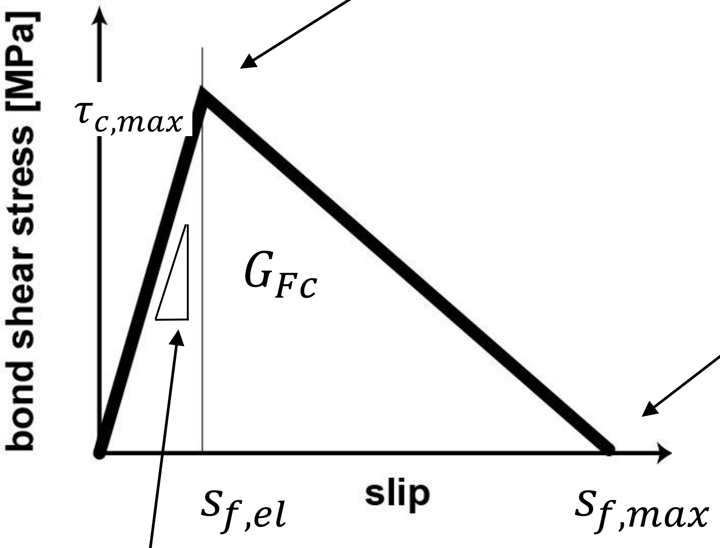
$$\tau_c(x) = \tau_{c,mean} \qquad (3)$$

with $l_{b0}(x) = \dfrac{F_{b0,R}}{\tau_{c,mean}\, b_f}$ and $s_f(x = l_{b0}) = s_{f,max}$ we get from Eq. (1) and (3): $s_{f,max} = \dfrac{F_{b0,R}^2}{2E_f t_f b_f^2 \tau_{c,mean}}$

and with $G_{Fc} = \tau_{c,mean} s_{f,max}$ (slide 40) we get $\boxed{F_{b0,R} = b_f\sqrt{2G_{Fc}E_f t_f}}$

Bond behavior depends on





Bond damage (Entfestigungsbereich, Verbundschädigung)

- concrete quality

maximum slip

- constant (~0.2 mm)

Additionally, the stiffness ($E_f t_f$) of the strip influences also the bond behaviour.

Elastic deformation

- shear modulus of adhesive and concrete
- thickness of adhesive plus a layer of concrete

Comparison with reinforcement

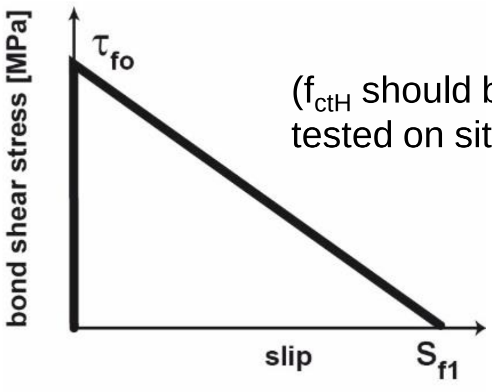
- Internal steel reinforcement is surrounded
  - Deflection perpendicular to longitudinal direction is not possible
  - Normal (confinement) stresses due to interlocking and friction

  → the longer the anchor length, the higher the anchor force up to yielding of the steel reinforcement

- Externally applied strip is free on one side
  - Deflection perpendicular to longitudinal direction is possible

  → maximum anchorage force (anchorage resistance) with corresponding length (active bond length)

CFRP strip according to SIA 166 (2004)



(f_{ctH} should better be tested on site)

$$\tau_{f0} = \frac{4}{3} f_{ctH} \quad G_{Fb} = \frac{1}{8} f_{ctH}$$

f_{ctH} : **mean** value of bond strength (Haftfestigkeit) determined according to DIN 1048 part 2

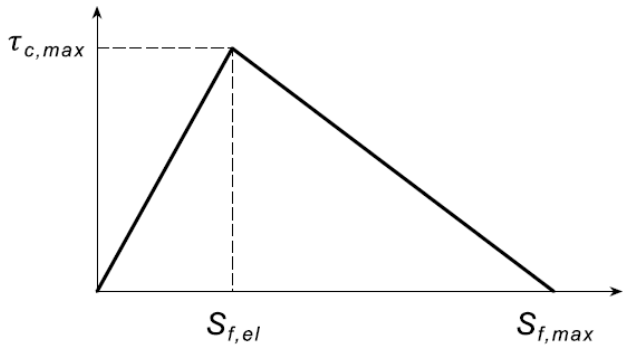
for C30/37: f_{ctm} = 2.9MPa

with $f_{ctm} = f_{ctH}$ (only as an example, the correlation is not correct!)

τ_{f0} = 3.9 MPa

G_{Fb} = 0.36 N/mm

CFRP strip according to SIA 166 (2024)



$$\tau_{c,max,k} = \frac{4}{3} f_{hk} \qquad G_{Fck} = \frac{1}{8} f_{hk}$$

f_{hk} : **characteristic** value of bond strength (Haftfestigkeit) determined according to SN EN 1542

for C30/37: f_{ctm} = 2.9MPa

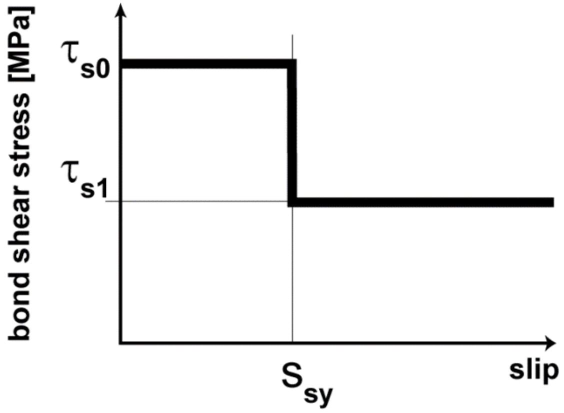
with $f_{hk} = 0.7\ f_{ctm}$ = 2.0 (only as an example and to show the idea, the relation is not correct!)

$\tau_{c,max,k}$ = 2.7 MPa

G_{Fck} = 0.25 N/mm

Internal steel reinforcement according to Sigrist and Marti: (Skript Stahlbeton Marti 2009)

ology

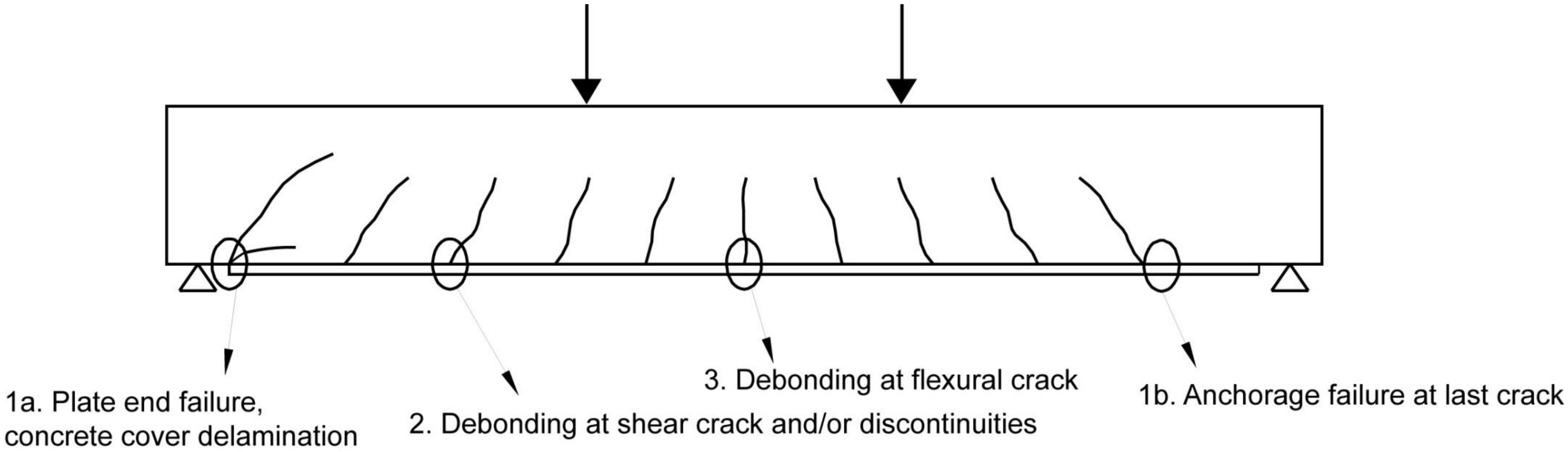


$$\tau_{s0} = 2 f_{ctm} \qquad \tau_{s1} = f_{ctm}$$

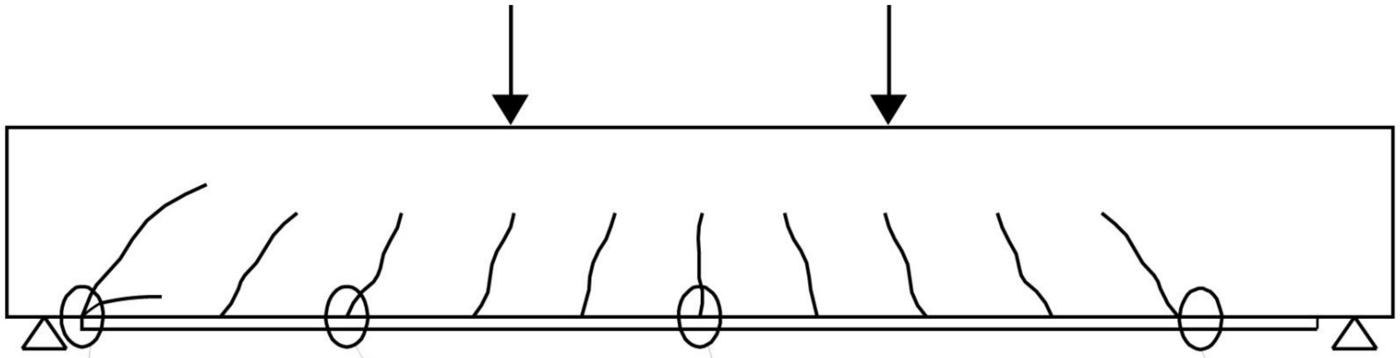
In SIA262 (2013): $f_b = 1.4 f_{ctm}$

τ_{s0} = 5.8 MPa **τ_{s1} = 2.9 MPa**

Debonding failure modes according to SIA 166



Debonding failure modes according to SIA 166



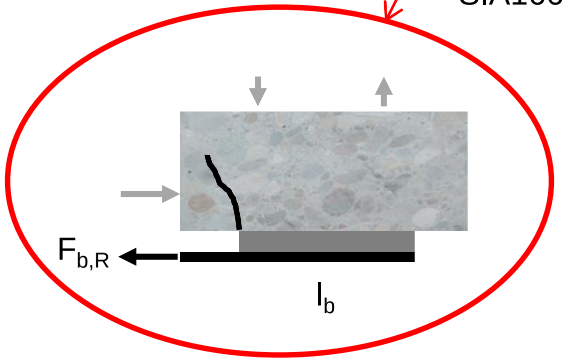
1a. Plate end failure, concrete cover delamination

2. Debonding at shear crack and/or discontinuities

3. Debonding at flexural crack

1b. Anchorage failure at last crack

Concept of SIA166



Equations for maximum anchorage resistance

SIA 166 (2024) $F_{b0,Rd} = b_f \sqrt{2 G_{Fcd} E_f t_f}$ with $G_{Fcd} = \frac{1}{8} \eta_u \eta_l \frac{f_{hk}}{\gamma_h}$ G_{Fcd} in N/mm f_{hk} in N/mm^2

reduction factors $\eta_u \eta_l$ according to SIA166 (2024)

***fib* Bulletin 14** $N_{fa,max} = \alpha \cdot c_1 \cdot k_c \cdot k_b \cdot b_f \cdot \sqrt{E_f \cdot t_f \cdot f_{ctm}}$

TR55 $T_{k,max} = 0.5 \cdot k_b \cdot b_f \cdot \sqrt{E_{fd} \cdot t_f \cdot f_{ctk}}$

$$k_b = 1.06 \sqrt{\frac{2 - \frac{b_f}{b}}{1 + \frac{b_f}{400}}} \geq 1$$

Italian Code $F_{fd} = b_f \sqrt{2 \cdot E_f \cdot t_f \cdot \Gamma_{Fk}}$; $\Gamma_{Fk} = 0.03 \cdot k_b \cdot \sqrt{f_{ck} \cdot f_{ctm}}$

Take care to symbols. They depend on the reference.

Active bond length

(the length which is actively involved in the force transfer from the strip to the concrete)

If we assume a constant bond shear stress:

$$l_{b0} = \frac{F_{b0,R}}{\tau_{c,mean}\, b_f}$$

with

$$F_{b0,R} = b_f \sqrt{2G_{Fc}E_f t_f}$$

$$\longrightarrow \quad l_{b0} = \frac{\sqrt{2G_{Fc}E_f t_f}}{\tau_{c,mean}} \quad \longrightarrow$$ proportional to $$\sqrt{\frac{G_{Fc}E_f t_f}{\tau_c^2}}$$

Equations for active bond length

(minimum necessary length for maximum anchor resistance $F_{b0,R}$)

SIA 166 (2024)	$l_{b0d} = 2.5\sqrt{\frac{G_{Fcd}E_f t_f}{\tau^2_{c,max,d}}}$	with $G_{Fcd} = \frac{1}{8}\eta_u\eta_l\frac{f_{hk}}{\gamma_h}$ $\tau_{c,max,d} = \frac{4}{3}\eta_u\eta_l\frac{f_{hk}}{\gamma_h}$ The reduction values η_u and η_l are tabulated in SIA 166(2024), they consider environment and loading conditions.
***fib* Bulletin 14**	$l_{b,max} = \sqrt{\frac{E_f \cdot t_f}{c_2 \cdot f_{ctm}}}$	
TR55	$l_{t,max} = 0.7 \cdot \sqrt{\frac{E_{fd} \cdot t_f}{f_{ctk}}}$	
Italian Code	$l_e = \sqrt{\frac{E_f \cdot t_f}{2 \cdot f_{ctm}}}$	

Example

Concrete C30/37

Sika CarboDur S512 tensile strength > 2800 MPa

tensile strain > 17‰

$$G_{Fcd} = \frac{1}{8}\eta_u\eta_l\frac{f_{hk}}{\gamma_h}$$

$$\tau_{c,max,d} = \frac{4}{3}\eta_u\eta_l\frac{f_{hk}}{\gamma_h}$$

for concrete
C 20/25 to C 50/60

$$G_{Fcd} = \frac{1}{8}1.0\;1.0\frac{2.9}{1.5} = 0.24\;\frac{N}{mm}$$

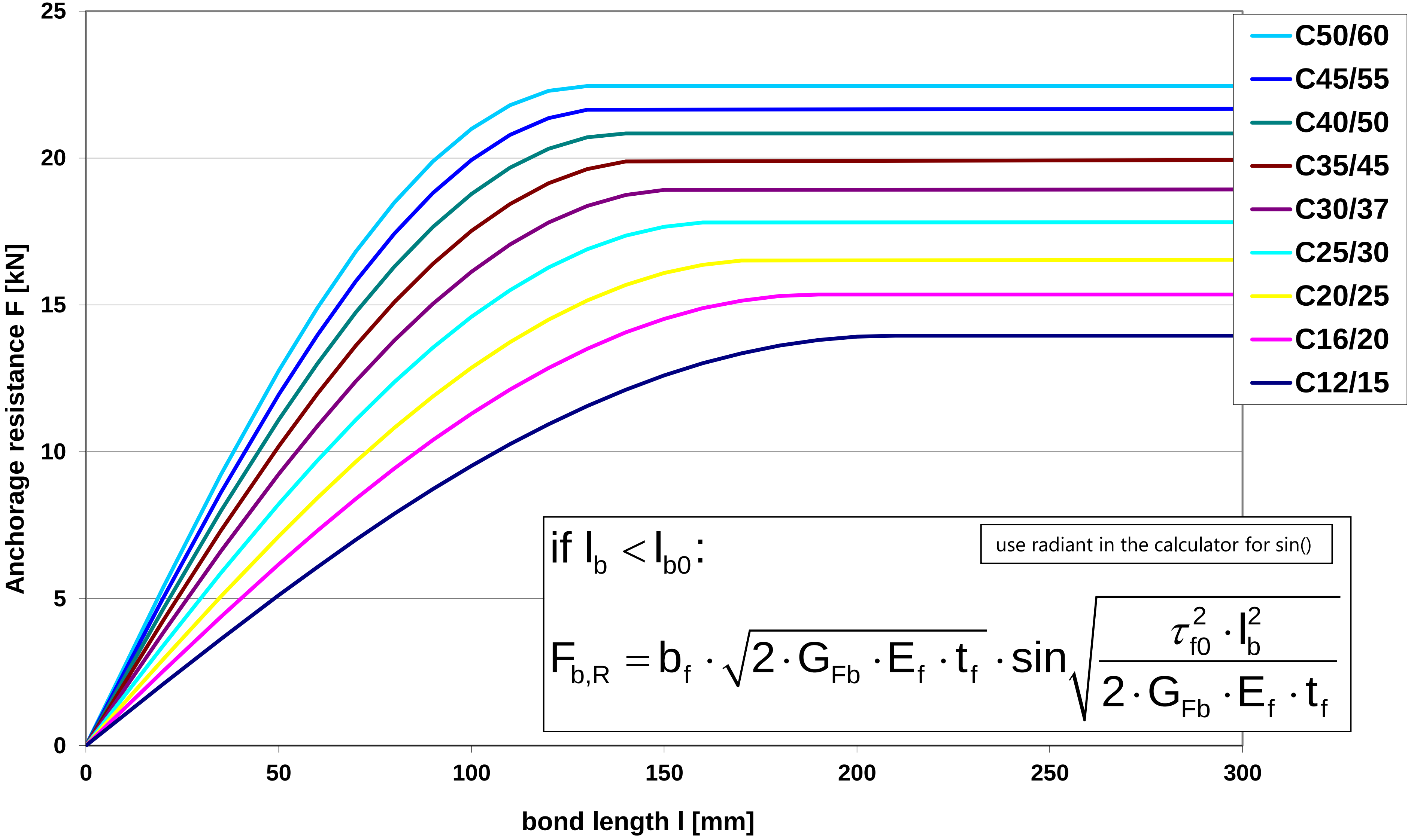
$$\tau_{c,max,d} = \frac{4}{3}1.0\;1.0\frac{2.9}{1.5} = 2.6\;MPa$$

$$F_{b0,Rd} = b_f\sqrt{2G_{Fcd}E_f t_f} = 50\sqrt{2\cdot 0.24\cdot 165000\cdot 1.2} = 15.5\;kN$$

$$\sigma_{b0,Rd} = \frac{F_{b0,Rd}}{b_f t_f} = 258\;MPa$$

$$\varepsilon_{b0,Rd} = \frac{\sigma_{b0,Rd}}{E_f} = 1.56‰$$

old SIA166 (2004)

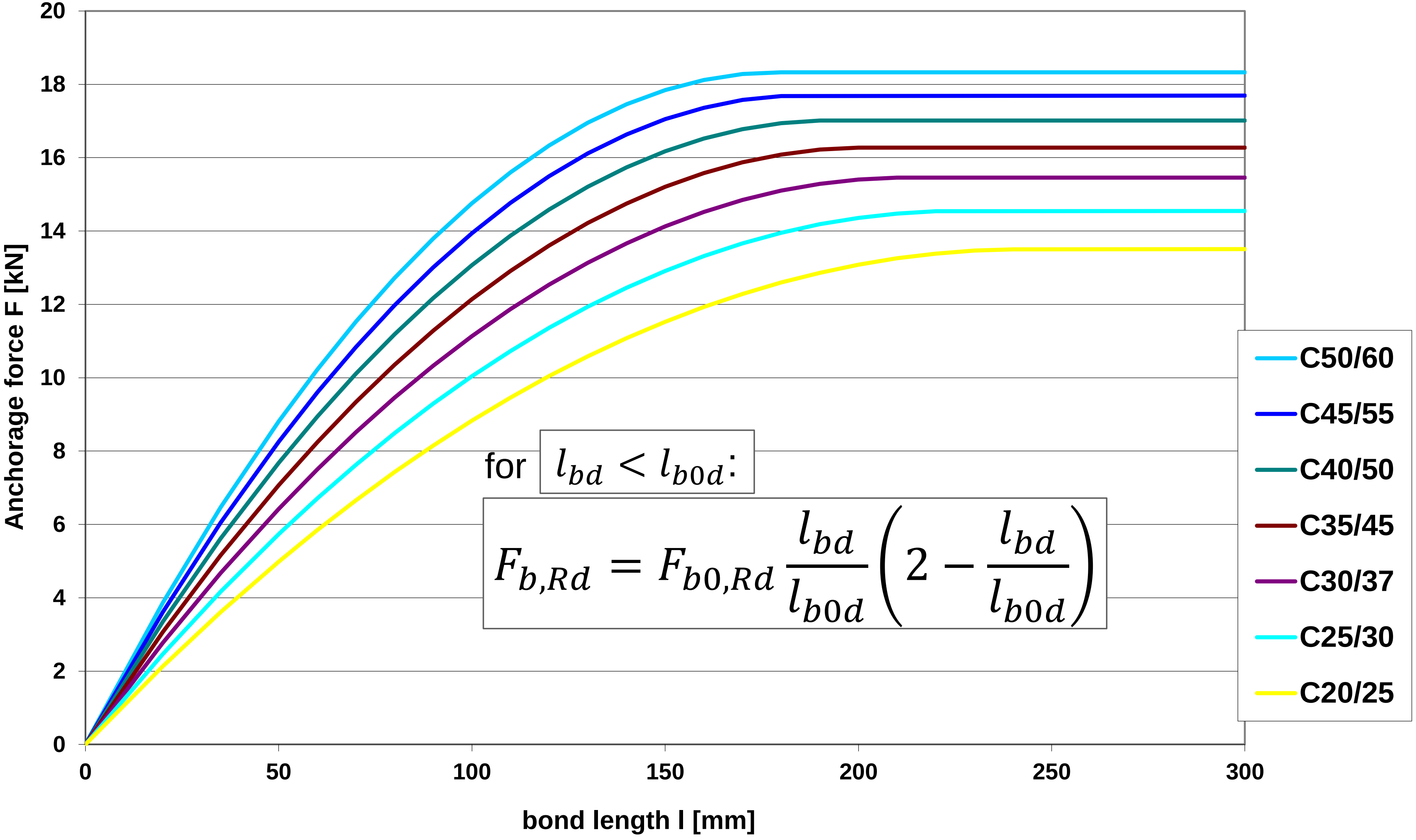


$$\text{if } l_b < l_{b0}:$$

use radiant in the calculator for sin()

$$F_{b,R} = b_f \cdot \sqrt{2 \cdot G_{Fb} \cdot E_f \cdot t_f} \cdot \sin\sqrt{\frac{\tau_{f0}^2 \cdot l_b^2}{2 \cdot G_{Fb} \cdot E_f \cdot t_f}}$$

SIA 166 (2024):



for $l_{bd} < l_{b0d}$:

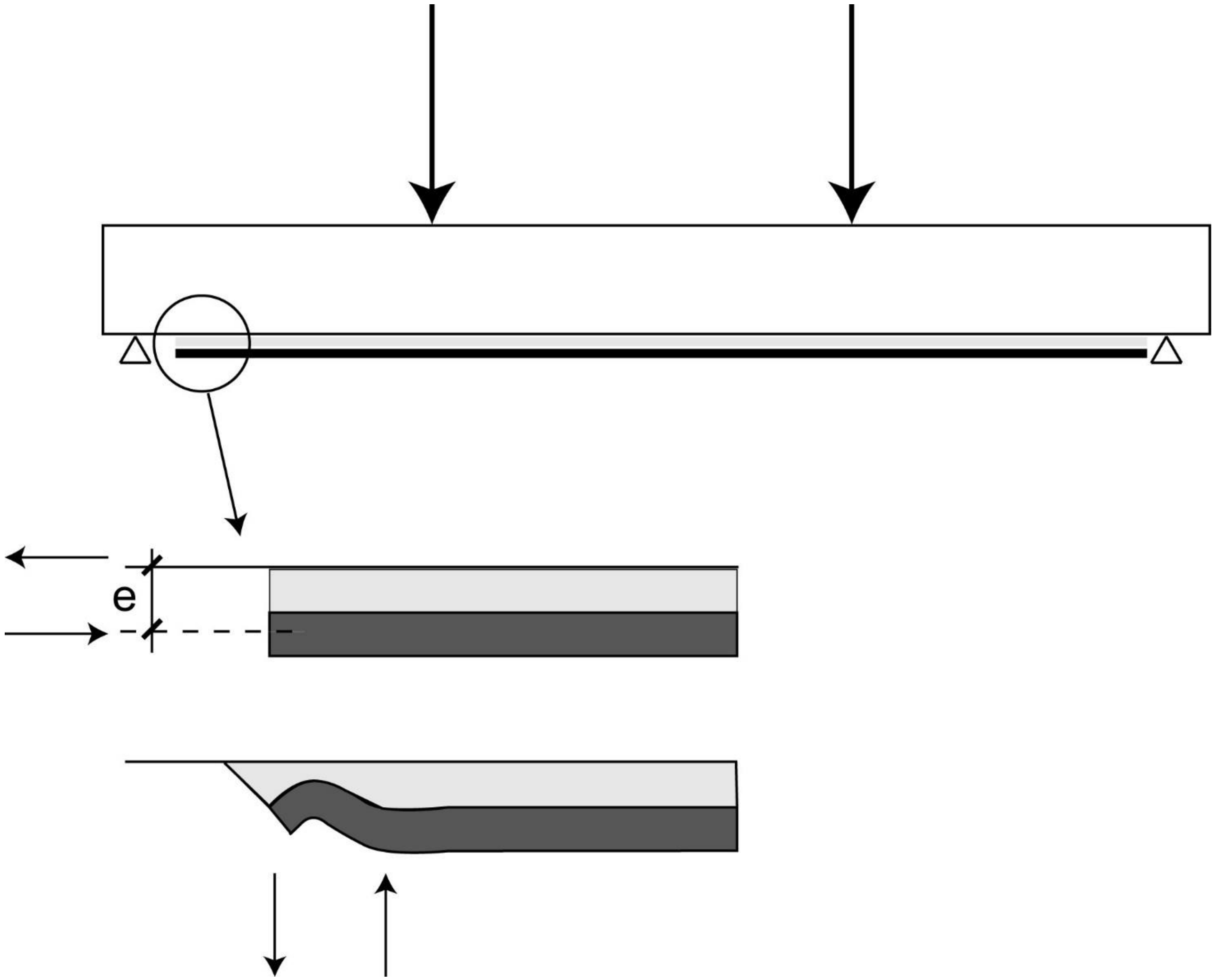
$$F_{b,Rd} = F_{b0,Rd} \frac{l_{bd}}{l_{b0d}} \left(2 - \frac{l_{bd}}{l_{b0d}} \right)$$

Design philosopy of preventing end anchorage failure

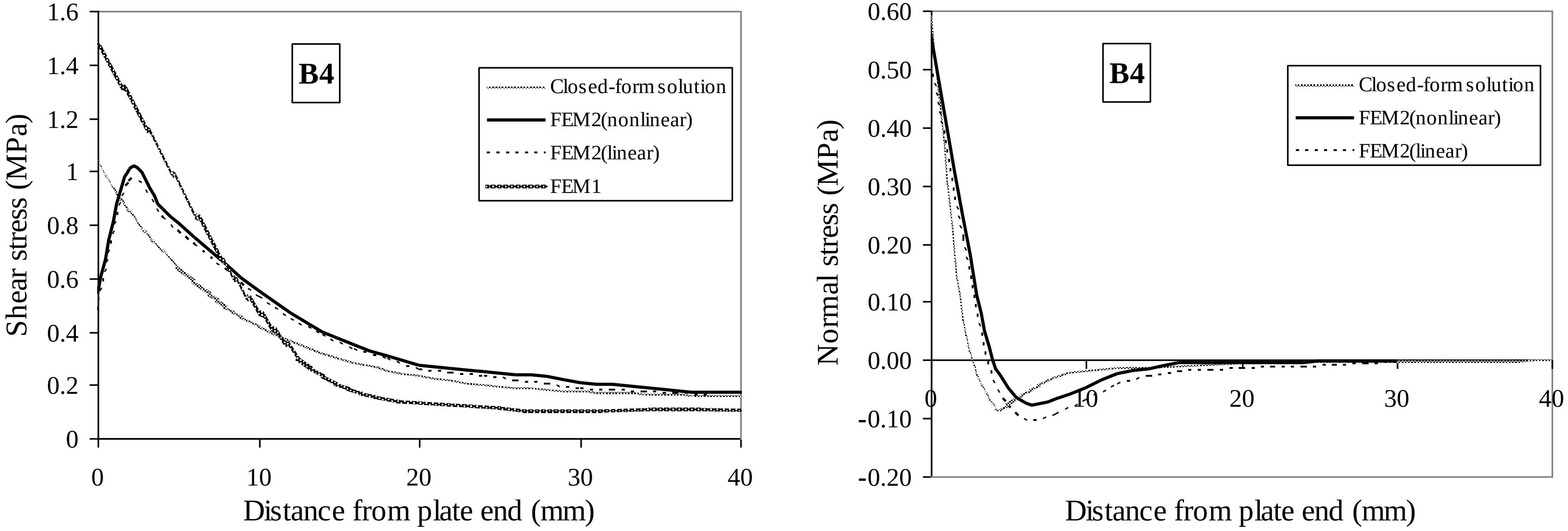
- SIA166: anchorage in the uncracked zone
- ACI:
    - If $V_u > 0.67\ V_c$ at strip end, then transverse reinforcement is necessary (they give a design equation for U-wrap reinforcement $A_{f,anchor}$)

  or (instead of detailed analysis)
    - for simply supported beams: length l_{df} after last crack
- Elastic solutions for calculating shear and normal stresses at strip end

End anchorage, normal stresses at strip end



Shear and normal stresses at strip end



see:

Aram, M.R., C. Czaderski, and M. Motavalli, Debonding failure modes of flexural FRP-strengthened RC beams. Composites Part B: Engineering, 2008. 39(5): pp. 826-841.

Safety concept of the new SIA 166 (2024)

Example: concrete tensile strength at the concrete surface

Mean value from tests	f_{hm} = 4.0 GPa
Characteristic value (5% fractile)	f_{hk} = 3.2 GPa

Design value:

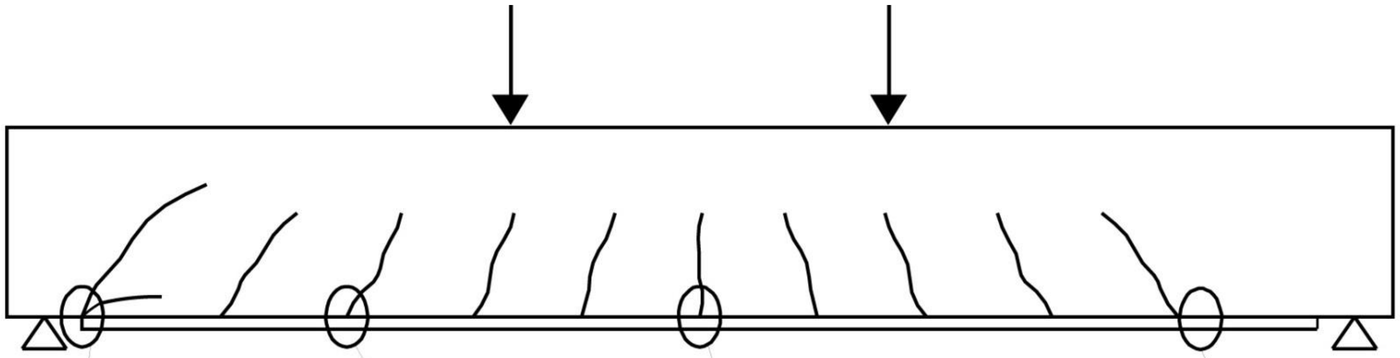
$$f_{hd} = \frac{f_{hk}}{\gamma_h} = \frac{3.2}{1.5} = 2.1 MPa$$

γ_h = 1.5, from Tabelle 5 in SIA166 (2024), see slide 103

Design value of fracture energy:

$$G_{Fcd} = \frac{f_{hd}}{8} = \frac{2.1}{8} = 0.26 N/mm$$

Debonding failure modes



1a. Plate end failure,
concrete cover delamination

3. Debonding at flexural crack

2. Debonding at shear crack and/or discontinuities

1b. Anchorage failure at last crack

Example

Concrete C30/37

Sika CarboDur S512 tensile strength > 2800 MPa

tensile strain > 17‰

$$F_{b0,Rd} = b_f \sqrt{2 G_{Fcd} E_f t_f} = 50\sqrt{2 \cdot 0.24 \cdot 165000 \cdot 1.2} = 15.5\, kN$$

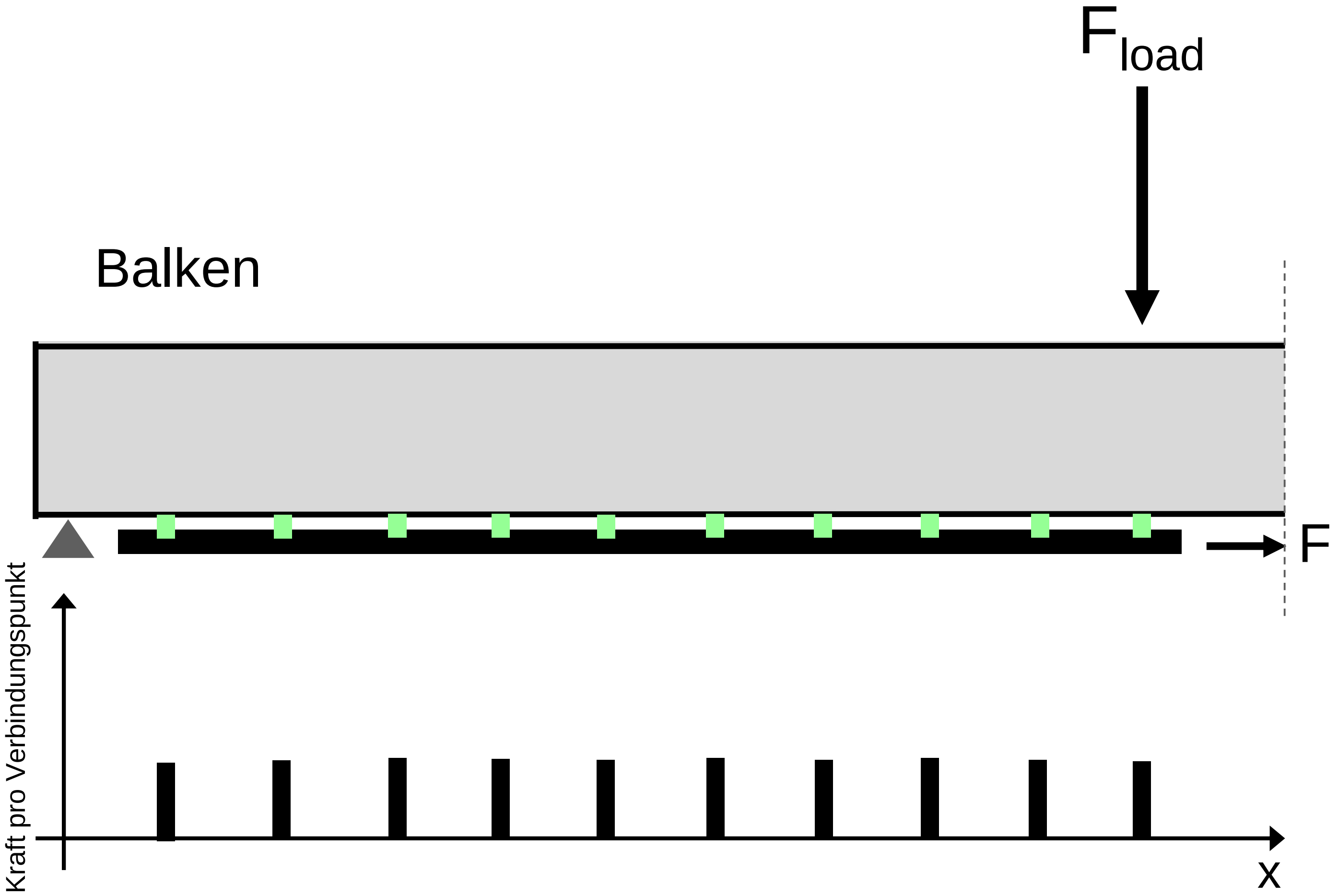
$$\sigma_{b0,Rd} = \frac{F_{b0,Rd}}{b_f t_f} = 258\, MPa \qquad \varepsilon_{b0,Rd} = \frac{\sigma_{b0,Rd}}{E_f} = 1.56‰$$

??

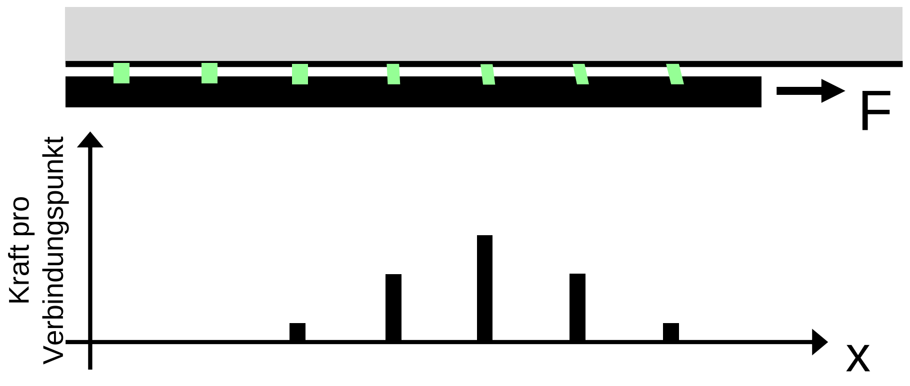
According to the old SIA166 (2004),

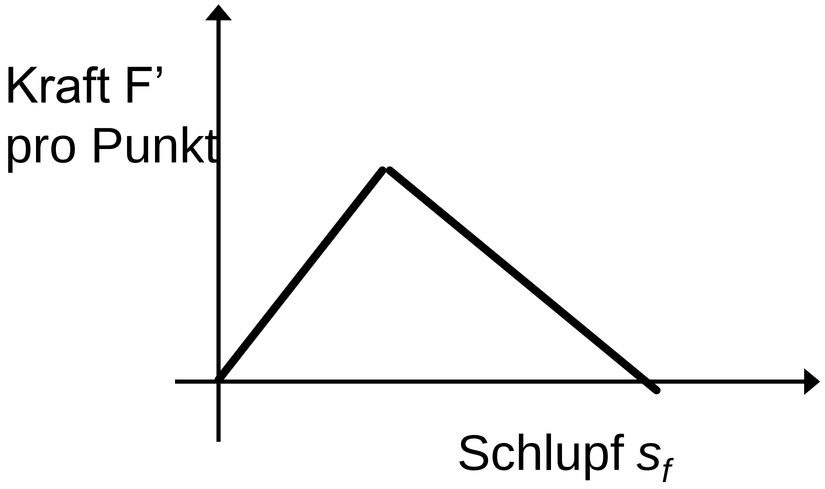
the maximum allowed strain was 8‰!

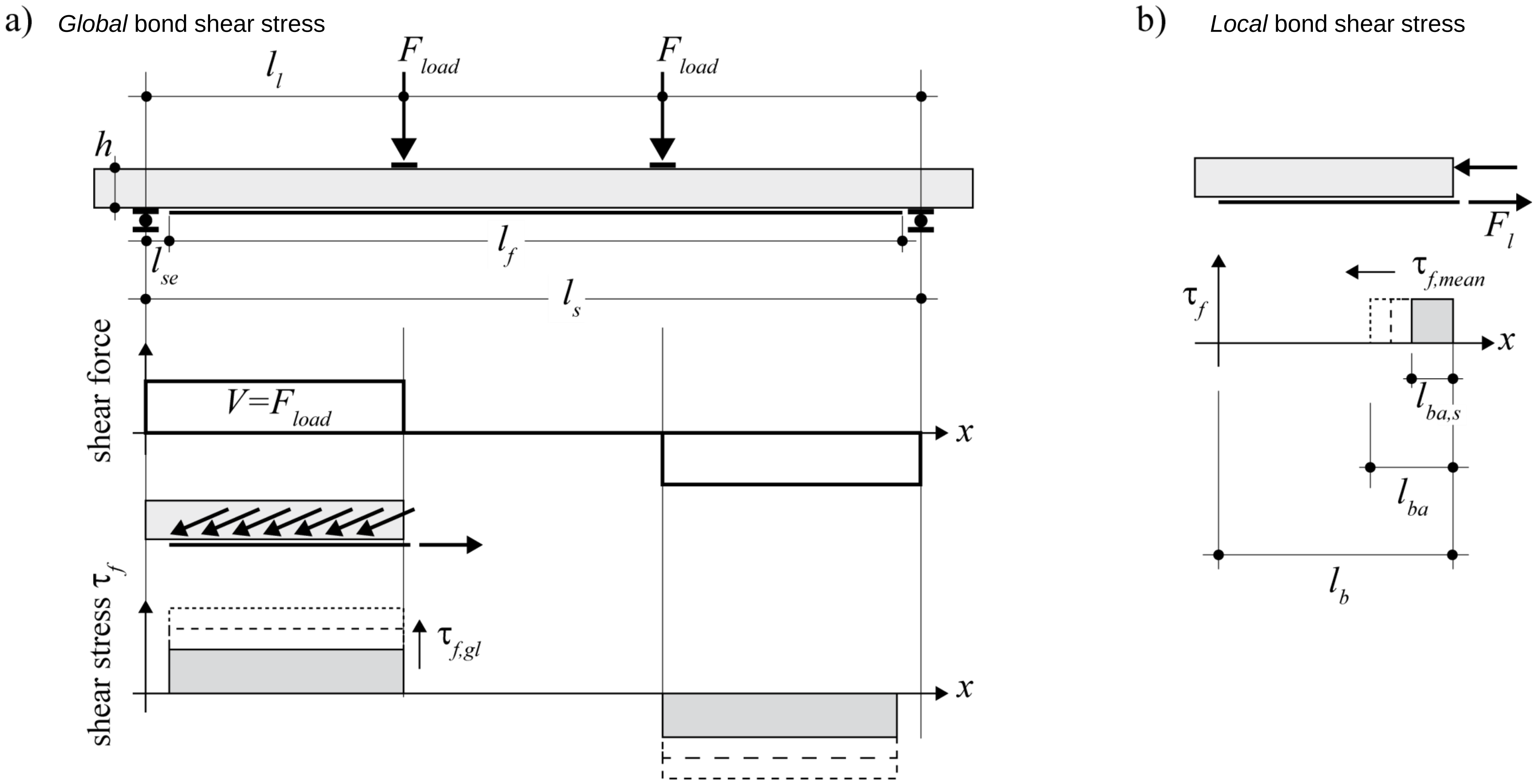
Balken



Abzugsversuch







a) *Global* bond shear stress

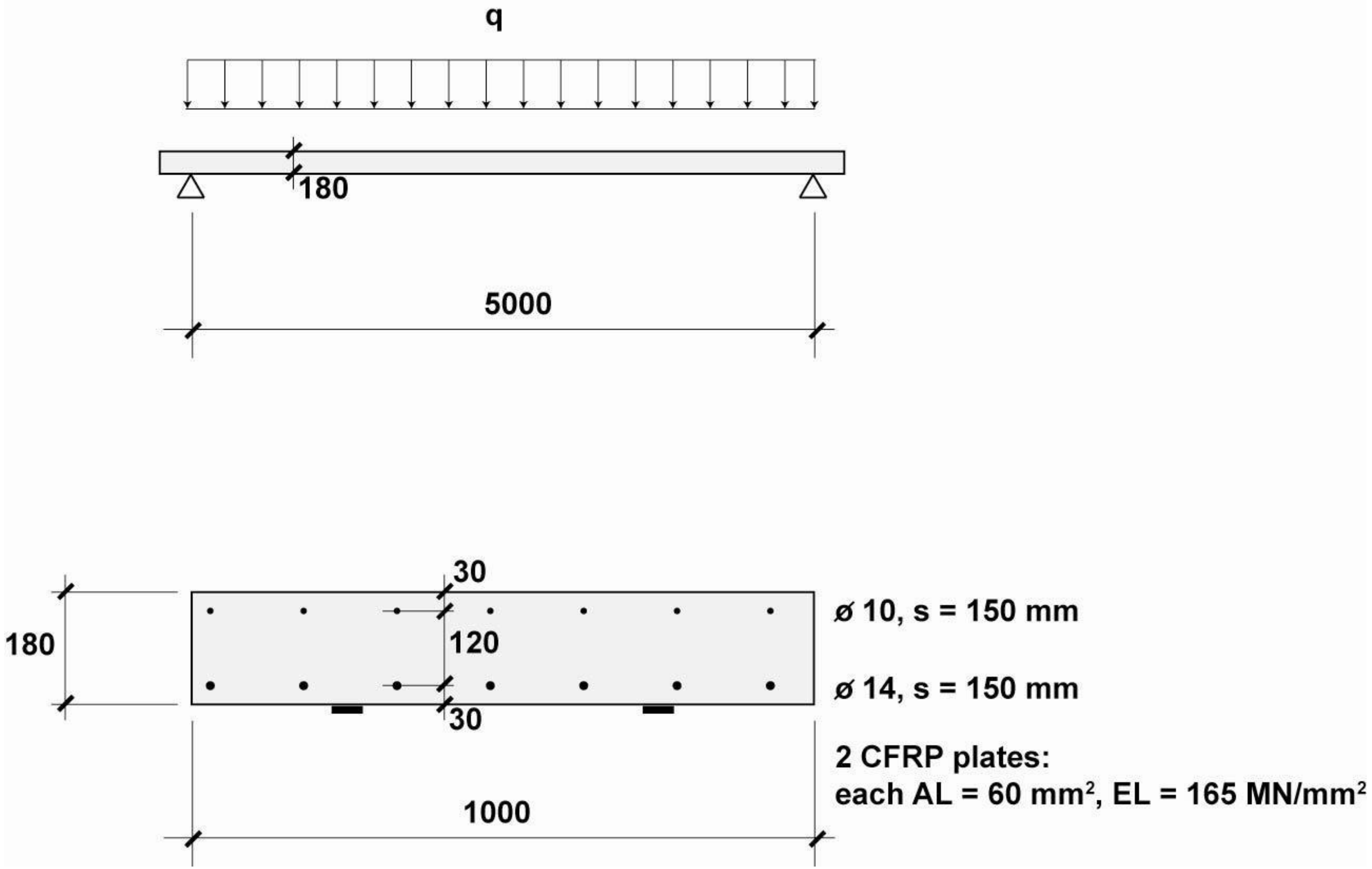
b) *Local* bond shear stress

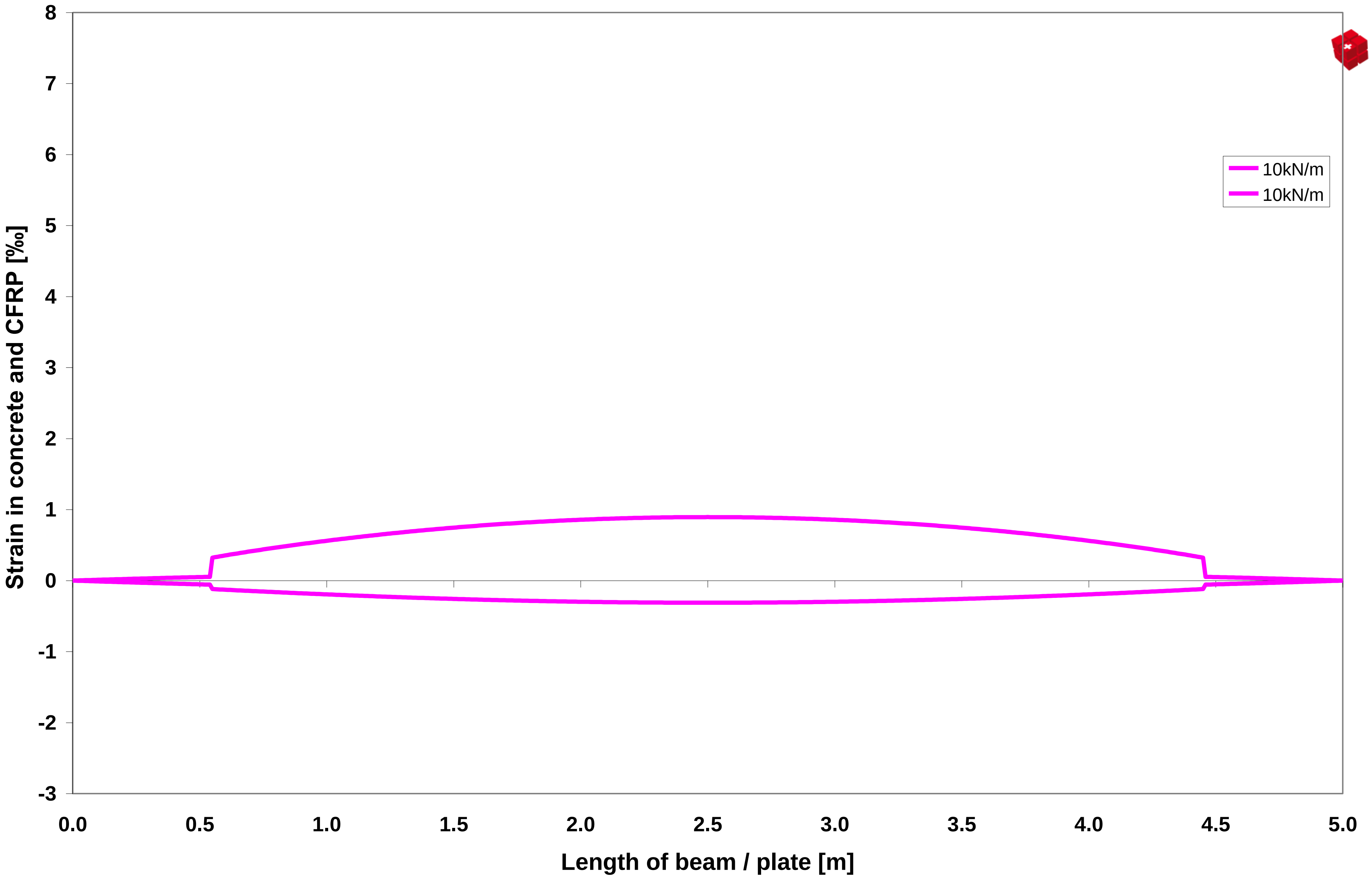
→ bond length constant,
bond shear stress increases

→ bond length increases,
bond shear stress constant

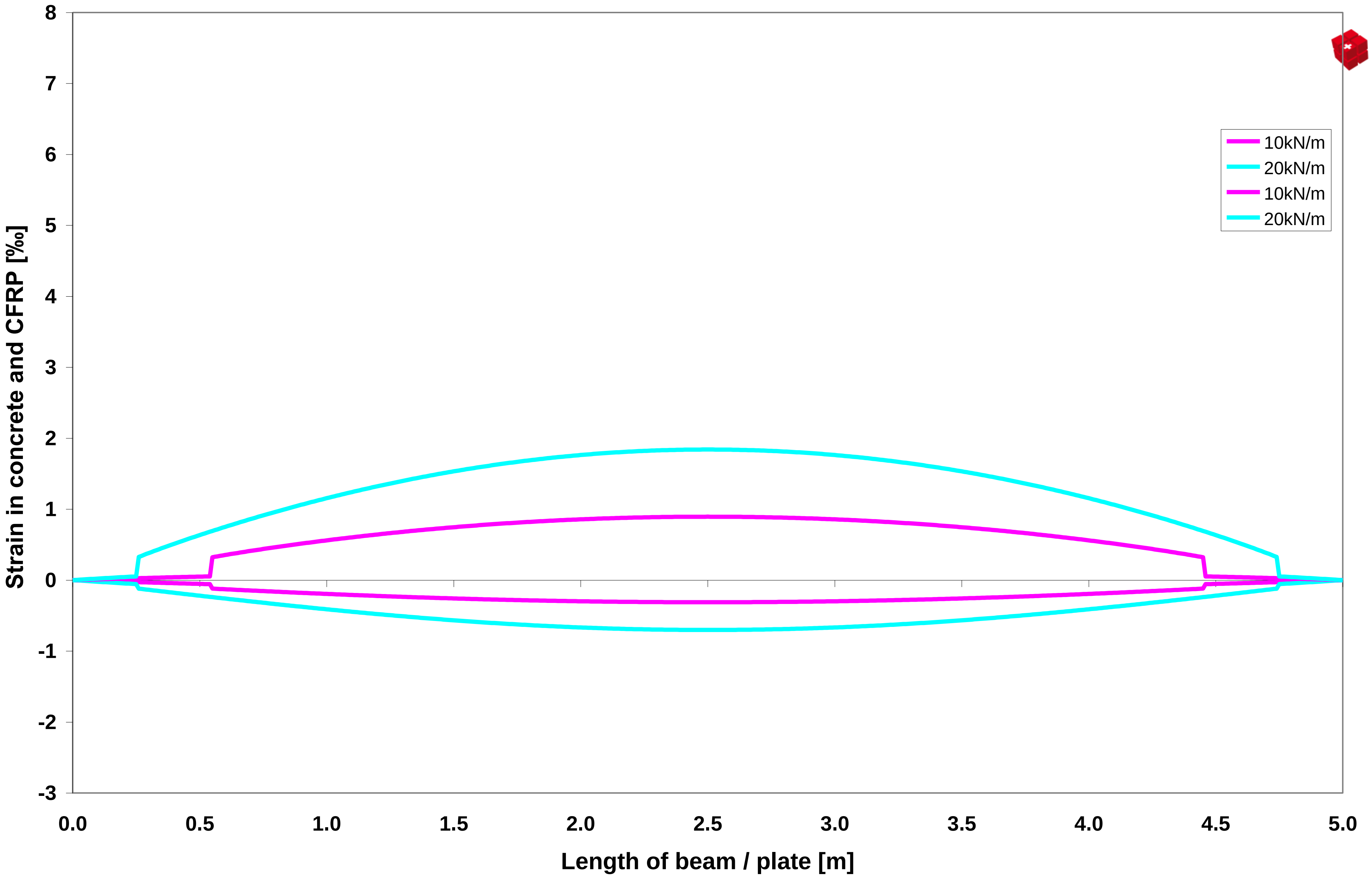
Figure 38 of PhD Thesis of C.Czaderski (Diss ETH No. 20504):

Simple supported plate





8
7
6
5
4
3
2
1
0
-1
-2
-3
Strain in concrete and CFRP [‰]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Length of beam / plate [m]
10kN/m
10kN/m



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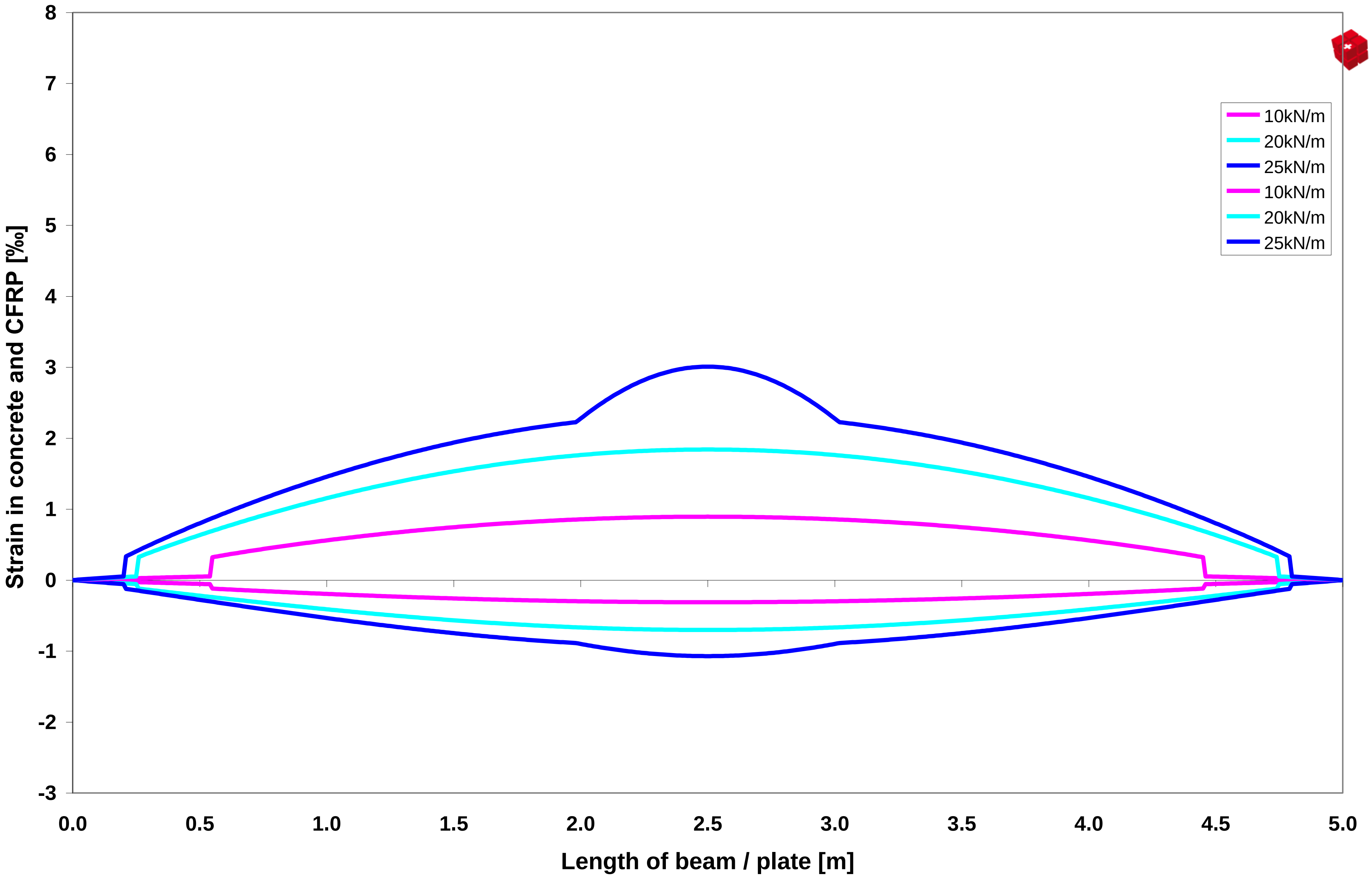
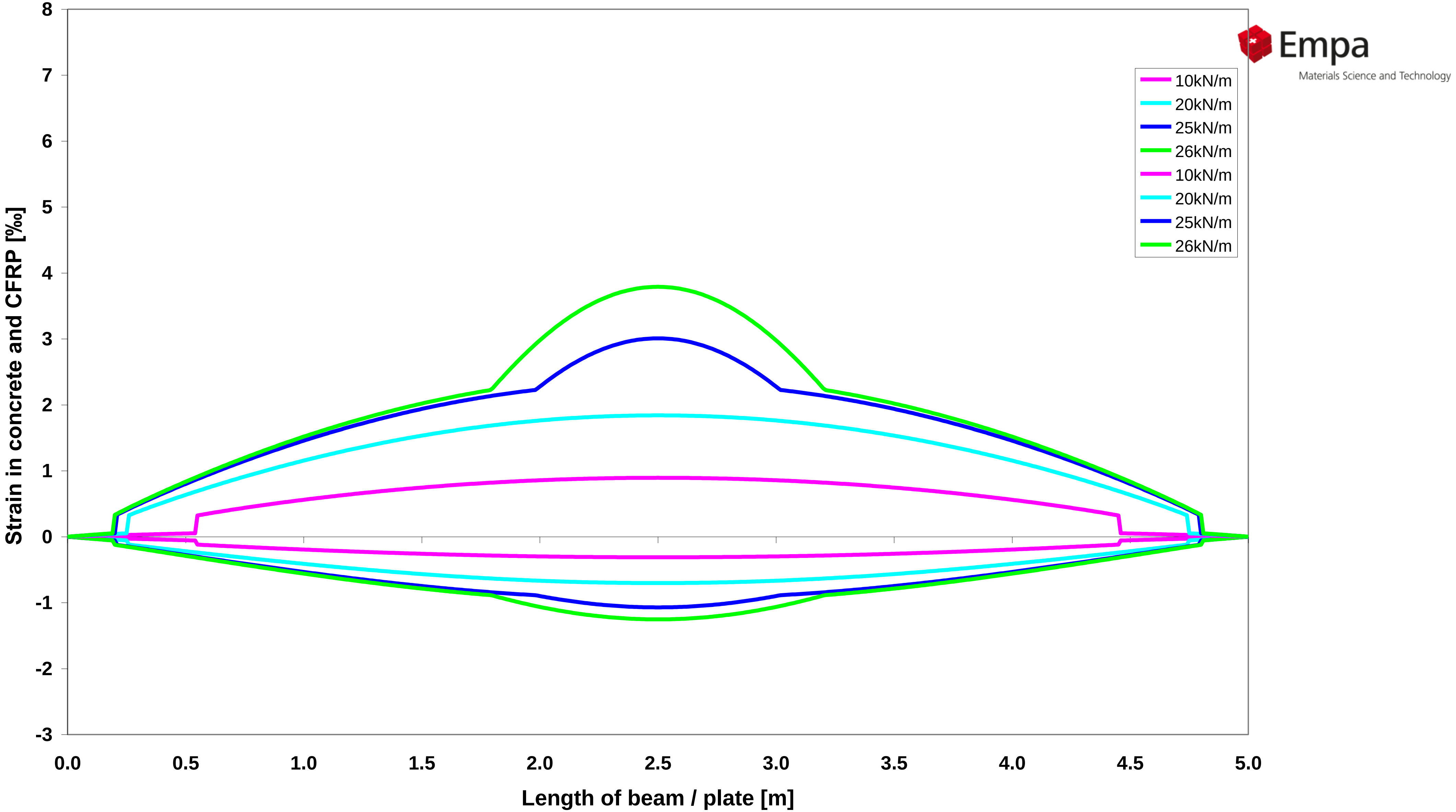


8
7
6
5
4
3
2
1
0
-1
-2
-3
Strain in concrete and CFRP [‰]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Length of beam / plate [m]
10kN/m
20kN/m
25kN/m
10kN/m
20kN/m
25kN/m


Strain in concrete and CFRP [‰]
Length of beam / plate [m]
8
7
6
5
4
3
2
1
0
-1
-2
-3
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
10kN/m
20kN/m
25kN/m
26kN/m
10kN/m
20kN/m
25kN/m
26kN/m
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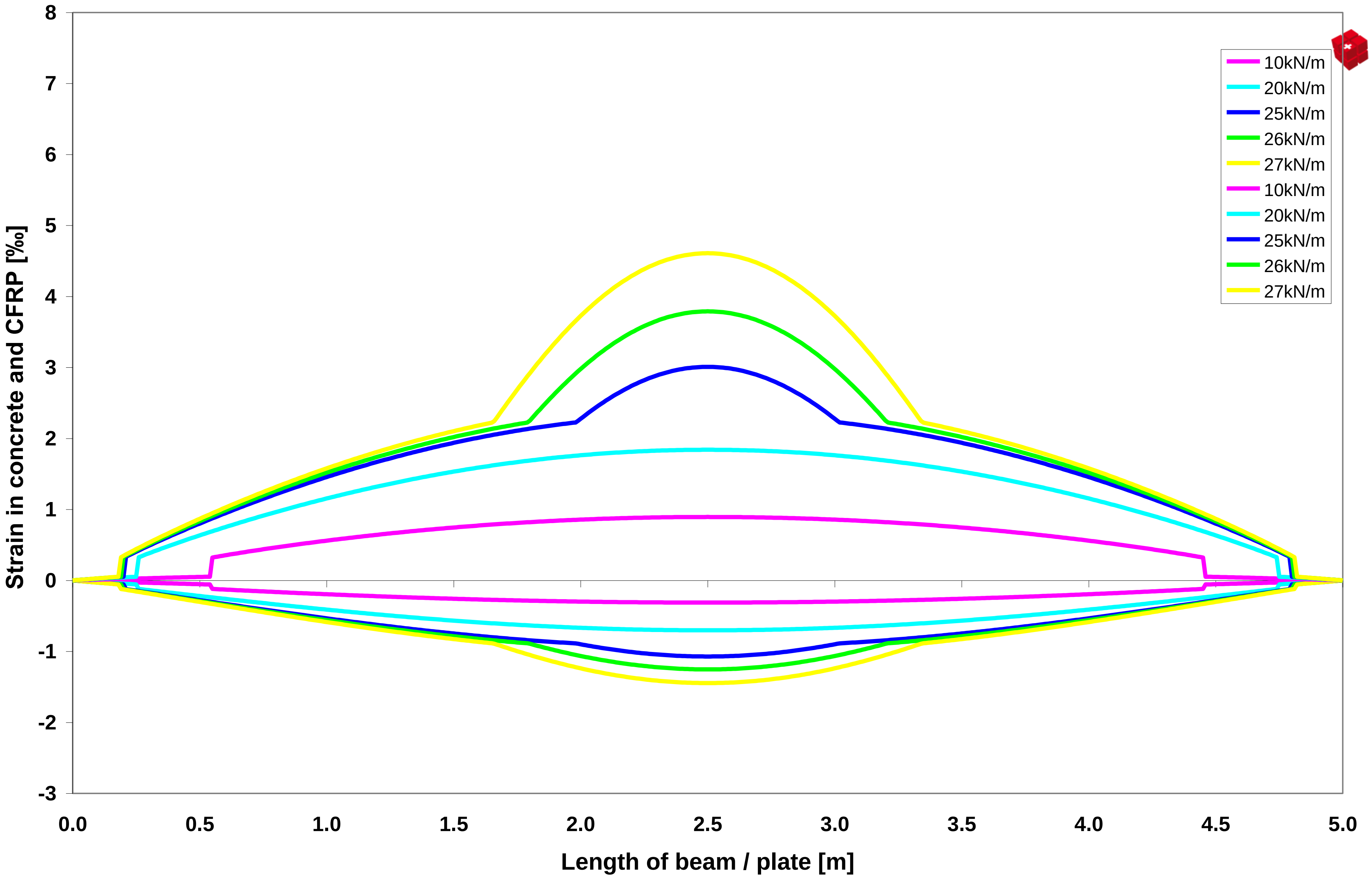
Materials Science and Technology



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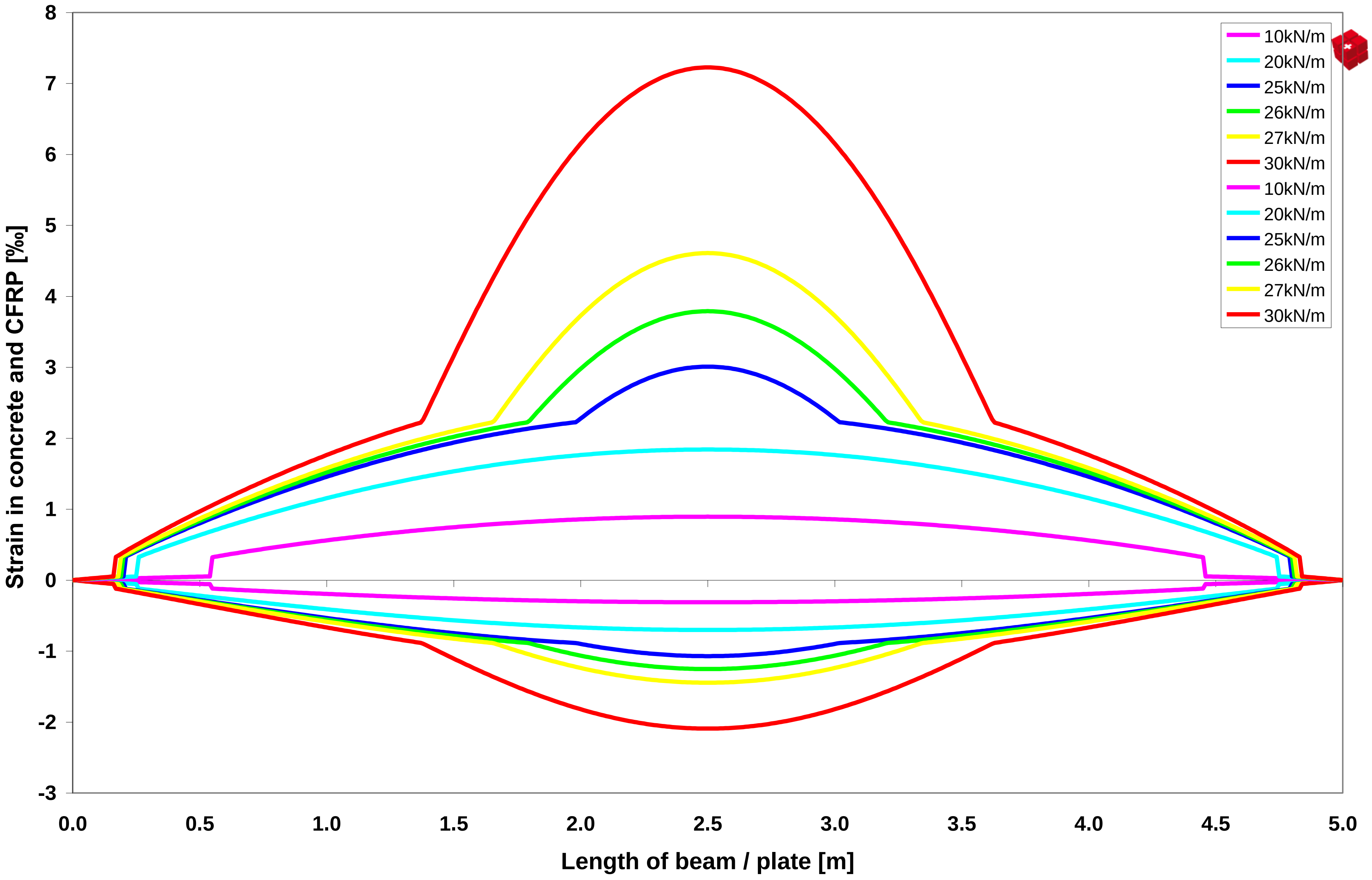

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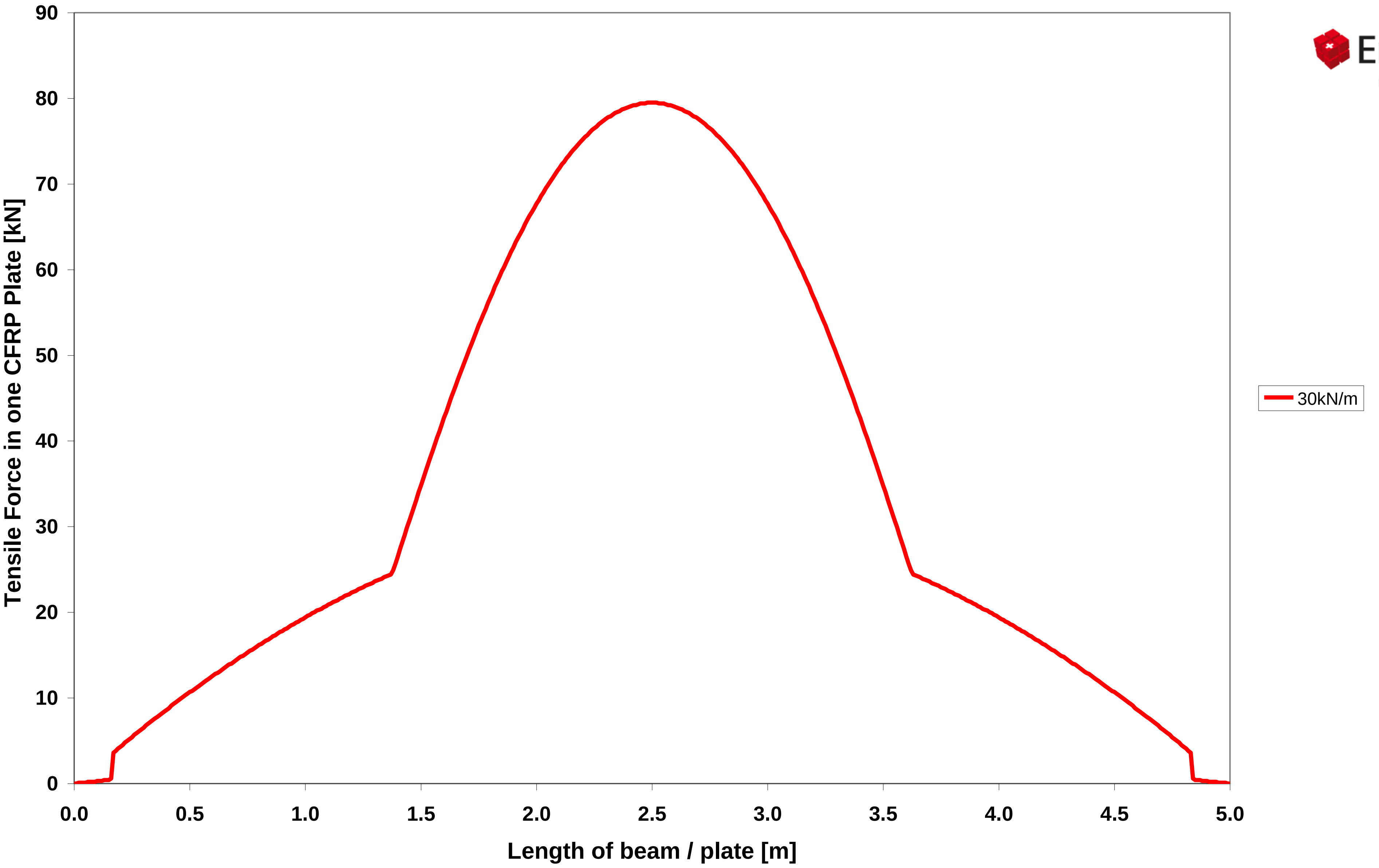

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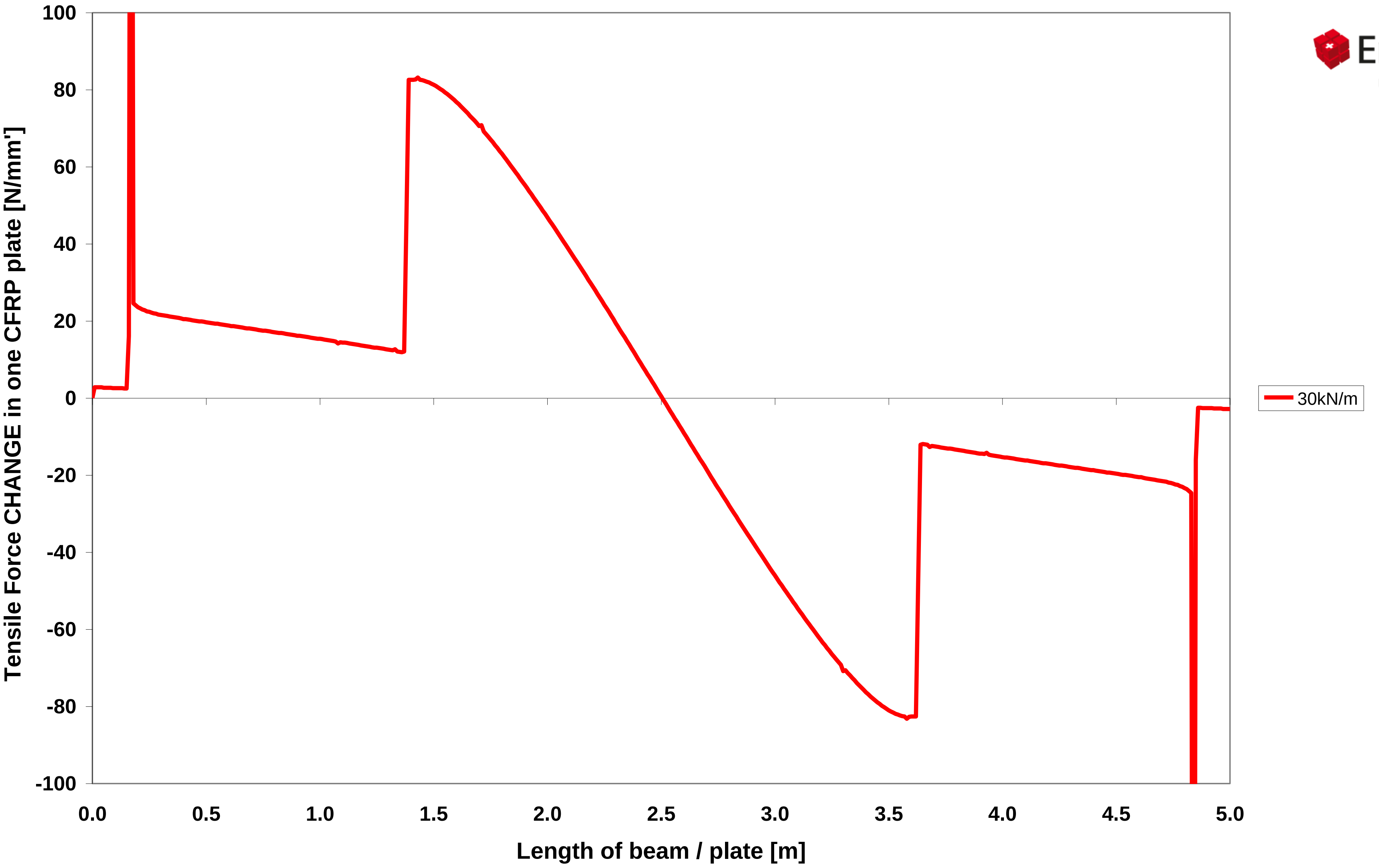


100
80
60
40
20
0
-20
-40
-60
-80
-100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Tensile Force CHANGE in one CFRP plate [N/mm']
Length of beam / plate [m]
30kN/m

Maximum Tensile Force CHANGE according to the old SIA 166(2004)

$$\left(\frac{\Delta F_f}{\Delta x}\right)_R = \tau_{f,lim} \cdot b_l$$

$$\tau_{f,lim} = 2.5 \cdot \tau_c = 2.5 \cdot 0.3 \cdot \sqrt{f_{ck}}$$

(τ_c from SIA 262)

Example

Concrete C30/37

Sika CarboDur S512

$$\left(\frac{\Delta F_f}{\Delta x}\right)_R = \tau_{f,lim} \cdot b_f = 205N/mm$$

$$\tau_{f,lim} = 2.5 \cdot \tau_c = 2.5 \cdot 0.3 \cdot \sqrt{30} = 4.1MPa$$

please note: without safety factors!!

Shear stress limitations, other guidelines

Empa
Materials Science and Technology

***fib* Bulletin 14 (approach 3)**

$$\tau_b \leq f_{cb}$$

$$f_{cb} = 1.8 \cdot f_{ctk} = 1.8 \cdot 0.7 \cdot 2.9 = 3.7MPa$$

***fib* Bulletin 14 (approach 2)** $\Delta\sigma_f$ **(between cracks …)**

TR55

$$\tau = V_{add}\alpha_f A_f \frac{h\text{-}x}{I_{cs} b_a}$$

$$\tau_t = \underbrace{t_f\left[\frac{\sigma_{fmax} - \sigma_{fy}}{\Delta x}\right]}_{\tau_m = \text{ mean shear stress}} + \underbrace{7.8\left[1.1\text{-}\frac{M_y}{M_{ed}}\right]f_{ctk}}_{\tau_{sc} = \text{additional shear stress due to stress concentration at flexural cracks}}$$

$$\tau_{lim,c} = 0.8 f_{ctk}$$ **outside yield zone**

$$\tau_{lim,y} = 4.5 f_{ctk}$$ **in the yield zone**

---

please note: without safety factors!!

Maximum strain in the strip according to old SIA 166(2004)

- Local debonding due to compatibility problems between strip and concrete at flexural cracks

$$F_{f,R} = A_f \cdot E_f \cdot \varepsilon_{f,lim} \leq A_f \cdot E_f \cdot \varepsilon_{fu}$$

$\varepsilon_{f,lim,d} = 8‰$ design value!

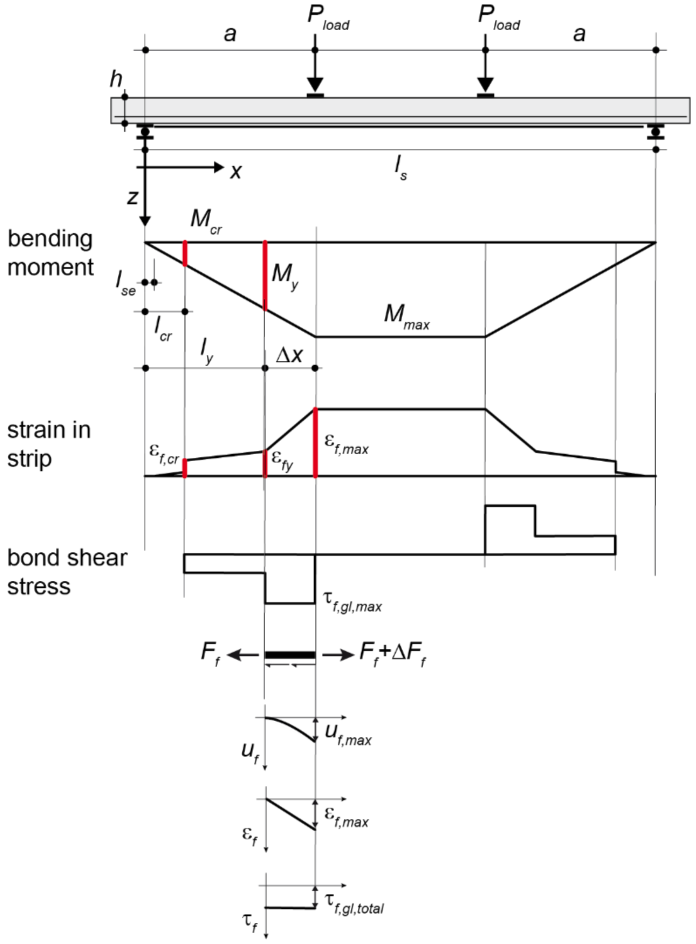
$\varepsilon_{fu} =$ supplier of the material

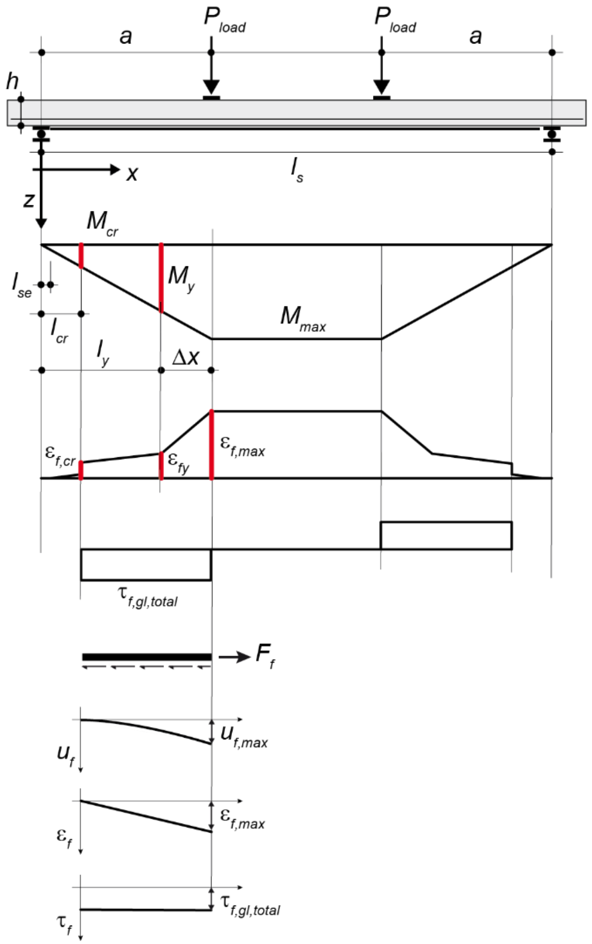
Maximum strain in strip, other guidelines

***fib* Bulletin 14 (approach 1)**	$\varepsilon_{f,lim} = 6.5 - 8.5‰$	
ACI	$\varepsilon_{fd} = 0.41\sqrt{\frac{f_c'}{n \cdot E_f \cdot t_f}}$ (equation for DFM 2 and 3)	**in SI units**
Italian Code	$\varepsilon_{fdd} = k_{cr}\sqrt{\frac{0.06k_b\sqrt{f_{ck}f_{ctm}}}{E_f \cdot t_f}}$ (equation for DFM 2 and 3)	**With k_{cr} = 3.0**
TR55	$\varepsilon_{fmax} + \underbrace{0.114\frac{\tau_{sc}}{\sqrt{E_{fd}t_f}}}_{} \le \varepsilon_{fd}$ τ_{sc}=localised strain increase at flexural cracks	

please note: without safety factors!!

The new approach in SIA166 (2024) combines the two debonding verifictions to one…





$\varepsilon_{f,d} = 8\text{‰}$

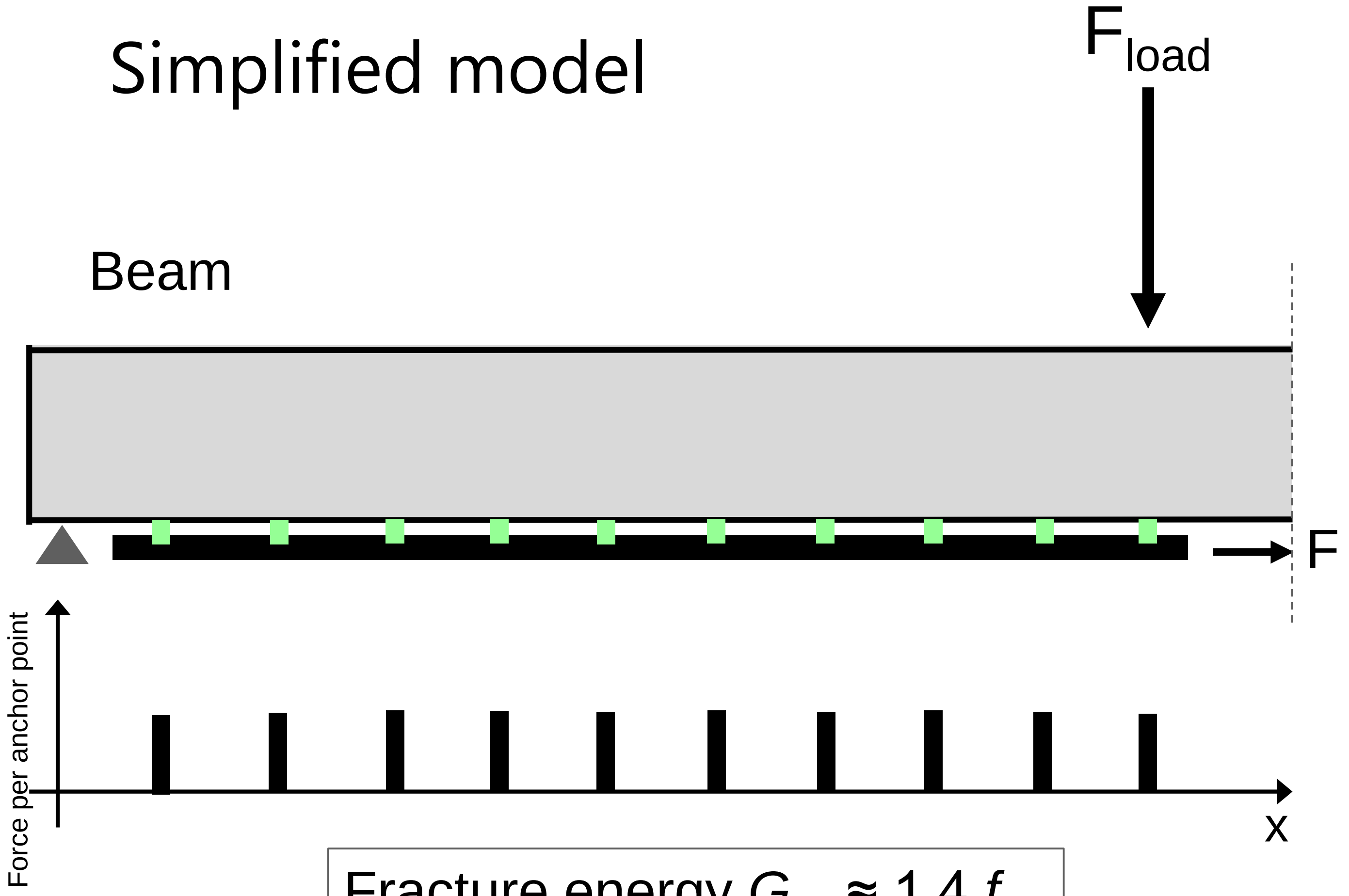
$\varepsilon_{f,y} \approx 3.5\text{‰}$

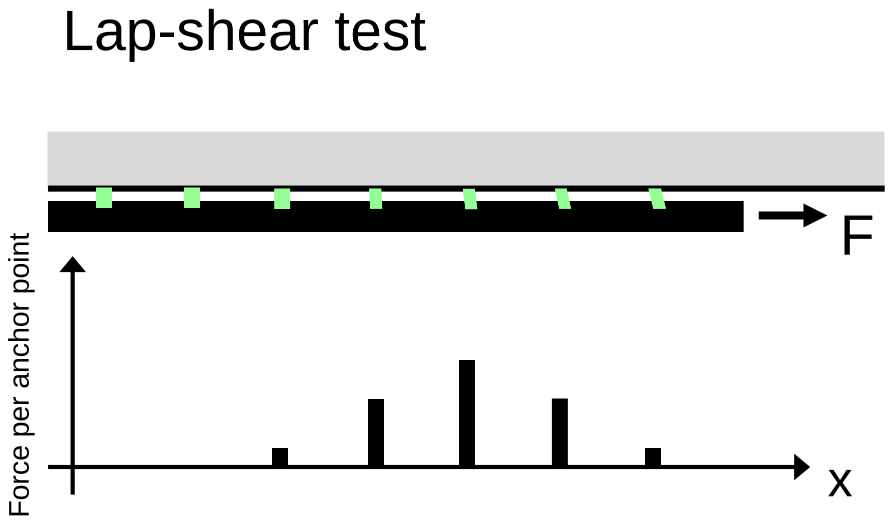
$$\tau_{f,gl,max} = \tau_{f,lim} = \frac{\left(\varepsilon_{f,max} - \varepsilon_{f,y}\right) E_f t_f}{a\left(1 - \frac{M_y}{M_{max}}\right)}$$

$$\boxed{\varepsilon_f \le \varepsilon_{f,lim,d} = 8\text{‰}}$$

$$\boxed{\left(\frac{\Delta F_f}{\Delta x}\right) \le \left(\frac{\Delta F_f}{\Delta x}\right)_R = \tau_{f,lim} \cdot b_f}$$

Simplified model





Fracture energy $G_{Fc} \approx 1.4\ f_h$

Fracture energy $G_{Fc} \approx f_h/8$

Specific fracture energy [N/mm] = [Nmm/mm^2]: $\approx \tau_{c,mean} s_{f,max}$

$$\boxed{F_{b0,Rd} = b_f \sqrt{2 G_{Fcd} E_f t_f}} \longrightarrow \boxed{F_{b0,Rd} = \varepsilon_f E_f b_f t_f = b_f \sqrt{2 G_{Fcd} E_f t_f}} \longrightarrow \boxed{\varepsilon_{fd,lim} = \sqrt{\frac{2 G_{Fcd}}{E_f t_f}}}$$

Flexural strengthening

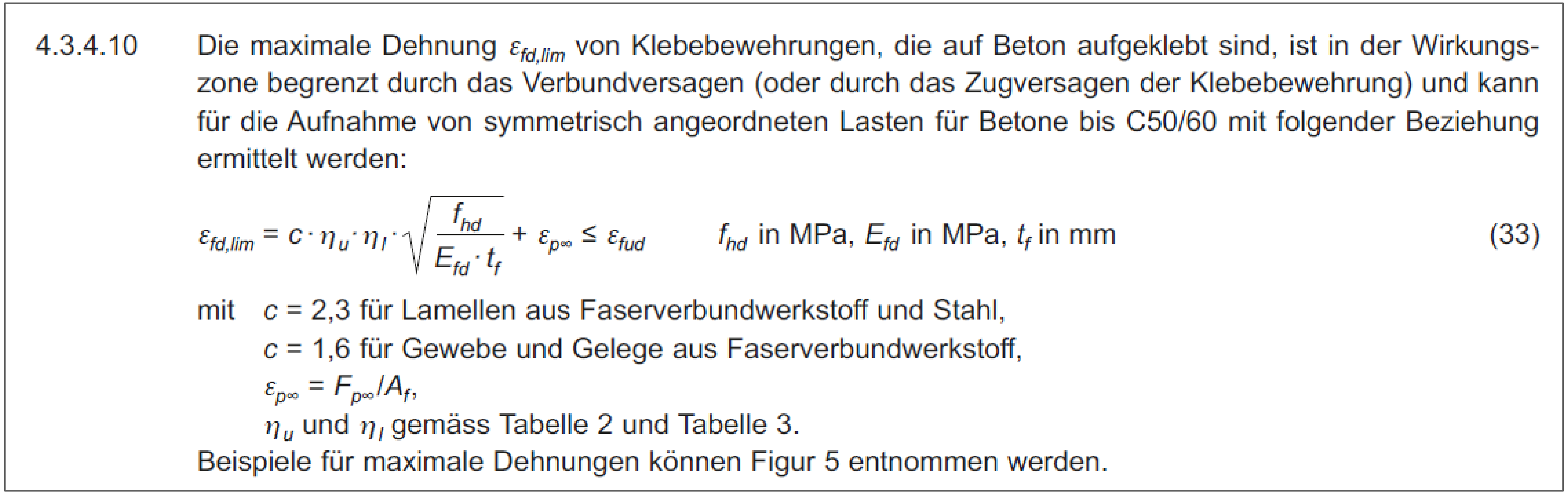
- SIA 166 (2004) 3 Verifications

1. End anchorage
2. Tensile force change
3. Limitation of strains ε=0.8%

- SIA 166 (2024) 2 Verifications

1. End anchorage Ziffer 4.3.2
2. Limitation of strains Ziffer 4.3.4

~~3. Limitation of strains ε=0.8%~~



4.3.4.10 Die maximale Dehnung $\varepsilon_{fd,lim}$ von Klebebewehrungen, die auf Beton aufgeklebt sind, ist in der Wirkungszone begrenzt durch das Verbundversagen (oder durch das Zugversagen der Klebebewehrung) und kann für die Aufnahme von symmetrisch angeordneten Lasten für Betone bis C50/60 mit folgender Beziehung ermittelt werden:

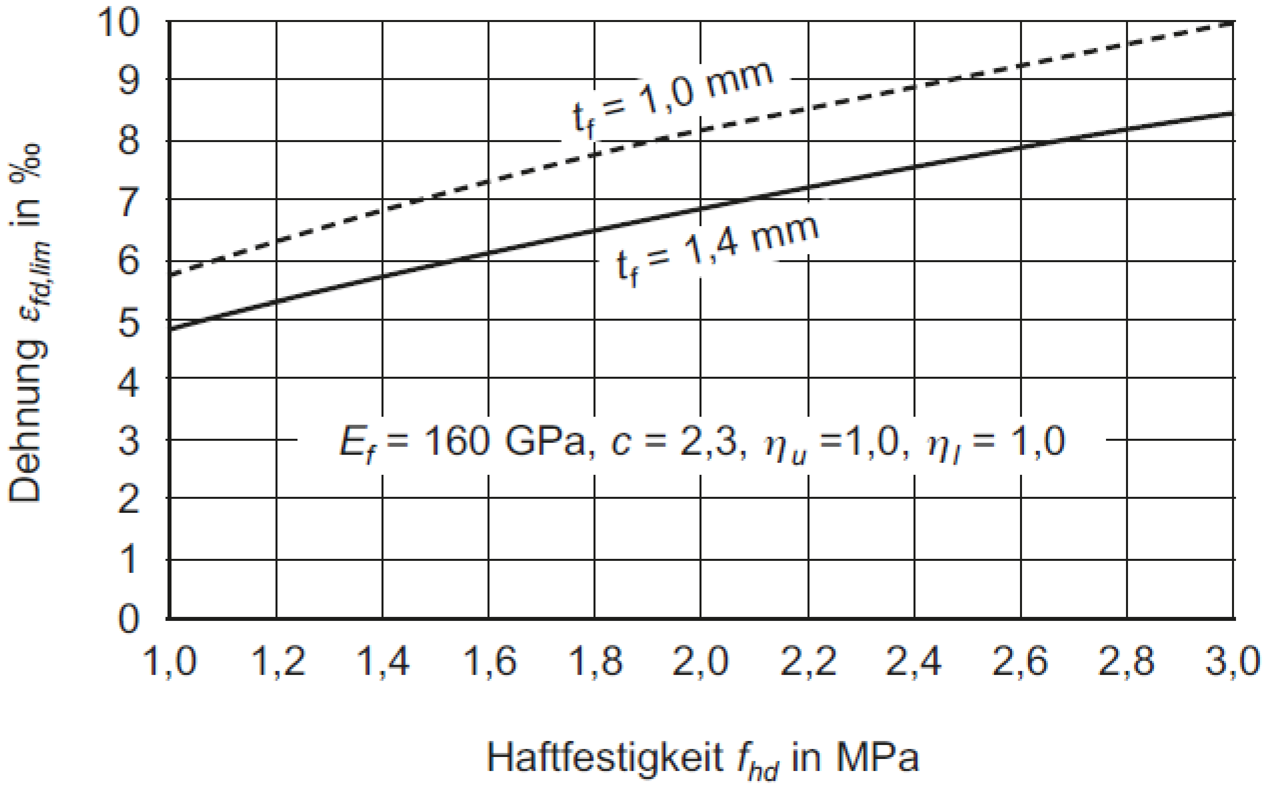
$$\varepsilon_{fd,lim} = c \cdot \eta_u \cdot \eta_l \cdot \sqrt{\frac{f_{hd}}{E_{fd} \cdot t_f}} + \varepsilon_{p\infty} \leq \varepsilon_{fud} \qquad f_{hd} \text{ in MPa, } E_{fd} \text{ in MPa, } t_f \text{ in mm} \qquad (33)$$

mit c = 2,3 für Lamellen aus Faserverbundwerkstoff und Stahl,
c = 1,6 für Gewebe und Gelege aus Faserverbundwerkstoff,
$\varepsilon_{p\infty} = F_{p\infty}/A_f$,
η_u und η_l gemäss Tabelle 2 und Tabelle 3.

Beispiele für maximale Dehnungen können Figur 5 entnommen werden.

SIA 166 (2024)

Figur 5 Beispiele für Bemessungswerte der maximalen Dehnung $\varepsilon_{fd,lim}$ für Lamellen gemäss Gleichung (33) in Abhängigkeit des Bemessungswertes der Haftfestigkeit des oberflächennahen Betons f_{hd}



Flexural design in SIA166 (2024)

- Debonding verification 1 end anchorage remains the same.
- Debonding verification 2 (shear stress) and 3 (maximum strain) are combined in one verification.
- The shear stress verification is omitted, however, the maximum strain is not constant 8‰ anymore, but depends on the concrete strength and strip stiffness $E_f t_f$
  - the thicker and larger the elastic modulus, the smaller is the maximum strain
  - the larger the concrete strength, the larger is the maximum strain

Cross-section analysis

- Cross-section analysis to determine the strains in the CFRP strips so that the debonding failure modes 1 and 2 according to SIA 166 can be verified.

by using e.g.

- Excel
- Matlab
- Software programs e.g. FAGUS
- …

Equations for cross-section analysis

Equilibrium:

$$C=T \rightarrow F_c + F_{s'} = F_s'' + F_f''$$

Tensile force:

$$T = F_s'' + F_f'' = \frac{\varepsilon_s}{\kappa_s} E_s A_s + \frac{\varepsilon_f}{\kappa_f} E_f A_f$$

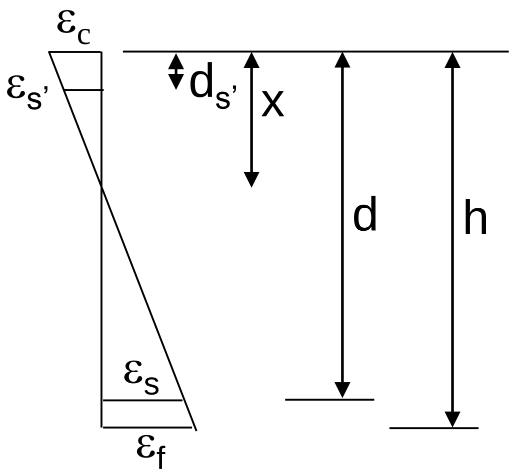
Compression force:

$$\begin{cases} F_{s'} = \varepsilon_{s'} E_s A_{s'} \\ F_c = \text{ see literature} \end{cases}$$

Compatibility:

$$\frac{\varepsilon_c}{x} = \frac{\varepsilon_f}{h-x}$$

$$\frac{\varepsilon_c}{x} = \frac{\varepsilon_s}{d-x}$$

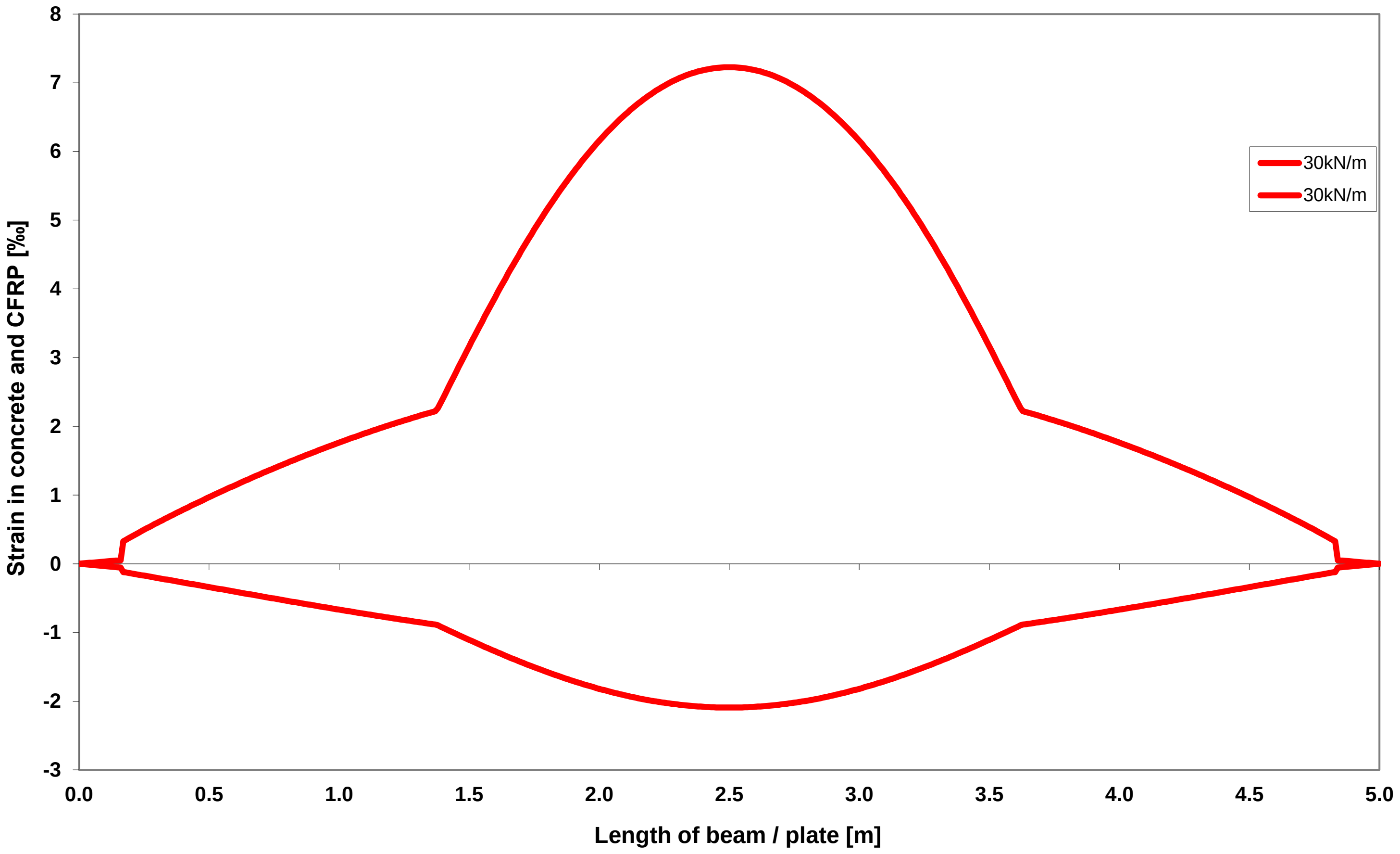


$$\frac{\varepsilon_c}{x} = \frac{\varepsilon_{s'}}{d_{s'}-x}$$

→ one equation with unknowns ε_c and x

Summary of calculation procedure: first step

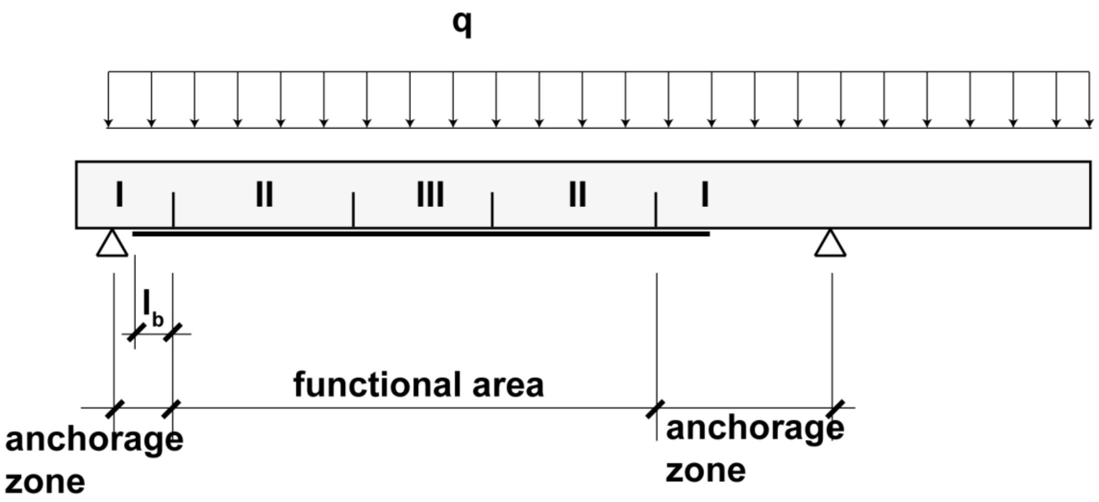
Cross-section analysis to determine the strain and forces along the structure for an assumed maximum load



Check debonding failure mode 1: end strip failure

Determine the location of last crack and define anchorage zone

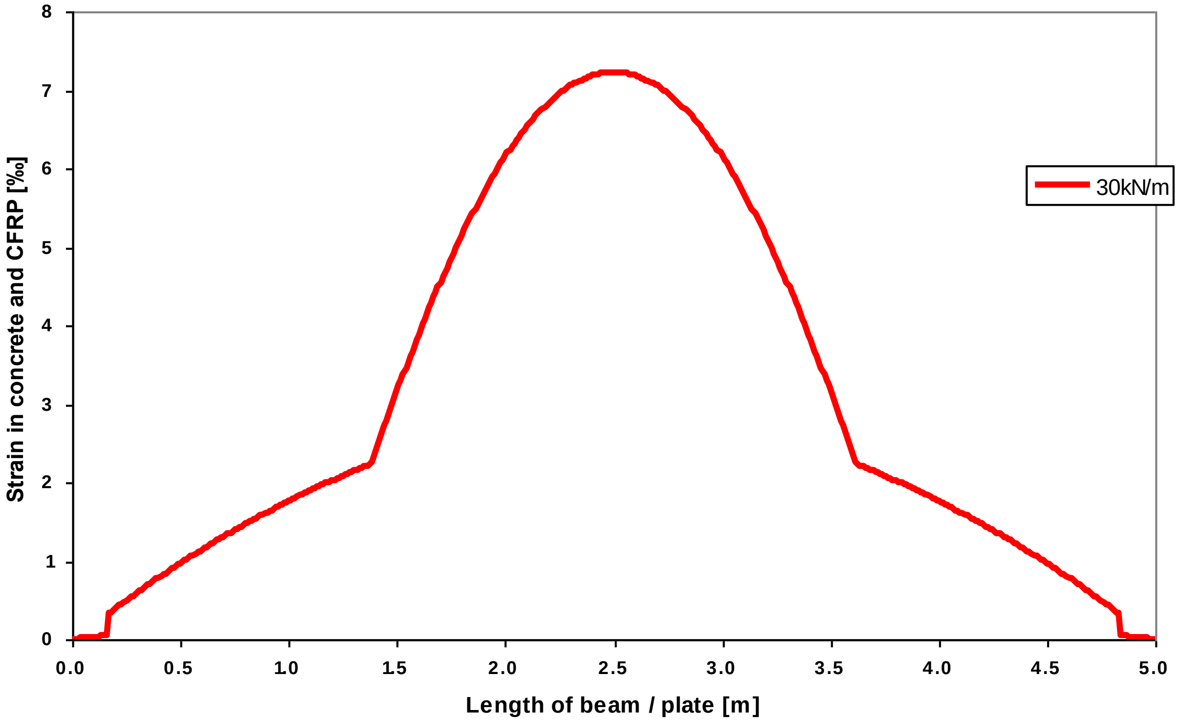
Compare the existing force in the strip at the last crack with anchorage resistance which can be anchored in the anchorage zone



- I: uncracked cross-section
- II: cracked cross-section, internal steel in elastic state
- III: cracked cross-section, internal steel in yielding state

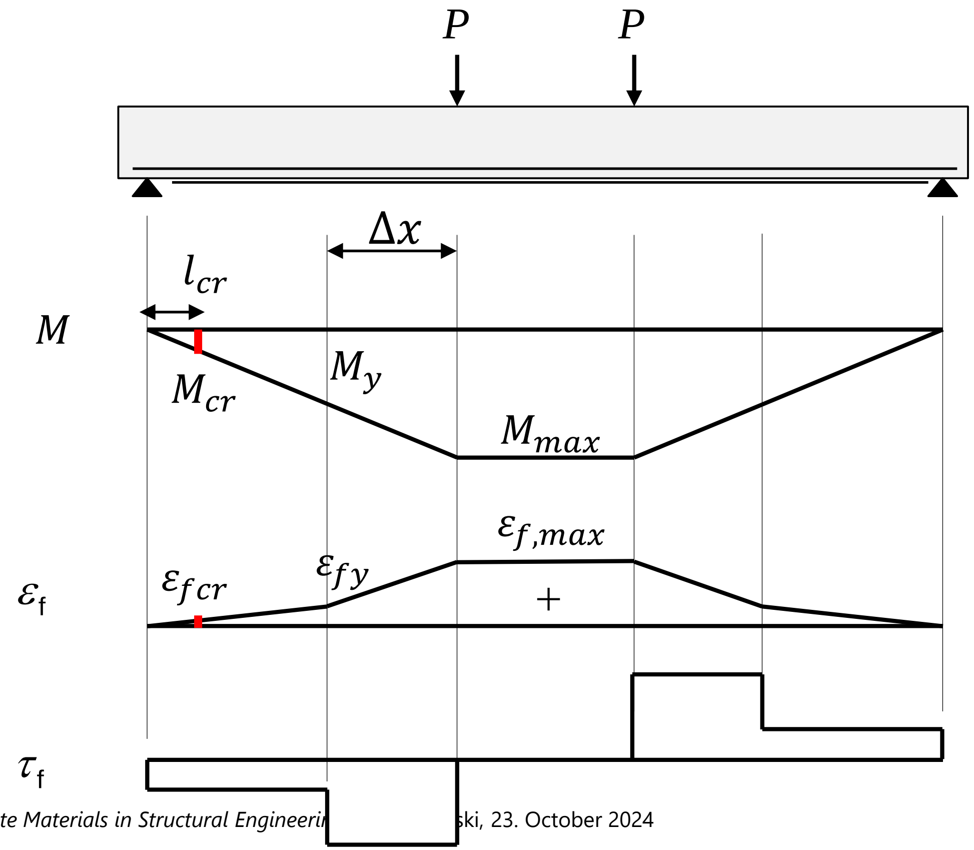
Check debonding failure mode 2:

Compare maximum existing strain with maximum admissible strain



Calculation procedure for a four point beam

1. Determination of the characteristic (or design) bond properties G_{Fck}, $\tau_{c,max,k}$, $F_{b0,Rk}$, $l_{b0,Rk}$, $\varepsilon_{fk,lim}$
2. By using cross-section analysis (CSA) calculation of cracking moment M_{cr} and maximum moment M_{max} at maximum strain
   → Strip strain at last crack and at the maximum strain
3. Calculation of the failure load P_{ult}
4. Drawing of the bending moment, strip strain, shear stress along the beam axis
5. Calculation of the location of the last crack l_{cr} and then the length l_b , the two SIA verifications (if not fulfilled, the verifications shall be repeated with a lower failure load P_{ult}



$$\Delta\varepsilon_f = \varepsilon_{f,max} - \varepsilon_{fy}$$

$$\tau_f = \frac{\Delta\varepsilon_f E_f b_f t_f}{\Delta x b_f}$$

Summary of the Equations from SIA

$$\boxed{F_{b0,Rd} = b_f \sqrt{2 G_{Fcd} E_f t_f}}$$

$$\boxed{l_{b0d} = 2.5 \sqrt{\frac{G_{Fcd} E_f t_f}{\tau_{c,max,d}^2}}}$$

$$\boxed{G_{Fcd} = \frac{1}{8} \eta_u \eta_l \frac{f_{hk}}{\gamma_h}}$$

G_{Fcd} in N/mm $\qquad$ f_{hk} in N/mm^2

$$\boxed{\tau_{c,max,d} = \frac{4}{3} \eta_u \eta_l \frac{f_{hk}}{\gamma_h}}$$

for $\boxed{l_{bd} < l_{b0d}:}$

$$\boxed{F_{b,Rd} = F_{b0,Rd} \frac{l_{bd}}{l_{b0d}} \left(2 - \frac{l_{bd}}{l_{b0d}}\right)}$$

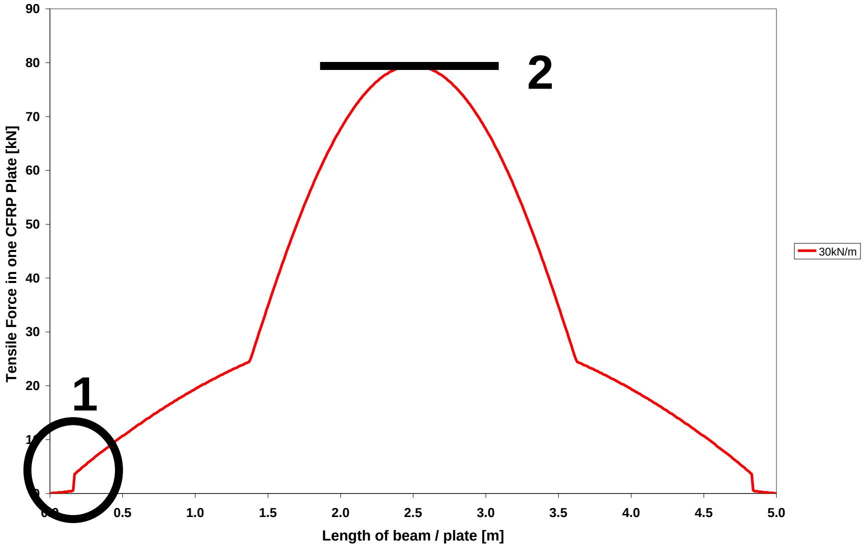
$$\boxed{\varepsilon_{fd,lim} = c\, \eta_u \eta_l \sqrt{\frac{f_{hd}}{E_f t_f}} \leq \varepsilon_{fud}}$$

c= 2.3 for strips, c=1.6 for fabrics

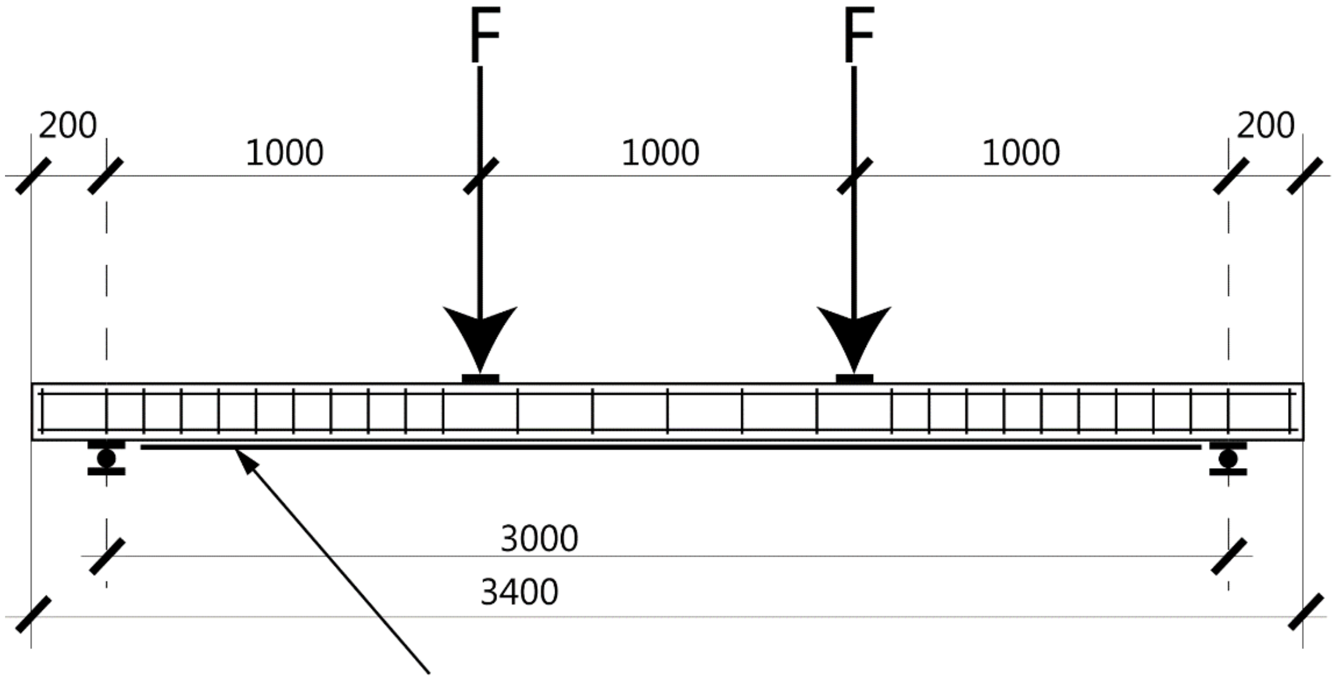
The reduction values η_u and η_l are tabulated in SIA 166(2024), they consider environment and loading conditions.

Summary of the two SIA 166 (2024) verifications

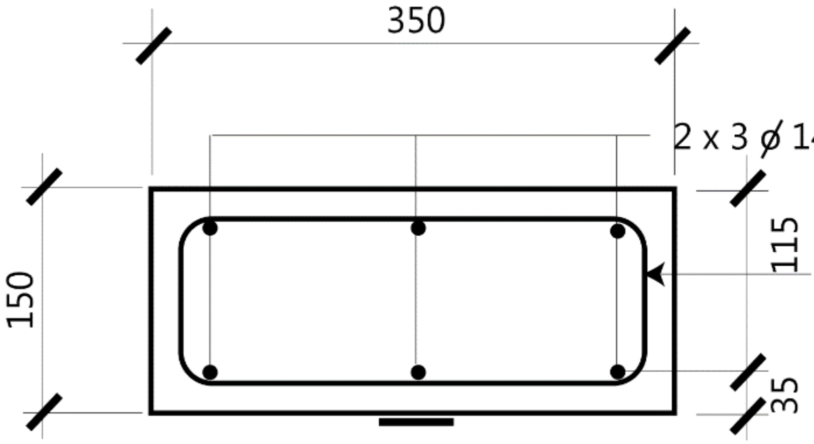
1. End strip debonding failure at the last crack $\boxed{F_{fcr} \leq F_{b,R}}$
2. Debonding at maximum strain $\boxed{\varepsilon_f \leq \varepsilon_{fd,lim}}$



Example



CFRP-strip from Company S&P
100x1.4mm, length 2850mm



2 x 3 ø 14

27 stirrups
ø 8 s = 100 and 200 mm

concrete cover 20 mm

Materialeigenschaften

Concrete

- Cylinder compressive strength f_{ck} =f_{cm} =42.3 MPa
- Tensile strength f_{ctm}=3.6 MPa

≈ C40/50 (assumption for QSA)

$f_{hk} \approx 2.5$MPa (assumption)

CFRP

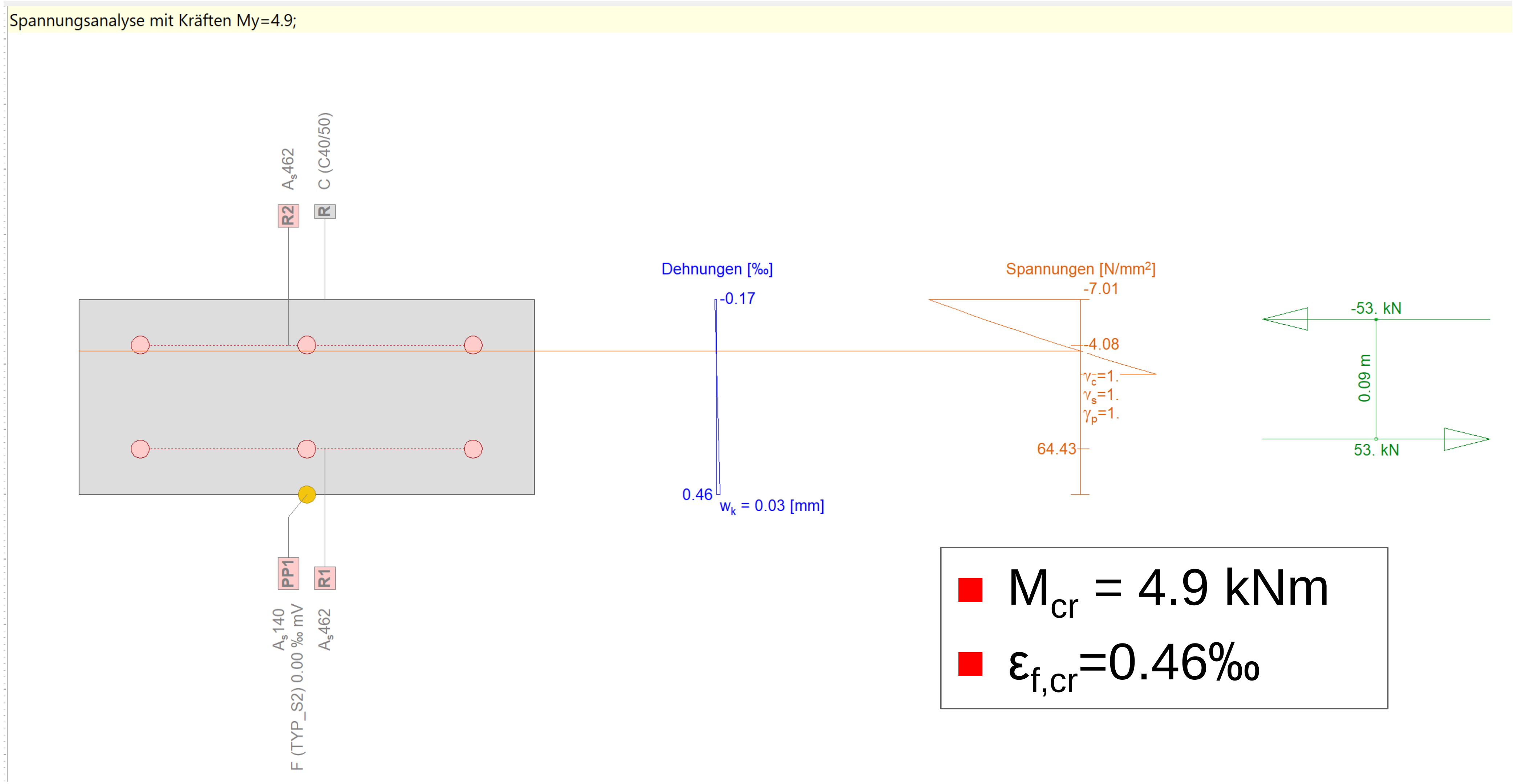
- Elasticity modulus E_f= 170 GPa
- Tensile strength f_f = 2971 MPa

Reinforcement

- f_s=545 MPa
- E_s =205 GPa

Calculation with FAGUS from the Company Cubus

Cracking moment

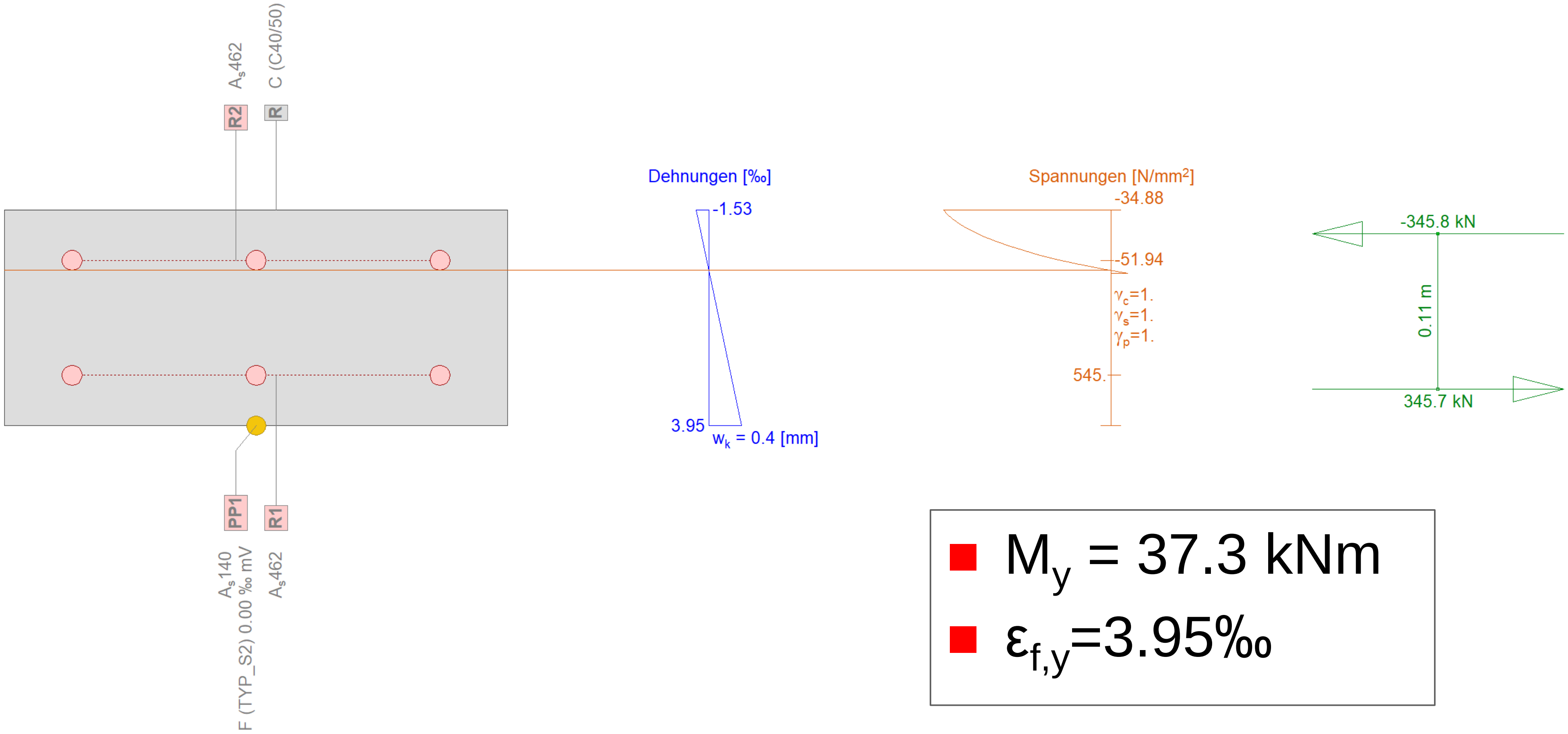


Spannungsanalyse mit Kräften My=4.9;

- M_{cr} = 4.9 kNm
- $\varepsilon_{f,cr}$=0.46‰

Yielding moment

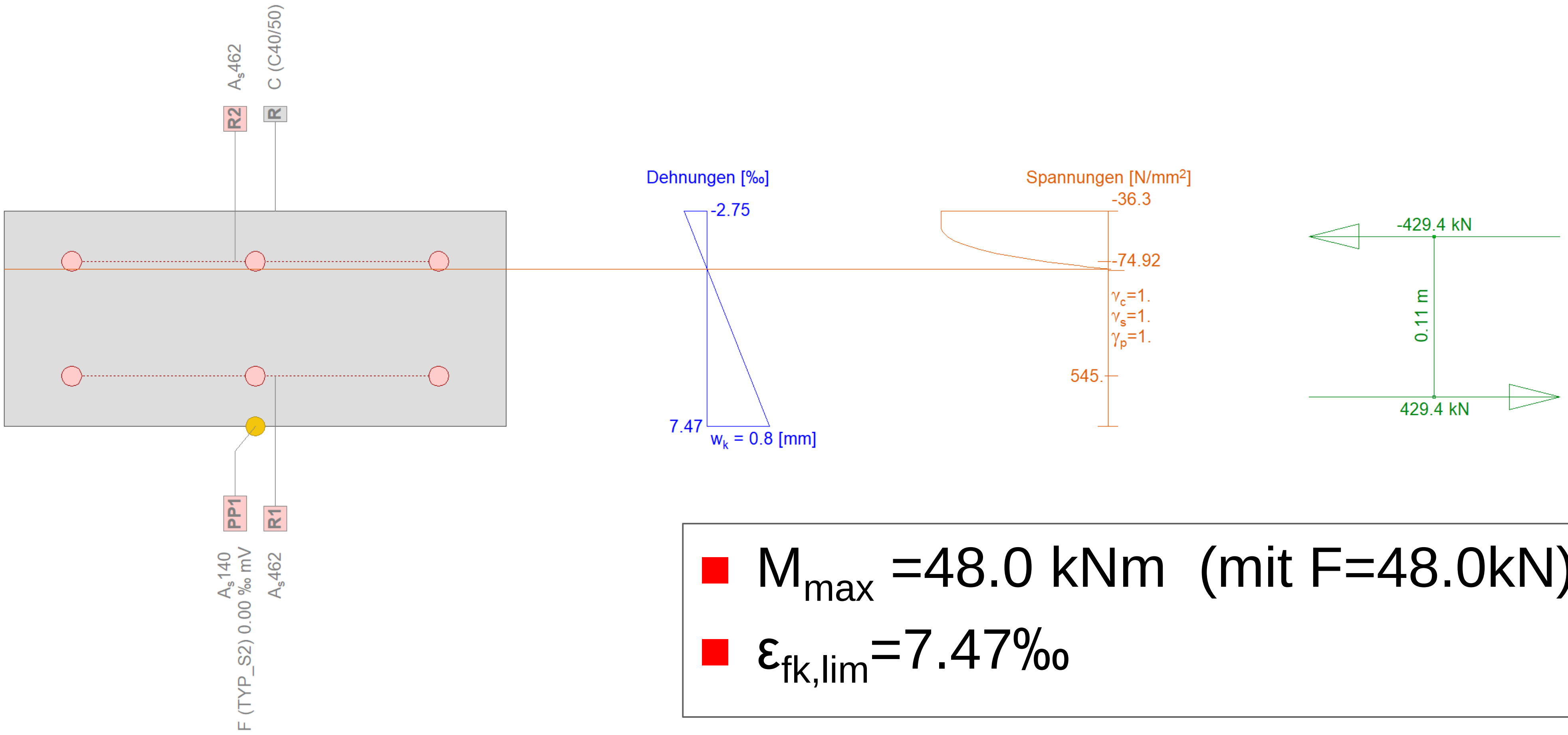
Spannungsanalyse mit Kräften My=37.3;



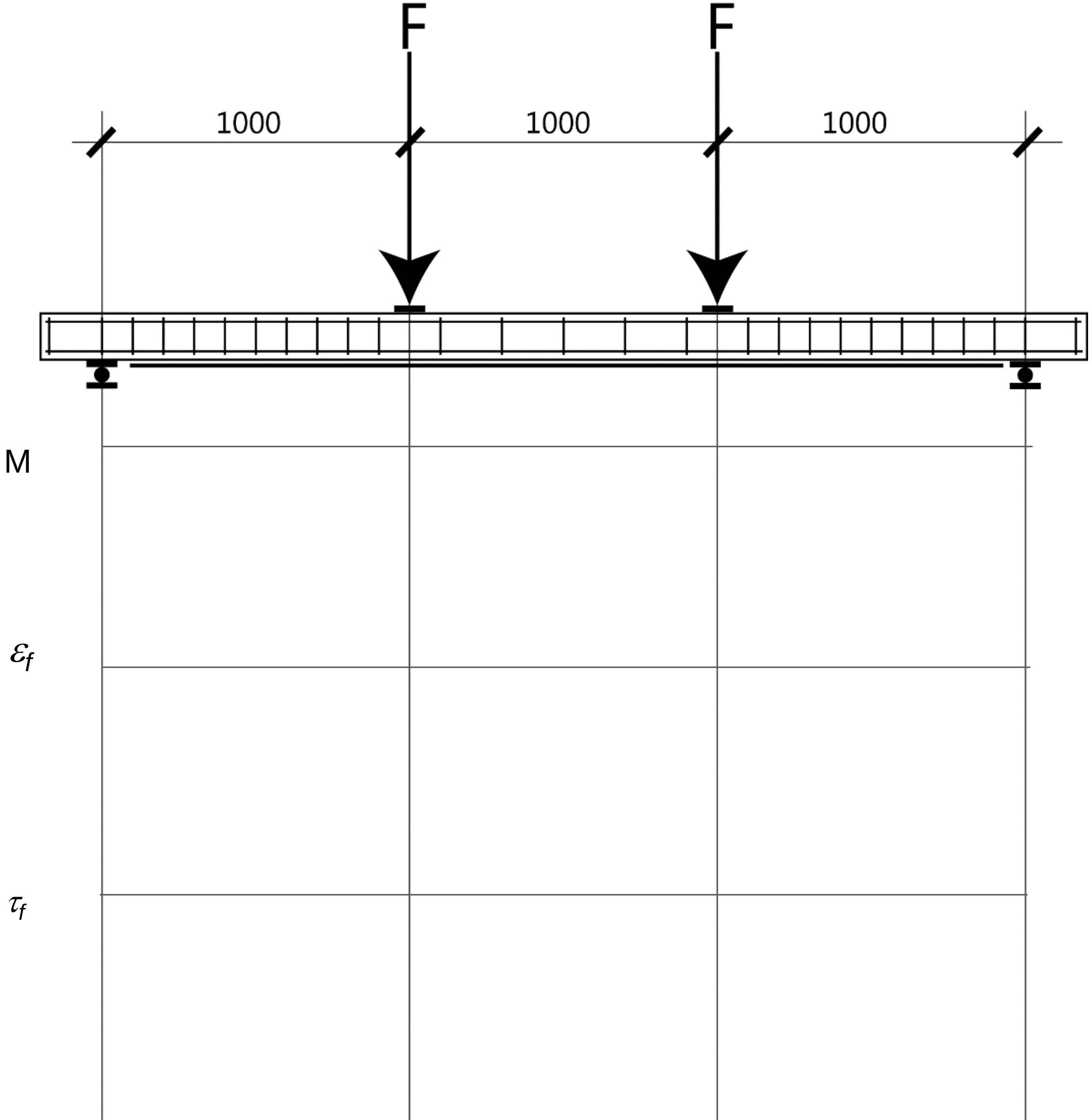
- $M_y = 37.3$ kNm
- $\varepsilon_{f,y}$=3.95‰

Bruchmoment

Spannungsanalyse mit Kräften My=48.0;



- M_{max} =48.0 kNm (mit F=48.0kN)
- $\varepsilon_{fk,lim}$=7.47‰



aus QA:

M_{cr} 4.9 kNm

$\varepsilon_{f,cr}$=0.46‰

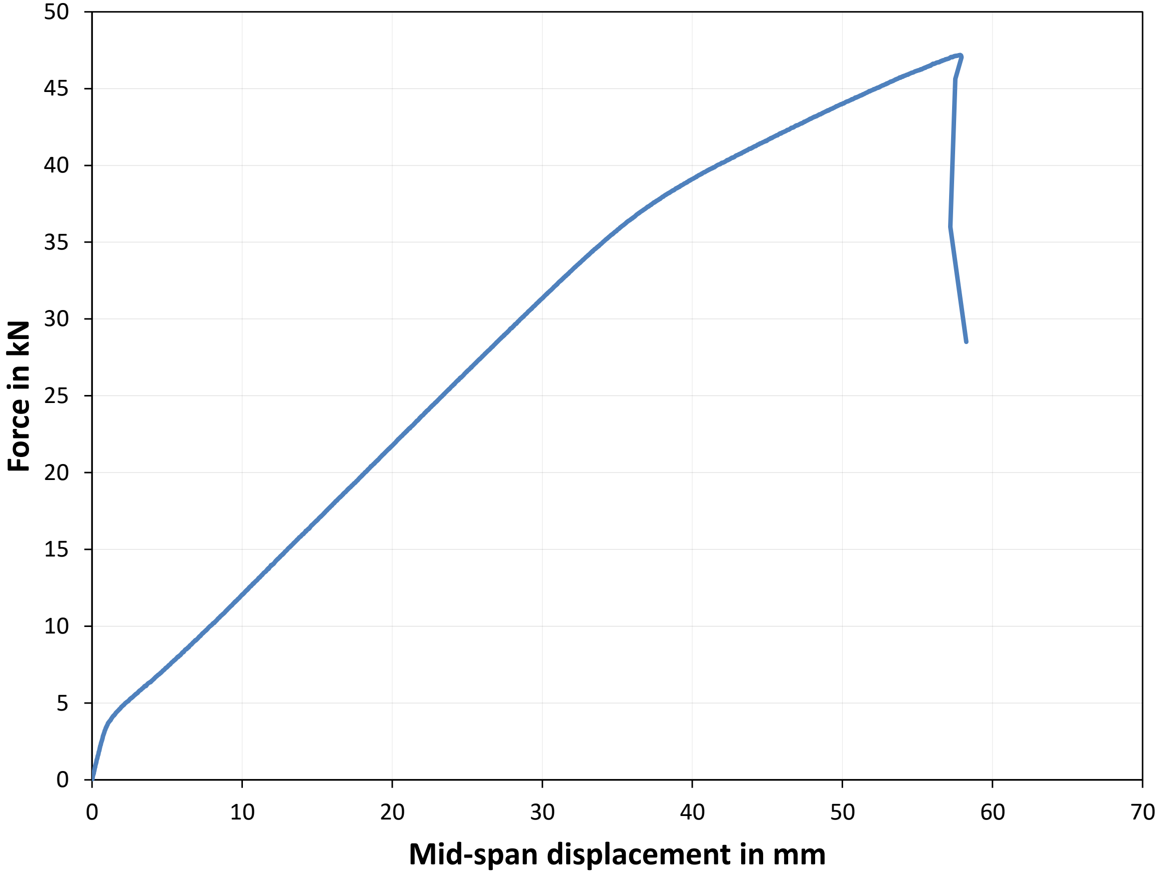
M_y = 37.3 kNm

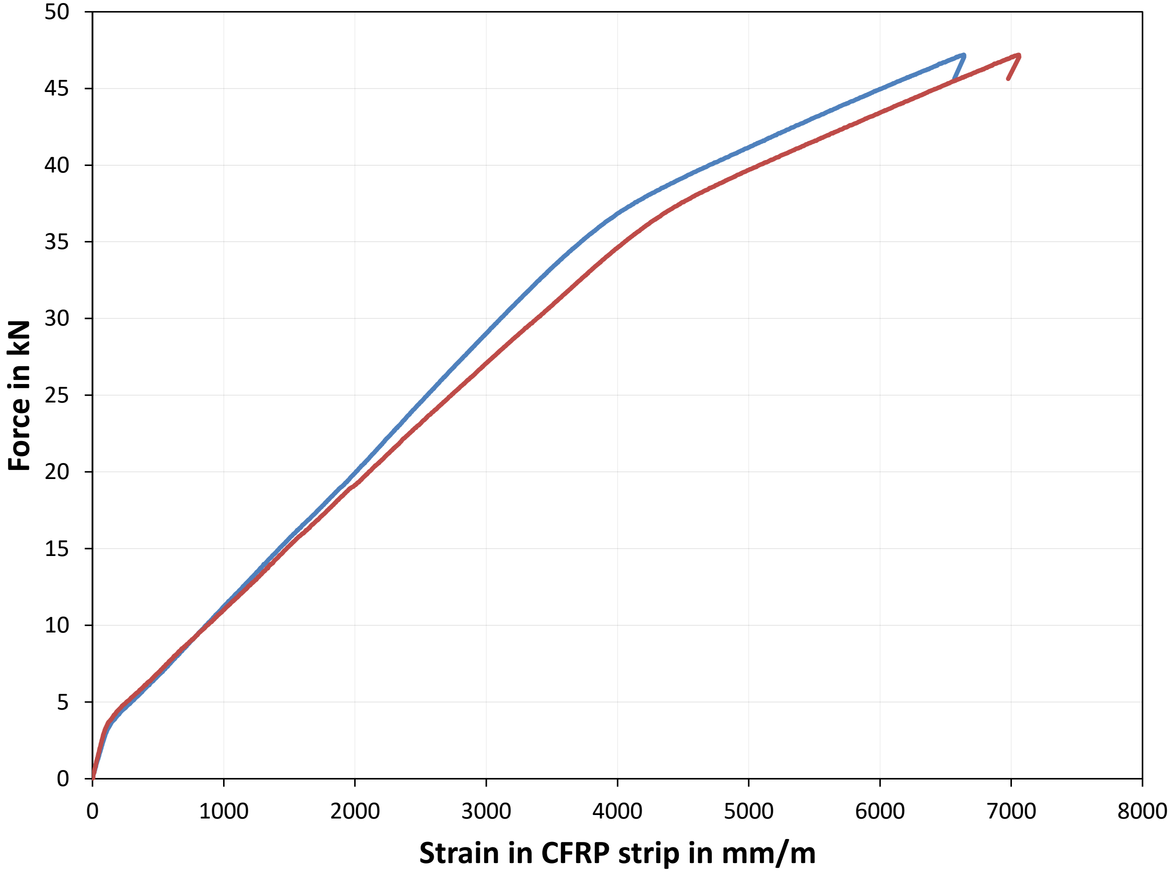
$\varepsilon_{f,y}$=3.95‰

M_{max} =48.0 kNm (mit F=48.0kN)

$\varepsilon_{f,max}$=7.47‰

Resultate





→ Video: Failure test

Several additional topics according to Swiss code 166 (2024)

- Assessment of existing structures
- Ultimate limit state (ULS)
- Serviceability (SLS)
    - Stresses
    - Deflections
- Check of deformation capacity

Assessment of existing structure

- Consider existing stresses and deflections in the structure before strengthening
- Good assessment: geometry, strength
- Internal reinforcement (we need a minimum value…, otherwise we risk a brittle behavior, risk of premature concrete crushing if steel is neglected in calculations)
- Concrete property (tensile strength good enough?)
- Static system
- …
- Use conversation codes (Erhaltungsnormen) to check if a strengthening is necessary or not!
    - SIA269 Basics
    - SIA269/1 Actions
    - SIA269/2 Reinforced Concrete
- If a strengthening is necessary, use SIA260, 261, 262 and 166

Ultimate limit state

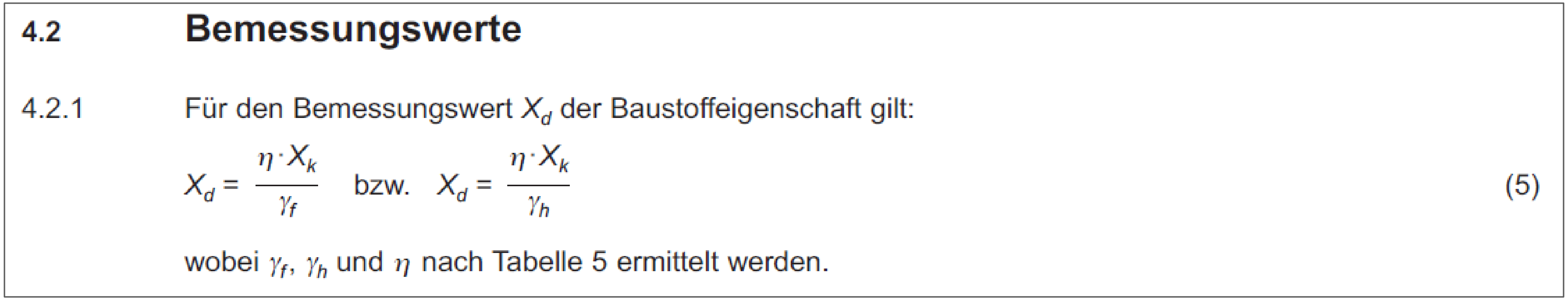
$$E_d \leq R_d$$

Design value of effects of action ≤ Design value of ultimate resistance

Definition of hazard scenarios (Gefährdungsbilder)

do not forget the hazard scenario “failure of externally bonded reinforcement” (accidential scenario)

Determination of the design values according to SIA 166 (2024)



4.2 Bemessungswerte

4.2.1 Für den Bemessungswert X_d der Baustoffeigenschaft gilt:

$$X_d = \frac{\eta \cdot X_k}{\gamma_f} \quad \text{bzw.} \quad X_d = \frac{\eta \cdot X_k}{\gamma_h} \tag{5}$$

wobei γ_f, γ_h und η nach Tabelle 5 ermittelt werden.

X_k = characteristic value of material property

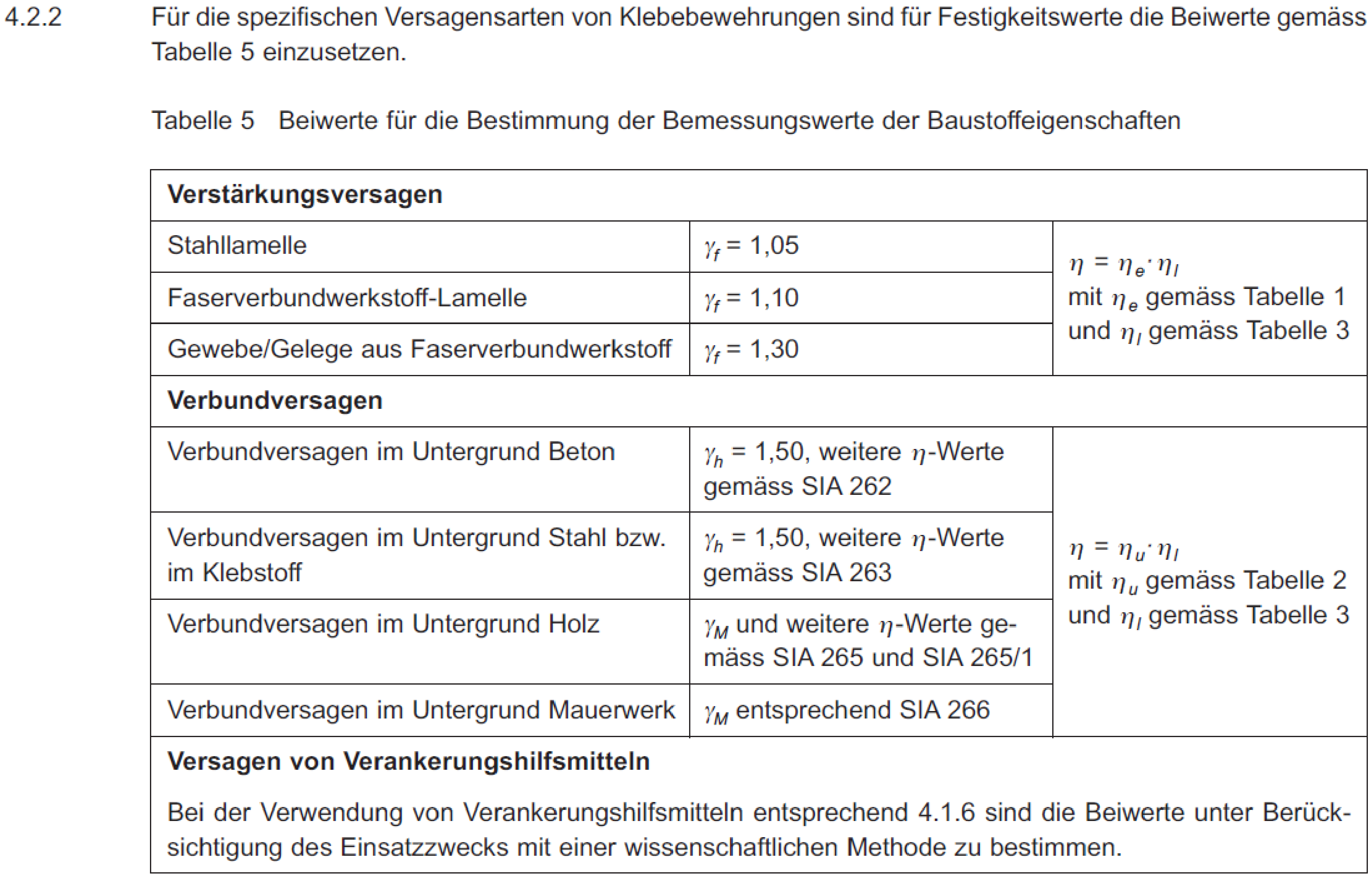
Depending on failure in strengthening material or bond failure:

η = reduction factor

γ_f or γ_h = resistance factor

→ see Table 5 in SIA166 (2024)

Table 5 in SIA 166(2024)



4.2.2 Für die spezifischen Versagensarten von Klebebewehrungen sind für Festigkeitswerte die Beiwerte gemäss Tabelle 5 einzusetzen.

Tabelle 5 Beiwerte für die Bestimmung der Bemessungswerte der Baustoffeigenschaften

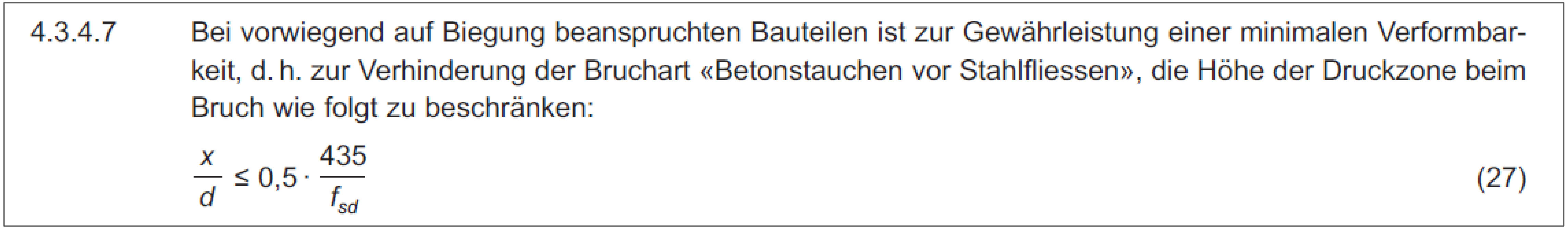
Verstärkungsversagen		
Stahllamelle	γ_f = 1,05	$\eta = \eta_e \cdot \eta_l$ mit η_e gemäss Tabelle 1 und η_l gemäss Tabelle 3
Faserverbundwerkstoff-Lamelle	γ_f = 1,10	
Gewebe/Gelege aus Faserverbundwerkstoff	γ_f = 1,30	
Verbundversagen		
Verbundversagen im Untergrund Beton	γ_h = 1,50, weitere η-Werte gemäss SIA 262	$\eta = \eta_u \cdot \eta_l$ mit η_u gemäss Tabelle 2 und η_l gemäss Tabelle 3
Verbundversagen im Untergrund Stahl bzw. im Klebstoff	γ_h = 1,50, weitere η-Werte gemäss SIA 263	
Verbundversagen im Untergrund Holz	γ_M und weitere η-Werte gemäss SIA 265 und SIA 265/1	
Verbundversagen im Untergrund Mauerwerk	γ_M entsprechend SIA 266	
Versagen von Verankerungshilfsmitteln Bei der Verwendung von Verankerungshilfsmitteln entsprechend 4.1.6 sind die Beiwerte unter Berücksichtigung des Einsatzzwecks mit einer wissenschaftlichen Methode zu bestimmen.		

SLS and evenness

- SIA 166: Serviceability (SLS)
  - Stresses in the internal reinforcement should not exceed the stresses as defined in SIA262 (depending on the requirements: normal, increased, high)
  - Deflections have to be checked

- Evenness of concrete surface
  - for 2 m measurement length (Messlatte): max. 5 mm tolerance
  - for 0.3 m measurement length (Messlatte): max. 1 mm tolerance

Deformation capacity according EN 166 (2024)



4.3.4.7 Bei vorwiegend auf Biegung beanspruchten Bauteilen ist zur Gewährleistung einer minimalen Verformbarkeit, d. h. zur Verhinderung der Bruchart «Betonstauchen vor Stahlfliessen», die Höhe der Druckzone beim Bruch wie folgt zu beschränken:

$$\frac{x}{d} \leq 0{,}5 \cdot \frac{435}{f_{sd}} \qquad (27)$$

x: height of bending compression zone
d: static height
f_{sd}: design value of yield strength of internal reinforcement steel

Literature: Codes/Guidelines

Empa
Materials Science and Technology

- SIA166 (2024) Klebebewehrungen für die Verstärkung bestehender Tragwerke (Adhesively bonded reinforcement for strengthening existing structures). Schweizerischer Ingenieur- und Architektenverein SIA
- SIA166 (2004) Klebebewehrungen (Externally bonded reinforcement). Schweizerischer Ingenieur- und Architektenverein SIA.
- SIA (2004) D 0209, Dokumentation, Klebebewehrung, Einführung in die Norm SIA 166.
- *fib* (2001) Externally bonded FRP reinforcement for RC structures - Bulletin 14. International Federation for Structural Concrete (fib), Switzerland.
- *fib* (2019) Externally applied FRP reinforcement for concrete structures - Bulletin 90. International Federation for Structural Concrete (fib), Switzerland.
- CNR (2004) Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures, CNR-DT 200/2004. CNR - Advisory Committee on Technical Recommendations for Construction, Rome, Italy.
- ACI (2008) ACI440.2R-08, Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. American Concrete Institute.
- TR55 (2012) Design guidance for strengthening concrete structures using fibre composite materials, Third Edition. Technical Report No. 55 of the Concrete Society, UK.

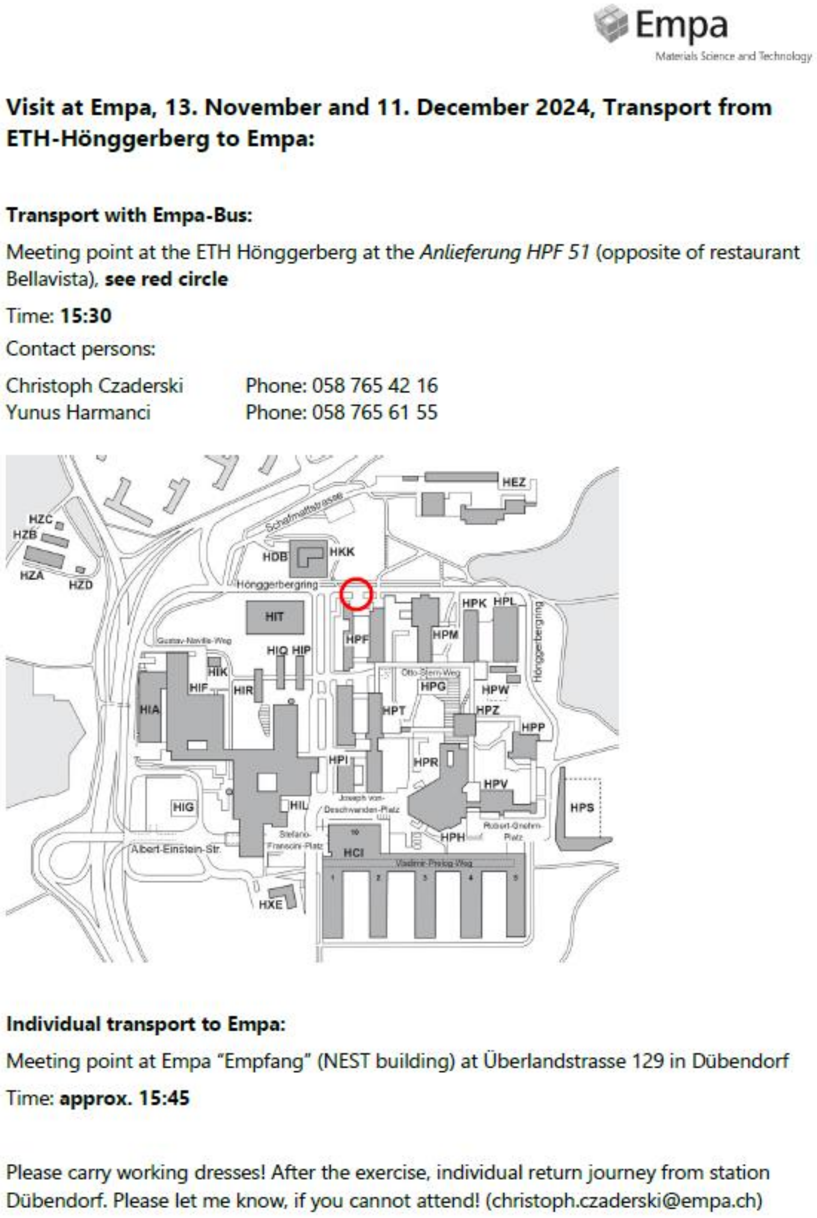
Literature

PhD Theses (can freely be downloaded from www.research-collection.ethz.ch)

- Ulaga T (2003) Dissertation ETH Nr. 15062, Betonbauteile mit Stab- und Lamellenbewehrung: Verbund- und Zuggliedmodellierung, http://dx.doi.org/10.3929/ethz-a-004525392
- Czaderski C (2012) Dissertation ETH No. 20504, Strengthening of reinforced concrete members by prestressed, externally bonded reinforcement with gradient anchorage, http://dx.doi.org/10.3929/ethz-a-007569614

Book chapters

- Motavalli, M., C. Czaderski, A. Schumacher, and D. Gsell, Fibre reinforced polymer composite materials for building and construction, in *Textiles, polymers and composites for buildings*, G. Pohl, Editor. 2010, Woodhead Publishing Limited: Cambridge UK. p. 69-128.
- Czaderski C., Flexural and Shear Strengthening of Reinforced Concrete Structures, in *The International Handbook of FRP Composites in Civil Engineering*, CRC Press, 2013.
  p. 235-252



Empa
Materials Science and Technology

Visit at Empa, 13. November and 11. December 2024, Transport from ETH-Hönggerberg to Empa:

Transport with Empa-Bus:

Meeting point at the ETH Hönggerberg at the *Anlieferung HPF 51* (opposite of restaurant Bellavista), **see red circle**

Time: **15:30**

Contact persons:

Christoph Czaderski	Phone: 058 765 42 16
Yunus Harmanci	Phone: 058 765 61 55

Individual transport to Empa:

Meeting point at Empa "Empfang" (NEST building) at Überlandstrasse 129 in Dübendorf

Time: **approx. 15:45**

Please carry working dresses! After the exercise, individual return journey from station Dübendorf. Please let me know, if you cannot attend! (christoph.czaderski@empa.ch)

Anlieferung HPF51

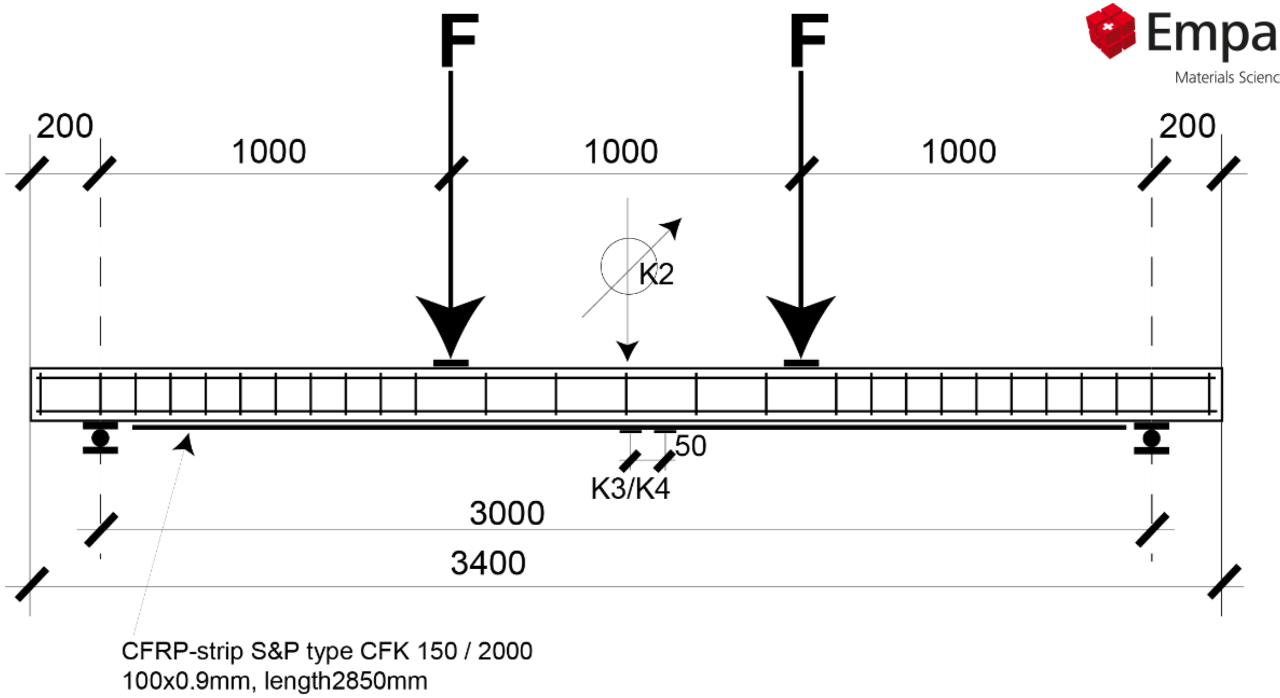
First part of the laboratory competition: prediction of the failure load of this beam

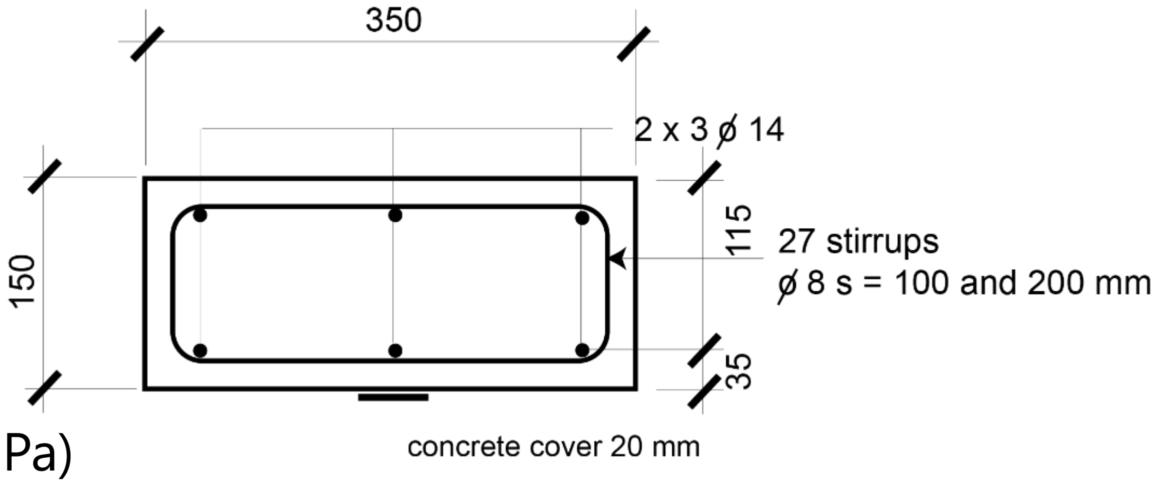
Concrete
C35/45

Steel
f_s = 487 N/mm^2
f_t = 566 N/mm^2

CFRP
E_f = 150'000 N/mm^2

$f_{c,cube}$ 68 days = 47.2 MPa
($f_c = 0.8 * f_{c,cube}$ = 37.8 MPa)
Possible assumption for calculations:
concrete C35/45 (f_{ctm} = 3.2 MPa, f_{ck} = 35 MPa)



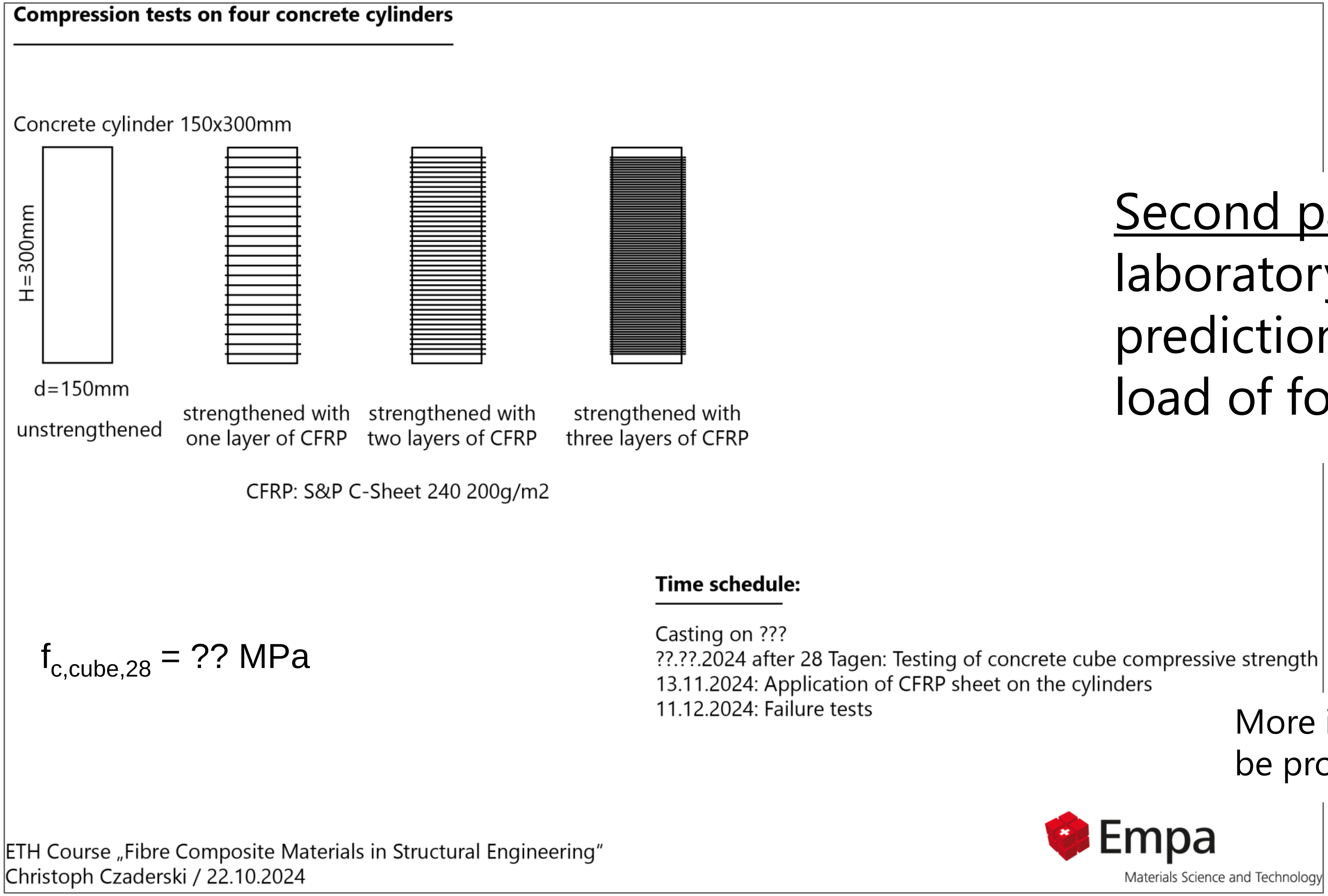


→ Video: application of the CFRP strip

Procedure for the determination of the failure loads
(see the example in slides 92-98 and its Musterlösung, and see slide 89):

1. Assumption of f_{hk}
2. Determination of the characteristic bond properties
3. CSA
4. Drawing of the bending moment, strip strain, shear stress
5. Determination of l_{cr}, l_b and then the verification of end anchorage and maximum strain

Second part of the laboratory competition: prediction of the failure load of four cylinders



Compression tests on four concrete cylinders

Concrete cylinder 150x300mm

H=300mm

d=150mm

unstrengthened

strengthened with one layer of CFRP

strengthened with two layers of CFRP

strengthened with three layers of CFRP

CFRP: S&P C-Sheet 240 200g/m2

$f_{c,cube,28}$ = ?? MPa

Time schedule:

Casting on ???
??.??.2024 after 28 Tagen: Testing of concrete cube compressive strength
13.11.2024: Application of CFRP sheet on the cylinders
11.12.2024: Failure tests

ETH Course „Fibre Composite Materials in Structural Engineering“
Christoph Czaderski / 22.10.2024

More informations will be provided later

Lab competition

Empa
Materials Science and Technology

- Video of the experiment on the beam will be presented on 13.11.2024
- Lap experiments on the cyclinders will be performed on 11.12.2024

- Who makes the best prediction? The best predictions are awarded with a price.
- Predictions (in kN):
  Failure load of the Beam (by 12.11.2024)
  Failure loads of Cylinders 1 to 4 (by 10.12.2024)

- →Submission of the calculations and the failure loads by email to: christoph.czaderski@empa.ch