Engineering of Existing Structures - CIVIL-511
Civil Engineering - Master 1 and 3
Teachers: Prof. Emmanuel Denarié, Prof. Alain Nussbaumer

Chapter 12

Engineering of Existing Structures - Strengthening (II): glued CFRP lamellas

Author: Prof. A. Nussbaumer

ENAC IIC **CONSTRUCT/RESSLAB**

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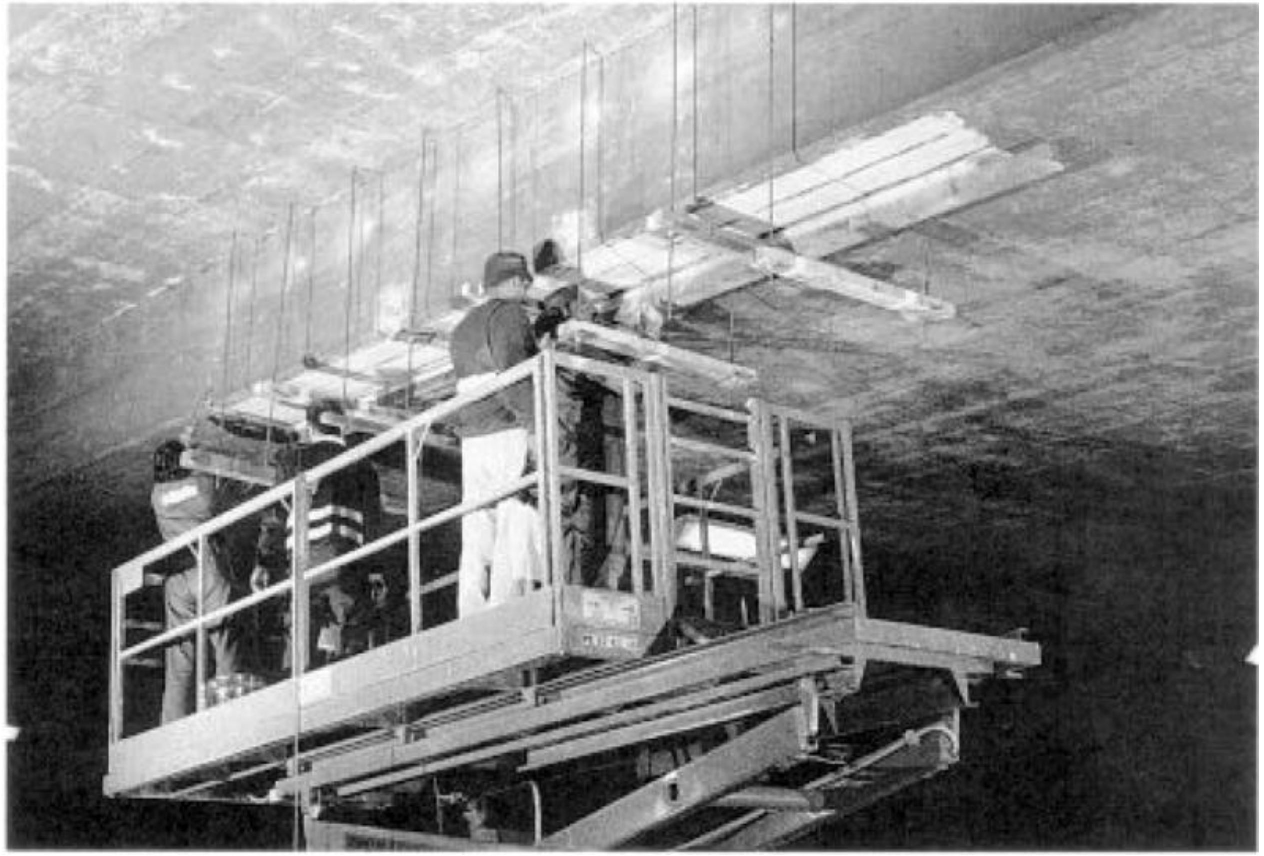
Chapter 12: strengthening (II): glued CFRP lamellas for static and fatigue

➔ Present some causes of deterioration where these methods are efficient

➔ Gives bases how to design the strengthening

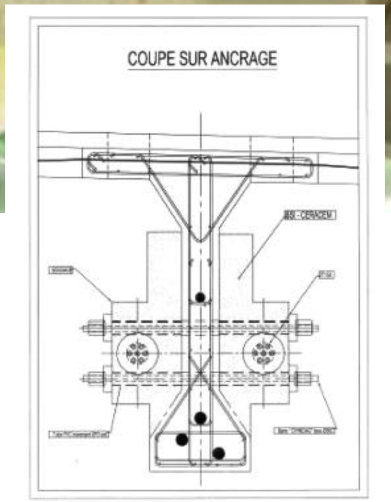
➔ As benefits of strengthening often depend on «activation», use prestressing

12.1 +30 years exp. with glued CFRP lamellas



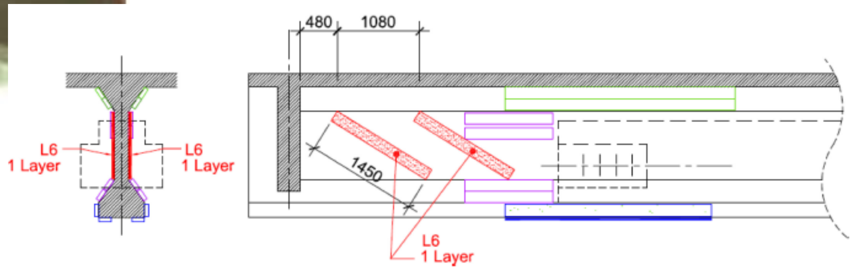
- In Year 1991
- First project of its kind in the world
- Following damage to prestressing
- Repair of a road bridge, Ibach near Lucerne 1991
- 6.2 kg of carbon fiber laminates
- Other examples around same period in USA, Japan, France

12.1 Motivation: strengthening of bridge over l'Huisne – Le Mans, (F), 2006



Thibaux (2008) – [3]

Glued CFRP laminate strips



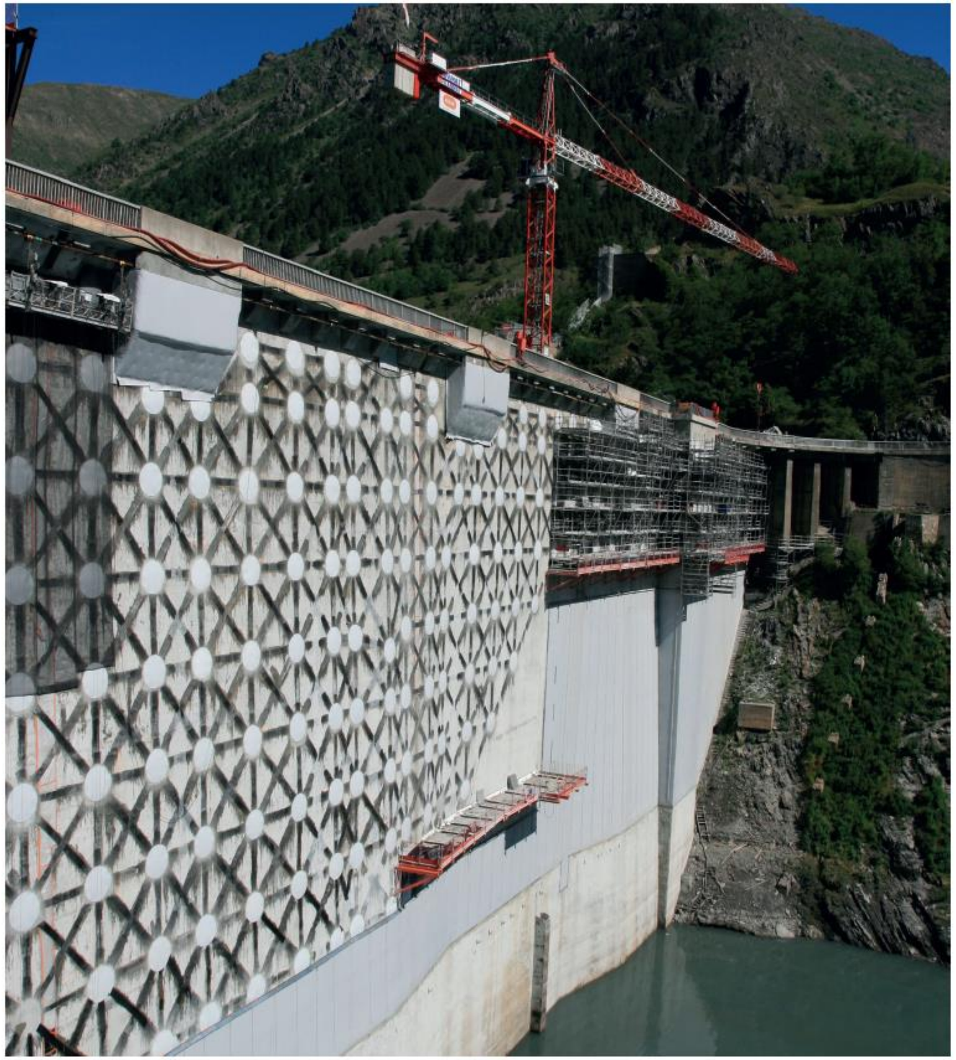
- Increase of traffic loads (lanes + tramway too)
- Increase of web thickness with cast-in place UHPFRC (BSI)
- High Emodulus of BSI (65 GPa) "drains" internal forces
- Additional external prestressing
- Glued CFRP strips to transfer shear loads where needed

12.1 Motivation : Transformation Hotel-restaurant Espen, Engelberg, 2018

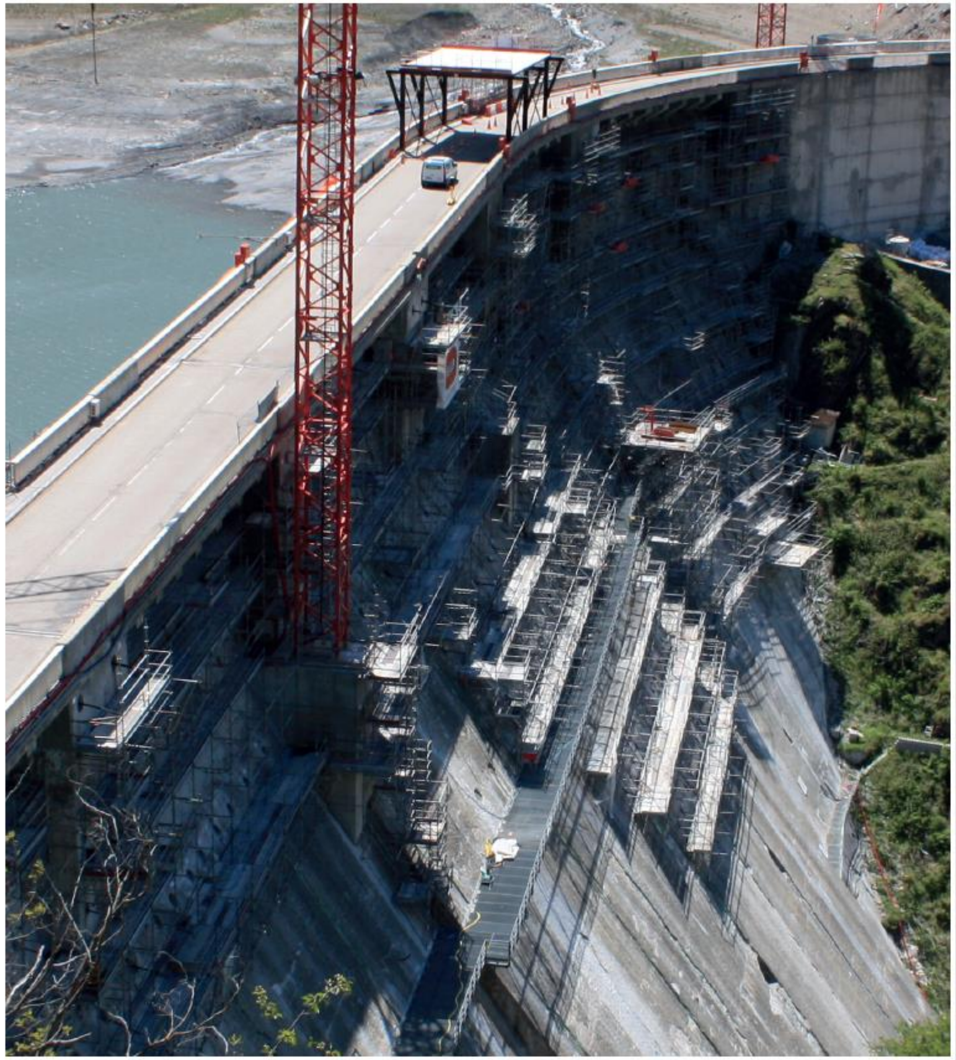
Adding a floor and change of use for group accommodation

S&P
A Simpson Strong-Tie® Company

12.1 Motivation : barrage du Chambon, renforcement pour pallier toute chute de bloc de béton



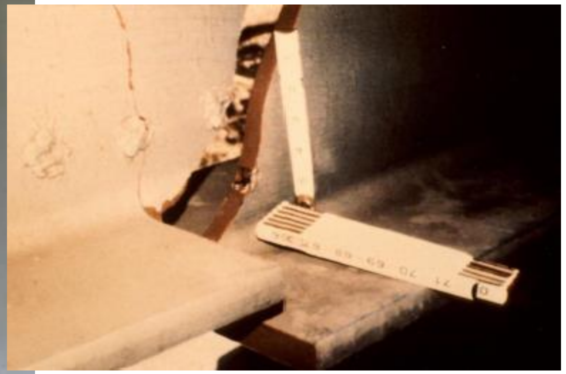
▲ *Vue du maillage en S&P C-Sheet 240 sur le parement amont du barrage*



Vue de l'échafaudage sur le parement aval du barrage ▲

12.1 Motivation: fatigue in structural elements, cracks/repair

Fracture of the US 422 Bridge



Fatigue cracks in the Diefenbaker Bridge

Collapse of the Mianus River Bridge

Aabach rail bridge, fatigue reinforcement of stringer-crossbem connections with prestressed CFRP rods

Sources: Design and Evaluation of Steel Bridges for Fatigue and Fracture–Reference Manual, 2016 (No. FHWA-NHI-16-016). And www.sp-reinforcement.ch/

12.1 SIA 269/x – List of principles of intervention

4	**Structural strengthening [SS]** Increase or restoration of the resistance of a structural member of the concrete structure	4.1 Addition or replacement of embedded or external reinforcement	SIA 262, SN EN 1504-10, SN EN 13670	
		4.2 Addition of reinforcement, anchored in grooves or boreholes	SIA 262, SN EN 1504-6 and -10	
		4.3 Reinforcement with plates (steel or fibre laminate)	SIA 166, SN EN 1504-4 and -10	+ EN 1992-1-1, Annex J
		4.4 Supplement cross section with concrete or mortar	SIA 262 and 179, SN EN 1504-3, -4 and -10	
		4.5 Grouting of cracks, cavities or defects	SN EN 1504-5 and -10	
		4.6 Filling of cracks, cavities or defects	SN EN 1504-5 and -10	
		4.7 External prestressing [1)]	SIA 262	

+ Columns: FRP jacketing (fib bulletin 103, chap. 2)
+ External post-tensioning (fib bulletin 103, chap. 11)

12.1 Additional reading

- EN 1992-1-1, Annex J (draft 2021)
- prSIA166 Projet-mis-en-consultation
- Berset ias 3.1995
- 2018_02 s&p étude de cas Hotel Espen
- Etude de cas Barrage du Chambon
- Sika renforcements d’ouvrages carbodur
- Ghafoori et al. - 2022 - Shape memory alloys for structural engineering

12.2 Static strengthening with glued lamellas

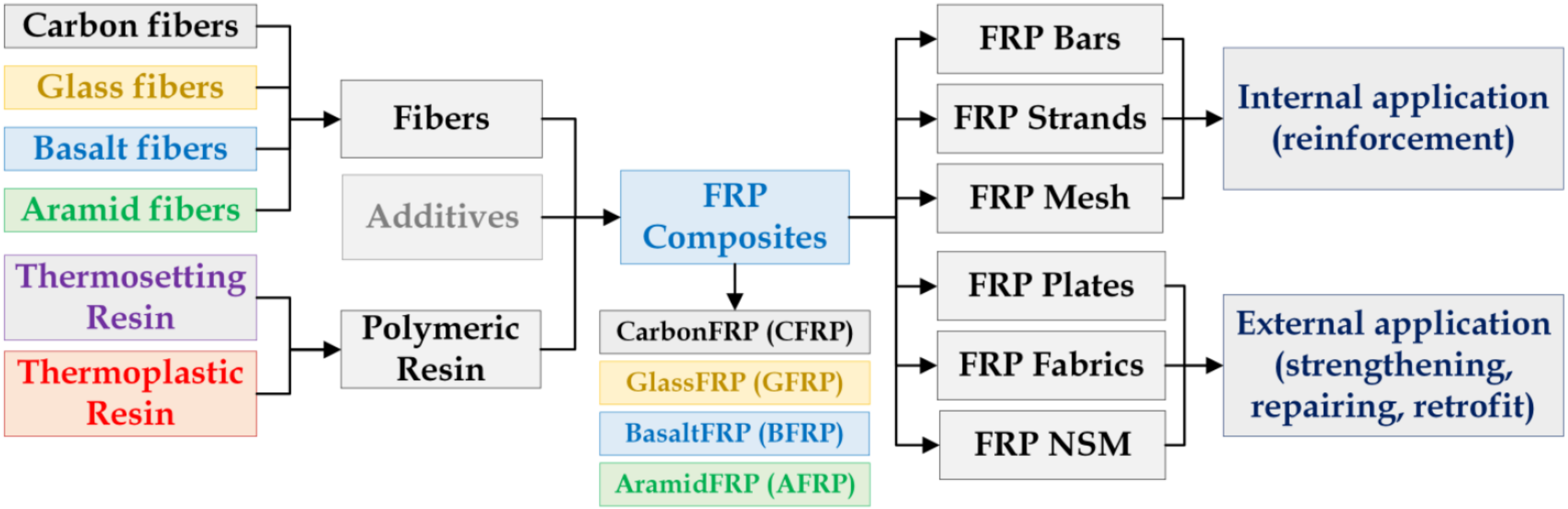
- Of elements made out of concrete, masonry, wood, steel
- Increase of
  - bending strength of slabs, beams
  - shear strength of beams
  - Same direction(s) as rebars
  - But also compression/shear (column confinement)
- Lamellas can be made of
  - Steels, plates, bars (rods or cables, see course 11)
  - CFRP
  - SMA, Iron-based shape-memory alloy

https://bau.sika.com/fr/referenzen.html

https://www.sp-reinforcement.ch/fr-CH

https://www.re-fer.eu/en/

12.2 Composite tree diagram for applications in concrete structures



J. D. Ortiz, S. S. Khedmatgozar Dolati, P. Malla, A. Nanni, and A. Mehrabi, 'FRP-Reinforced/Strengthened Concrete: State-of-the-Art Review on Durability and Mechanical Effects', *Materials*, vol. 16, no. 5, p. 1990, Feb. 2023, doi: 10.3390/ma16051990.

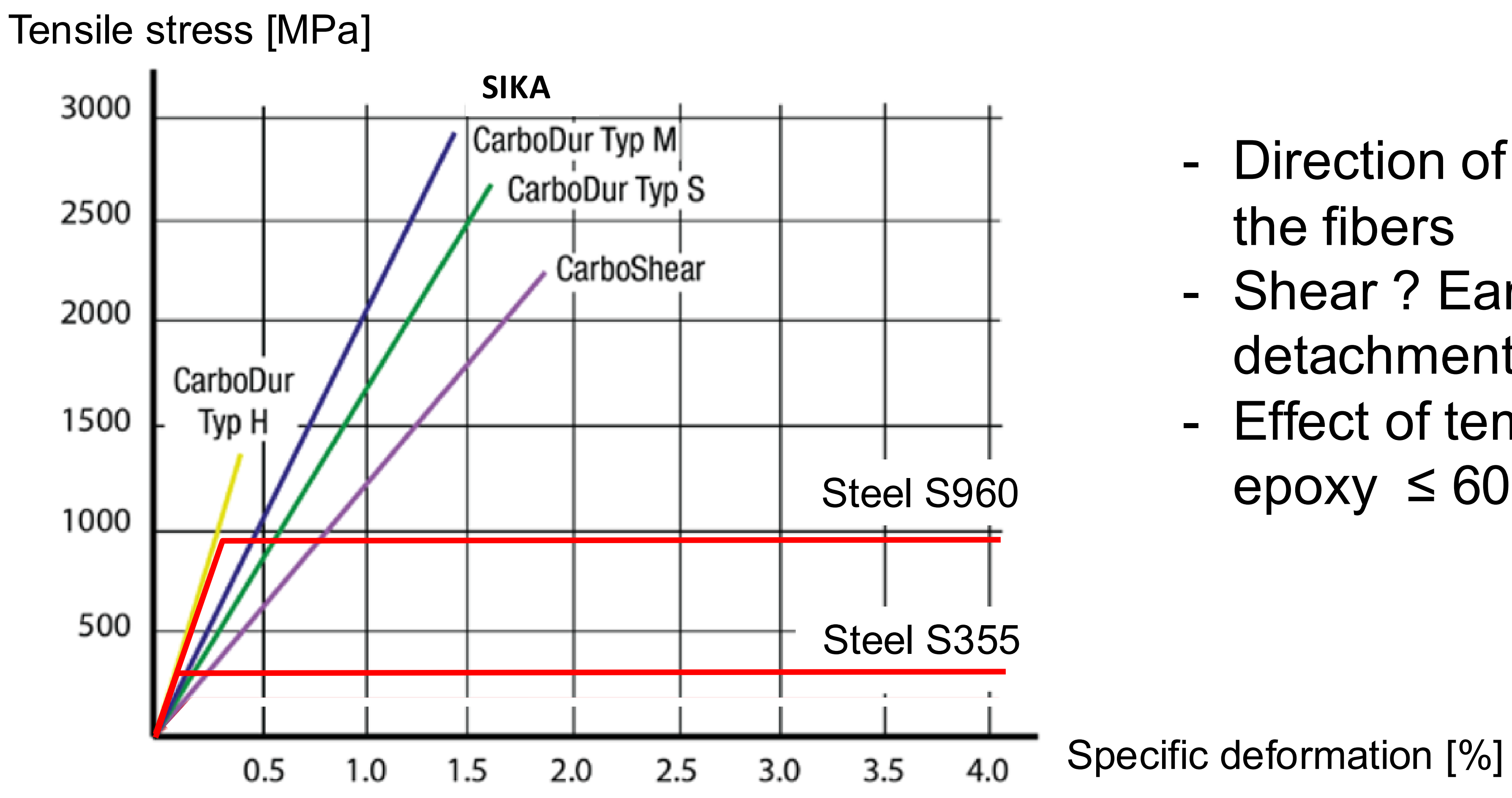
12.2 General guidelines

- Design of reinforcement is similar, bond between substrate and reinforcement is achieved using epoxy resin

- Guidelines for substrate preparation
  - Concrete: dry sandblast, to obtain a rough, uniform surface in every area; remove dust deposits and non-adhesive particles by brushing vigorously
  - If needed, reprofiling irregularities with a two-component, thixotropic, epoxy resin-based adhesive
  - Steel: remove non-adhesive oxidizing parts and degrease the surface
  - Wood: expose sound material by removing, for ex. layers of paint or areas contaminated after a fire

S&P reinf., bridge Riddes, 2021

12.2 Steel flat bars ⬄ Carbon fiber laminates



- Direction of stress = that of the fibers
- Shear ? Early failure, detachment of laminate
- Effect of temperature, epoxy ≤ 60°C

Design tensile strength of CFRP reinforcement: (prEN1992-1-1 § J.5)

$$f_{\mathrm{fud}} = \frac{\eta_f \cdot f_{\mathrm{fuk}}}{\gamma_{\mathrm{f}}}$$

By default: $\eta_f = 0.7$

12.2 Steel flat bars ⇔ Carbon fiber laminates

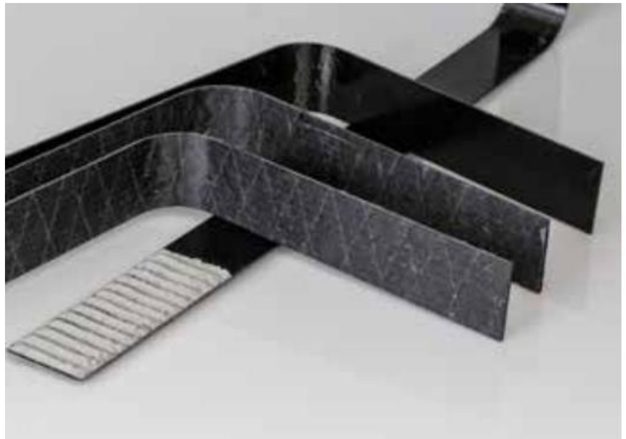
	Steel plates	Carbon fiber laminates
Strength (longi.)	355 to 960 MPa	very high (2200 to 2900 MPa)
Modulus of elasticity	210 GPa*	130 to 200 GPa
Fracture behaviour	ductile	brittle
Coefficient α_t	$10 \cdot 10^{-6}$ [1/°K]	$0.2 \cdot 10^{-6}$ [1/°K]
Volumetric load	heavy (80 kN/m^3)	light (16 kN/ m^3)
Corrosion	susceptible	durable
Lengths of lamellae	limited	unlimited
Maniability, execution	difficult	easier
Strength (transv.)	Ident.	Very low (80 MPa)
Modulus of el. (transv.)	Ident.	7.8 GPa

* rebars: E_s = 200 GPa

12.2 Carbon fiber laminates installation

Source: *S&P Clever Reinforcement Company AG*

S&P C-Laminate



SYSTÈME Sika® CarboShear

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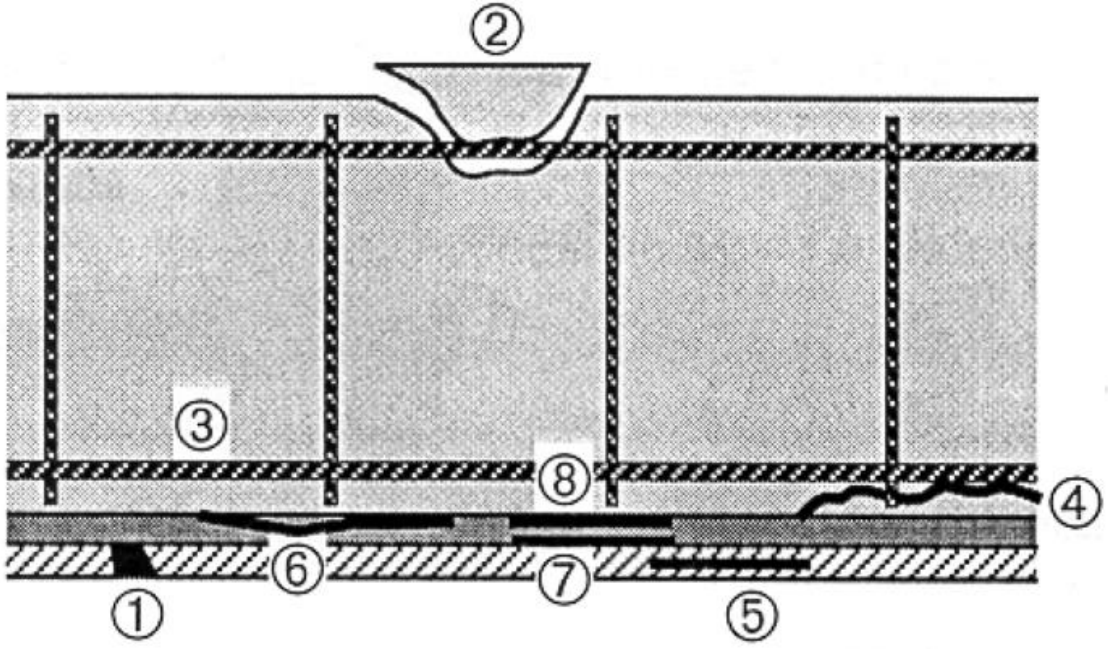
12.3 Flexural design, SIA 166: failure modes of element with CFRP



(source : Deuring, *CFK - Lamellen im Bauwesen, SIA n°26*, 1994)

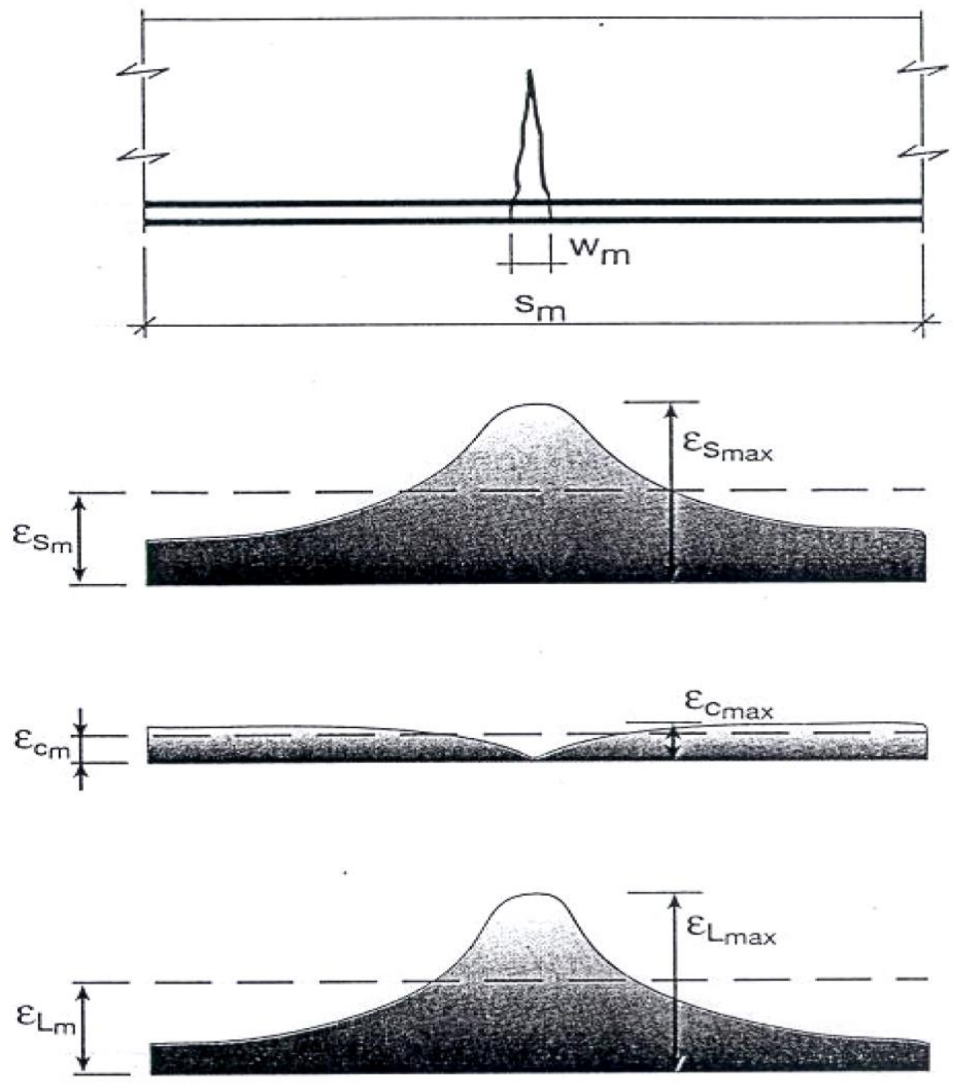
Design and verification

1) of the carbon fibre lamina
2) of the concrete in the compressed zone
3) of the longitudinal reinforcing steels
4) shear failure of the embedding concrete

Quality assurance (products, installation)

5) in the resin (poor preparation of mix, unfavourable temperature conditions)
6) in the lamina
7) at the interface lamina-glue
8) at the interface glue-concrete

12.3.1 Flexural design: specific strains

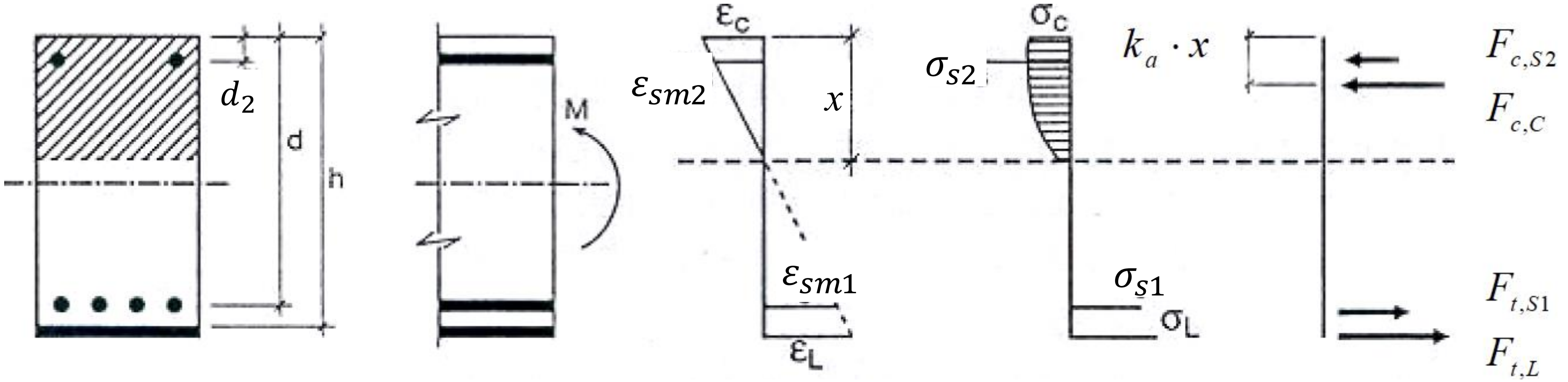


- Material strains vary considerably at a crack
- Carbon fibre laminates: average strain ε_{Lm} = 0.6 to 0.8 ε_{Lmax} (design bond coefficient: k_L = 0.8)
- Plane of deformations calculated with ε_{Lm}
- But laminate and steel reinforcement forces calculated with ε_{Lmax}
- At ULS: **lamina breaks** while steel yields, without concrete crushing

$$\sigma_L = E_L \cdot \varepsilon_{Lmax} = E_L \cdot \frac{\varepsilon_{Lm}}{k_L}$$

- For design, respect strain limitations:
  - Laminates, ε_{Lm} = 5 $^o/_{oo}$ (average strain)
  - Rebars, 4 $^o/_{oo}$ ≤ ε_s ≤ ε_{su} = 5 $^o/_o$
  - Concrete, ε_c ≤ ε_{cu} = 3 $^o/_{oo}$ (SIA)
    3.5 $^o/_{oo}$ (EN)

12.3.1 Cross sectional analysis – composite member

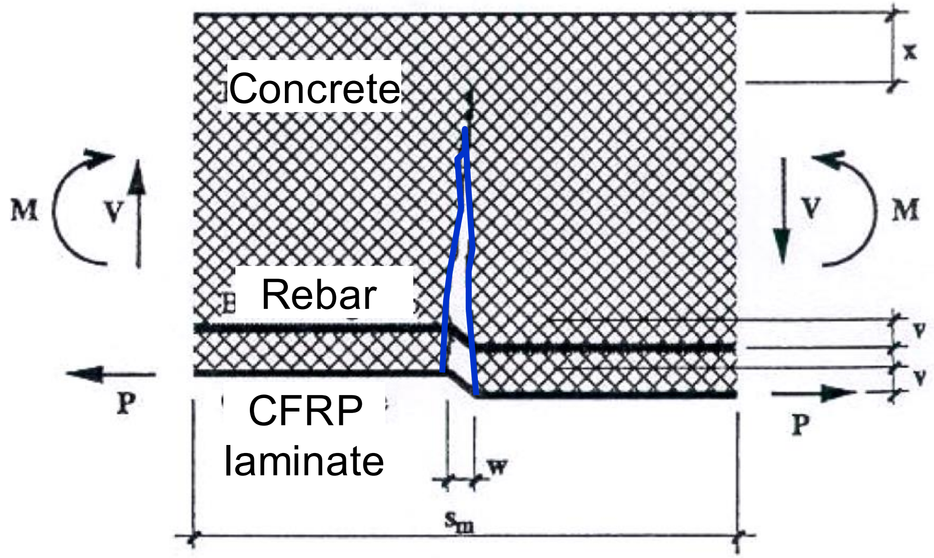


- Pure bending (no or negligible shear)
- "Bernoulli" + Materials laws + equilibrium

➔ Neutral axis position (assumptions)

➔ Solve for position x of neutral axis

➔ Find resisting Moment



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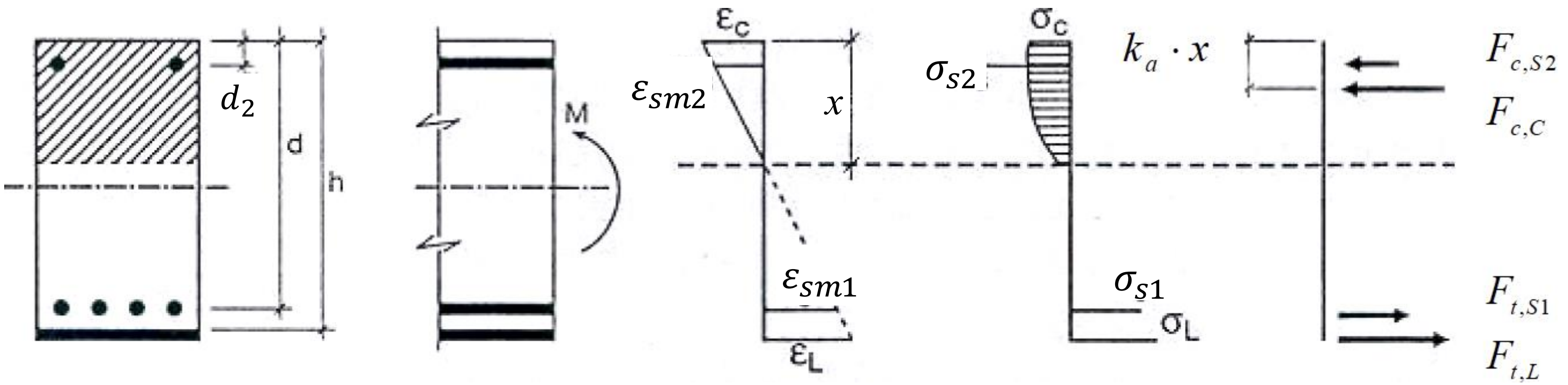
12.3.1 Cross sectional analysis – composite member



- Neutral axis x determination: Iteratively
- Assumptions: for slabs, in first approximation, one can use $\alpha_R = 0.8$ and $k_a = \alpha_R/2 = 0.4$ (or adapt Excel from exercise 11, slab = beam 1m wide, see slides in annex)
- Ultimate bending moment: $M_R = F_{t,L}(h - k_a x) + F_{t,S1}(d - k_a x) - F_{c,S2}(k_a x - d_2)$
- Simplification, SIA 166: $\gamma_M = 1.20$ (for laminates and reinforced concrete)

12.3.1 prEN1992-1-1: Annex J CFRP strengthening

- § J.5 Design tensile strength of CFRP reinforcement: $f_{\text{fud}} = \dfrac{\eta_f \cdot f_{\text{fuk}}}{\gamma_{\text{f}}}$

  By default: $\eta_f = 0.7$

- § J.8.1.1 (4) Limit of application 12 MPa $\leq f_{\text{ck}} \leq$ 50 MPa

12.3.1 prEN1992-1-1: Partial factors for adhesively bonded CFRP strengthening

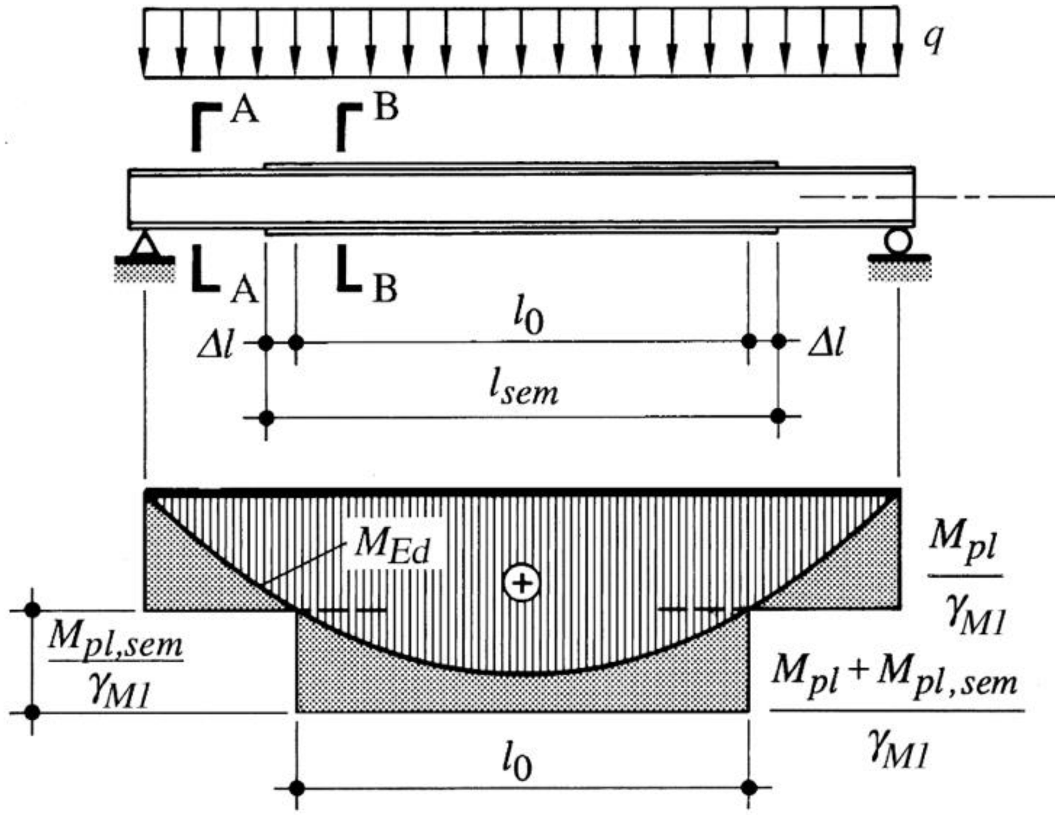
Table J.1(NDP) — Partial factors for ABR CFRP strengthening

Design situation	Tensile strength		Bond strength
	CFRP strips and bars	In-situ lay-up CF sheets	Failure in concrete or adhesive
Designation	γ_f		γ_{BA}
Persistent and transient	1,30	1,40	1,50
Accidental	1,05	1,10	1,20
Serviceability	1,00	1,00	1,00
Fatigue	1,30	1,40	1,30

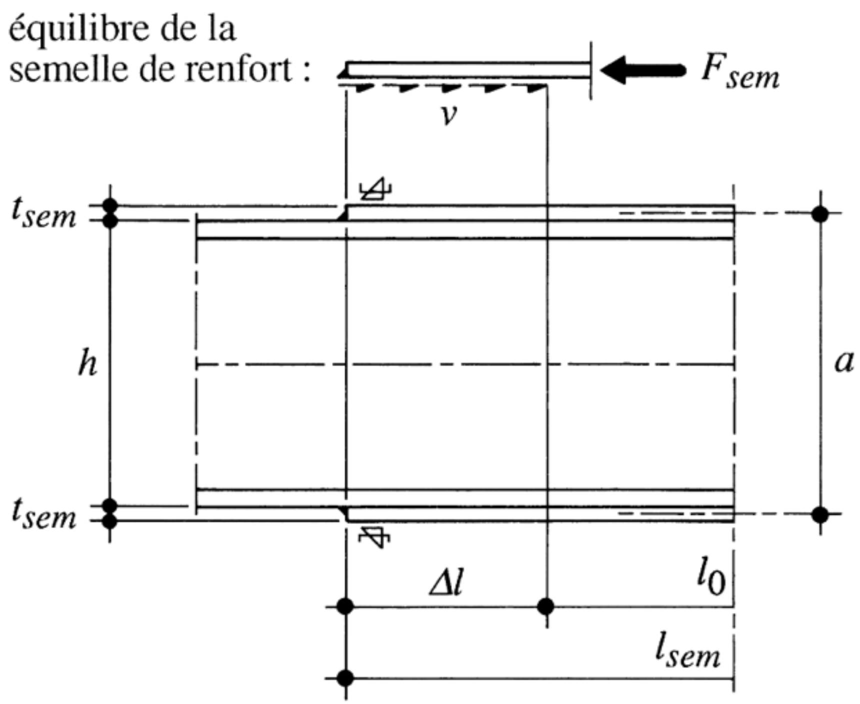
Note: SIA 166 $\gamma_M = 1.20$ (may change) $\gamma_M = 1.50$

12.3.2 Anchoring of laminate ANALOGY:

a) General view of a reinforced steel beam



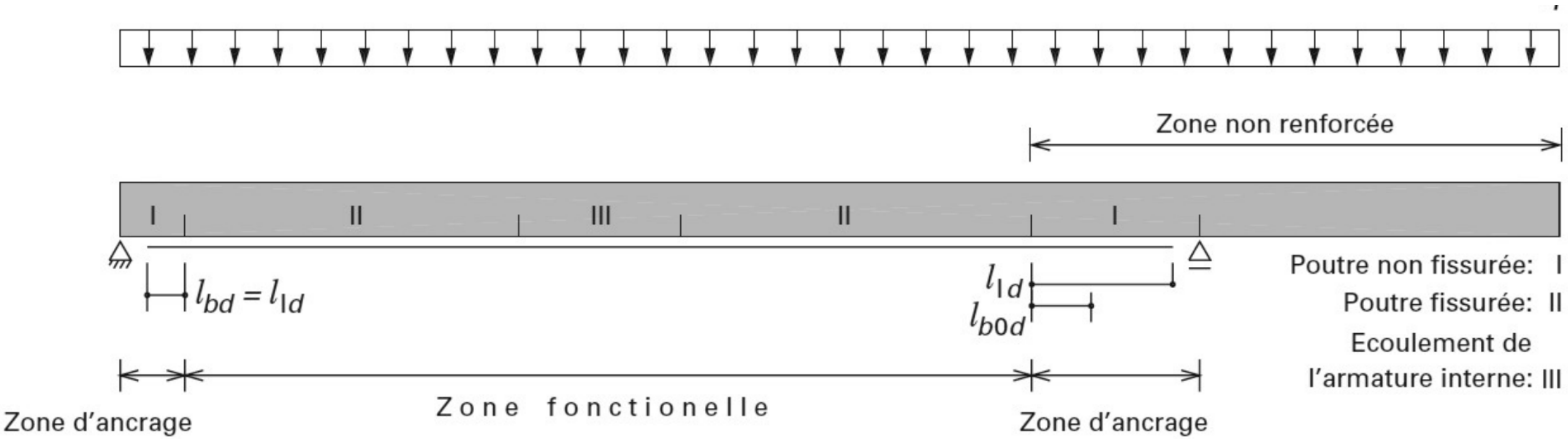
b) Anchorage length of the coverplates Δl



But instead of welded, bonded, quid of shear stress distribution ?

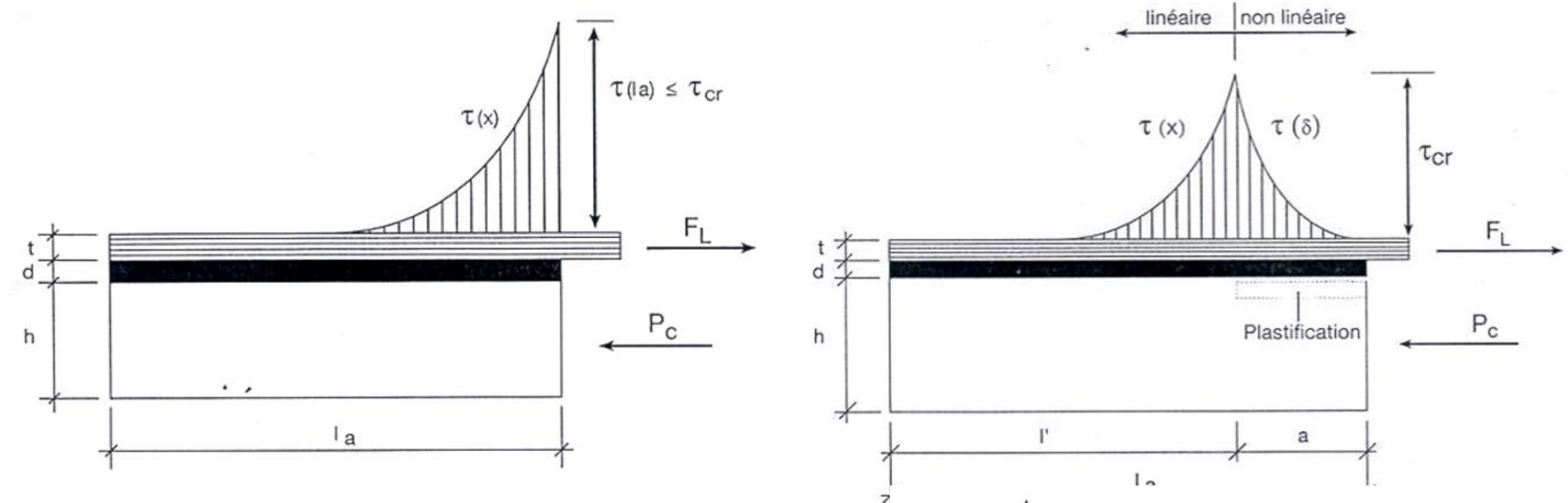
12.3.2 Anchoring of laminate

From SIA 166:

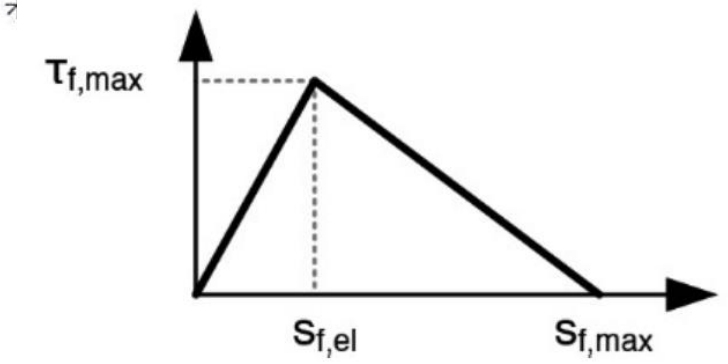


12.3.2 Anchoring of laminate

From literature ([1] J.-D. Berset, 1995) :
The assumption of constant shear stresses - used for other dimensioning cases - is not valid



From SIA 166: Adhesion law for determining ultimate strength of bonded anchors



12.3.2 Anchoring of laminate

- For the maximum anchorage resistance $F_{b0,Rd} = b_L \cdot \sqrt{2 \cdot G_{Fbd} \cdot E_L \cdot t_L}$ in [N]
- For the anchorage length $\Delta l_{bd} = \frac{\pi}{2} \cdot \sqrt{2 \cdot \frac{G_{Fbd} \cdot E_L \cdot t_L}{\tau_{l0d}^2}}$ in [mm]
- G_{Fbd} design value for specific failure energy of substrate, in first approximation, proportional to pull−out strength :

$$G_{Fbd} = \frac{1}{8} \cdot \frac{f_{ctm}}{\gamma_M}$$ G_{Fbd} in [N/mm]

- τ_{l0d} design value of maximum shear stress the substrate can withstand : $\tau_{l0d} = \frac{4}{3} \cdot \frac{f_{ctm}}{\gamma_M}$

- f_{ctH} mean value of pull−out strength
- γ_M partial strength factor (γ_M = 1.5)
- t_l thickness of lamina
- b_l width of lamina
- E_l modulus of elasticity of lamina

12.3.2 Anchoring of laminate with blocs

5.2 Ancrage d'extrémité des S&P CFK-Lamelles collées en surface

Lorsque la pente des moments est abrupte près d'un appui ou lorsque plusieurs lamelles CFK doivent être collées les unes sur les autres, le dimensionnement montre souvent qu'il n'est pas possible d'ancrer uniquement par adhérence. Dans de telles situations, d'autres moyens d'ancrages aux extrémités de la lamelle sont nécessaires:

A) Système d'ancrage

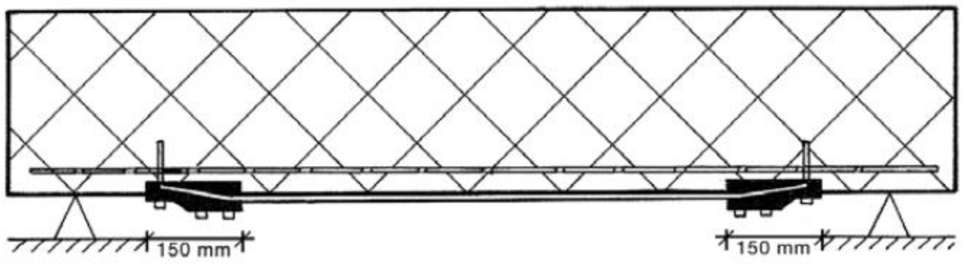


Image 13: Système d'ancrage S&P breveté

S&P a développé un système d'ancrage garantissant un transfert des efforts aux extrémités des lamelles et évitant ainsi le délaminage.
Les *S&P CFK-Lamelles* sont pincées dans 2 sabots en aluminium aux extrémités de celle-ci. La pression sur les lamelles, le collage, ainsi que le rayon de celle-ci induit par la courbure des pièces en aluminimum garantissent l'ancrage.

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12.3.2 Anchoring of laminate with blocs

5.2 End anchorage of S&P CFK-laminations glued onto the surface

When the moment gradient is steep near a support or when several CFK laminates have to be glued on top of each other, dimensioning often shows that it is not possible to anchor solely by bond. In such situations, other means of anchorage at the ends of the laminates are necessary:

A) Anchorage system

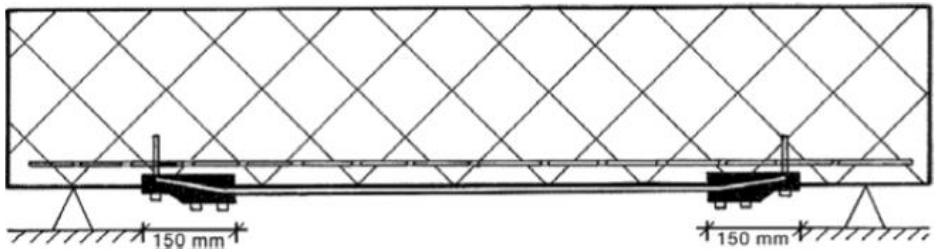
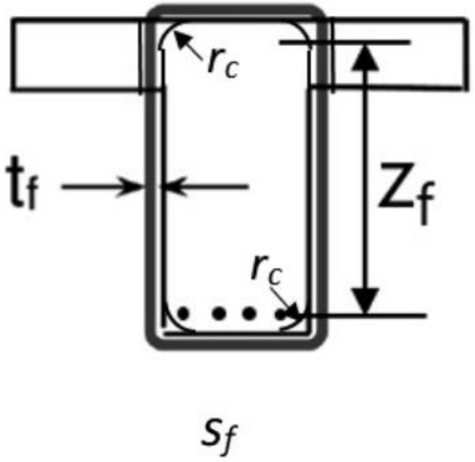


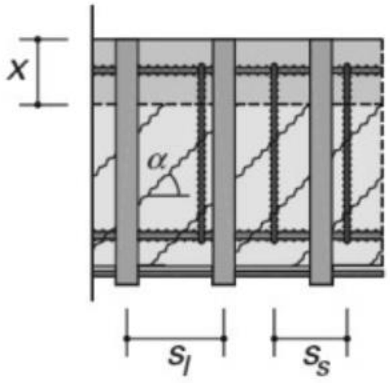
Image 13: Patented S&P anchorage system

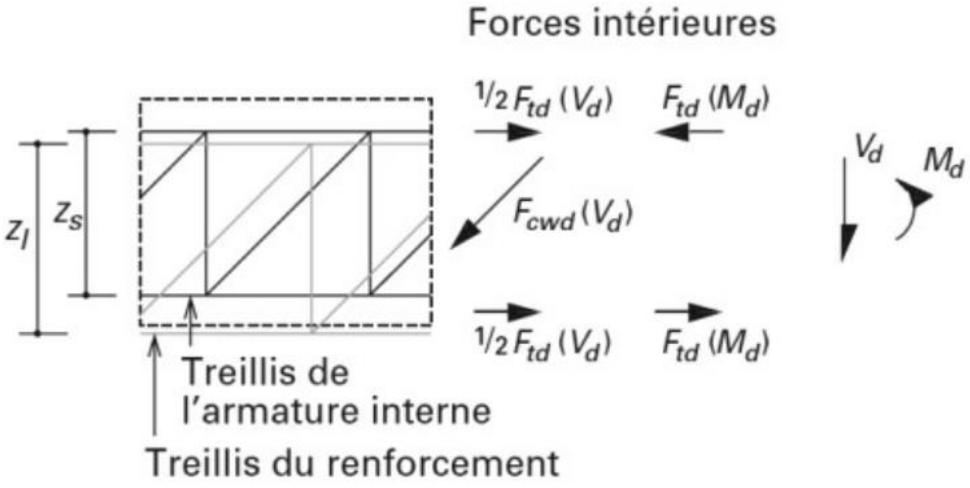
S&P has developed an anchorage system that guarantees the transfer of forces at the ends of the laminates, thus preventing delamination.
S&P CFRP laminates are clamped into two aluminum clamps at their ends.
The pressure on the laminates, the bonding, and the radius of the laminates induced by the curvature of the aluminum parts ensure anchorage.

12.4 Model of the effect of shear reinforcement

Extract SIA 166





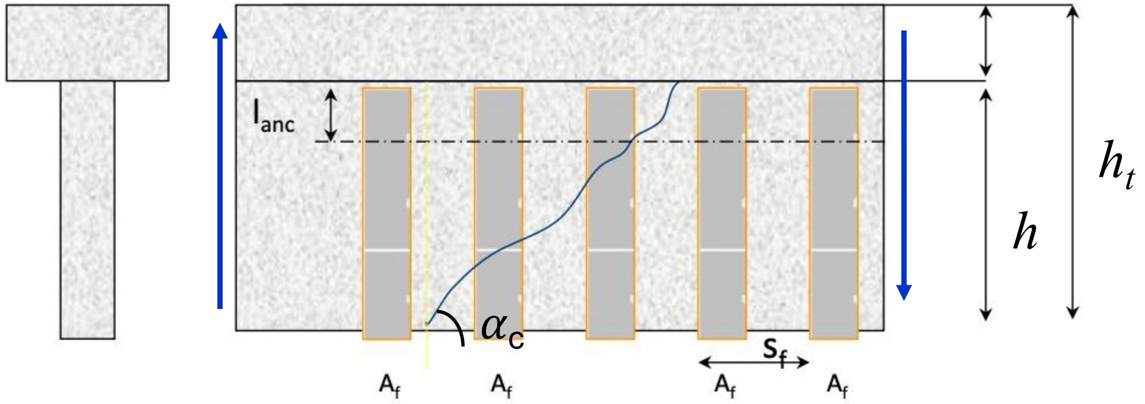


12.4 Shear reinforcement

Laboratoire des Matériaux Composites pour la Construction

Université Claude Bernard Lyon 1

Efficacité des renforts composites dans le cas de l'effort tranchant



Total resistance $V_{Rd} = V_{Rd,s} + V_{Rd,f}$

Top part of CFRP not taken into account, α_c = 45° from bottom

$$V_{Rd,s} = \left[\frac{A_{sw}}{s_s}\frac{f_{sk}}{\gamma s} 0{,}9d\right] \qquad V_{Rd,f} = \left[\frac{A_{fw}}{s_f}\frac{f_{fk}}{\gamma_f}\right](h - l_{anc})$$

Conditions of cracking, min. distance between 2 reinf.: $s_f \leq h - l_{anc}$

Recall course 11: Design values for ultimate resistance of concrete and rebars NEAR support

$$V_{Rd,c} = \frac{f_{cd} \cdot b_w}{2}\left[\frac{x}{\sin \alpha_c} \cdot (1 - \cos \alpha_c)\right]$$

$x = 0{,}9 \cdot \omega_m \cdot d_{eq}$ Compression zone

$$\omega_m = \frac{A_{sc}\, f_{sd} + A_U\, f_{Utud} + A_{sU}\, f_{sUd}}{A_c\, f_{cd}}$$

$$d_{eq} = \frac{d_{sc}\, A_{sc}\, f_{sd} + d_U\, A_U\, f_{Utud} + d_{sU}\, A_{sU}\, f_{sUd}}{A_{sc}\, f_{sd} + A_U\, f_{Utd} + A_{sU}\, f_{sUd}}$$

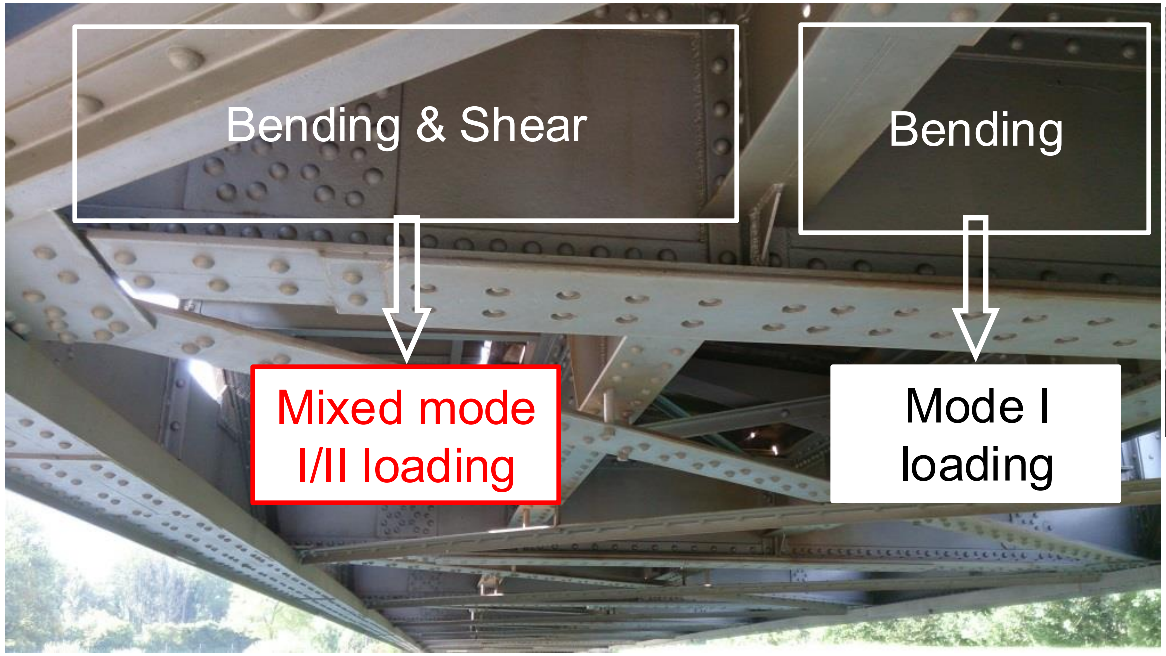
Design value for ultimate resistance of the vertical shear reinforcement bars

$$V_{Rd,s} = \frac{A_{sw}}{s} \cdot (d_{sc} - x) \cdot cot\alpha_c \cdot f_{sd}$$

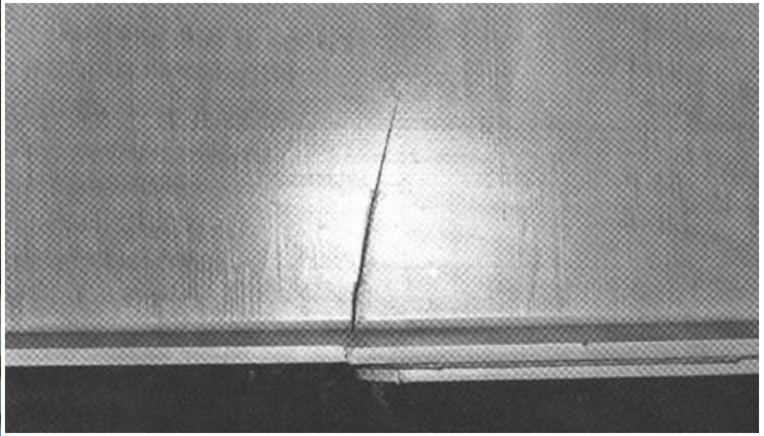
12.5 Fatigue strengthening with glued lamellas

- Mode I fatigue crack arrest in metallic members
- Additional anchorage systems: clamping plates
- Mixed mode I/II fatigue crack arrest in metallic members
- Prestressed strengthening of real-scale metallic members

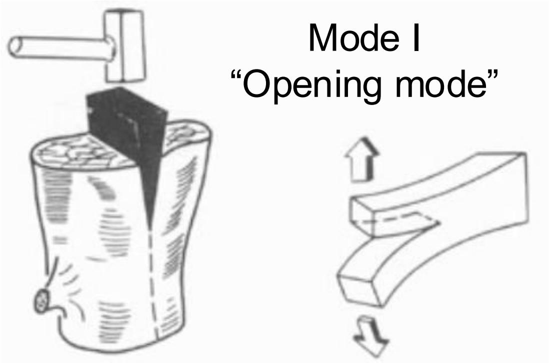
12.5 Mode I and Mixed mode fatigue problem

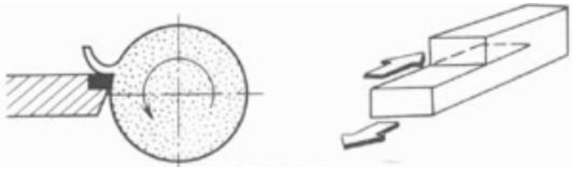


Linthkanal bridge (Switzerland), strengthened with welded cover plates.



Yellow Mill Pond Bridge, USA (from: Fatigue and Repair Cases in Steel Bridges. 2nd International Conference on Bridge Maintenance, Safety and Management, 2014).

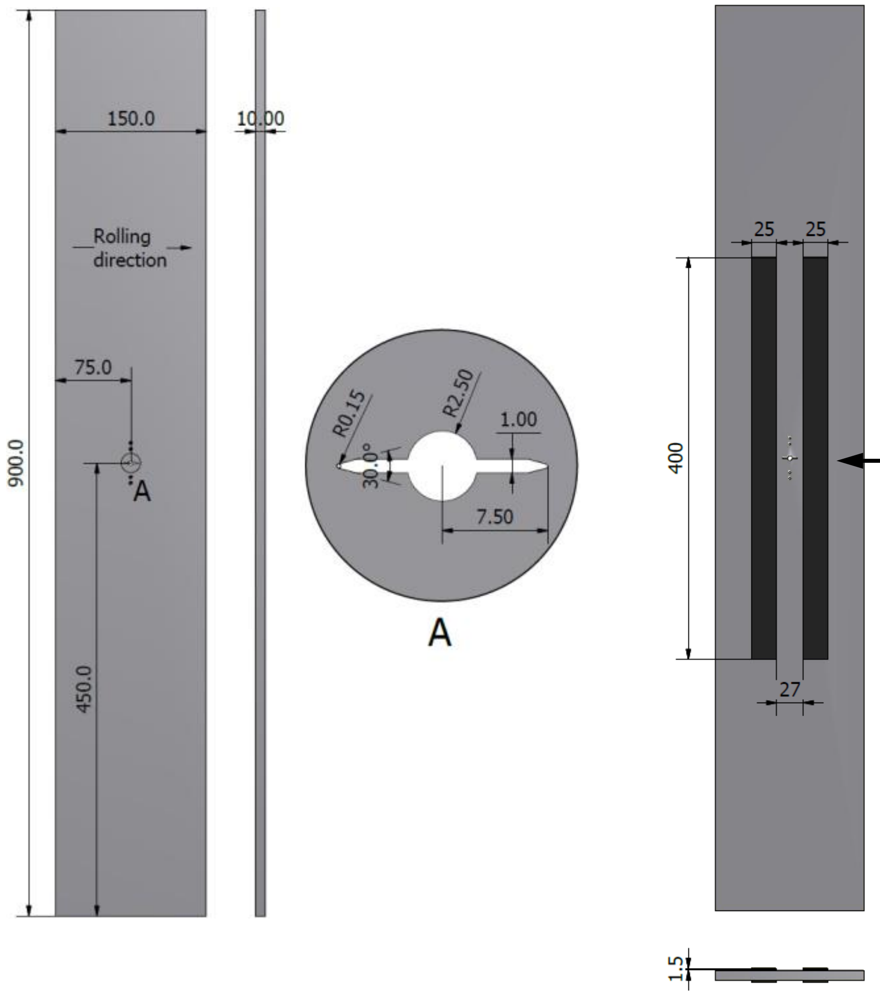




From: Fracture Mechanics from Theory to Practice. Parton V.Z. Page 66, Figure 47.

Mode I fatigue crack arrest – Nonprestressed reinforcement

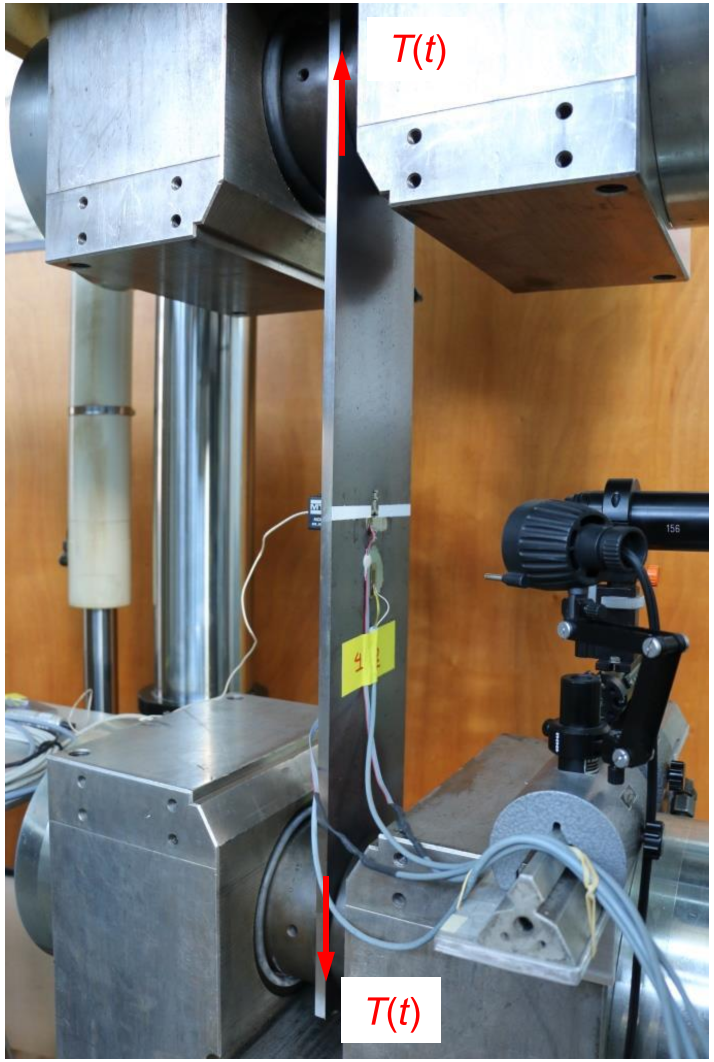
Reference specimen →

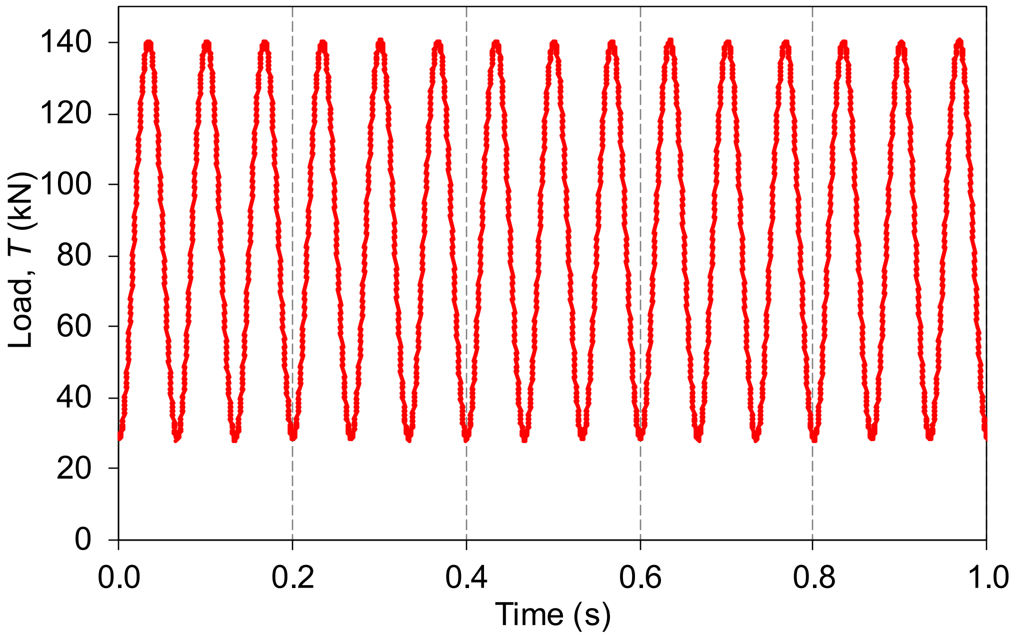


← Nonprestressed bonded UHM CFRP plates (NPBR-UHM)

- Steel: S355J2+N (E_s = 201 GPa; $\sigma_{y,n}$ = 355 MPa)
- UHM CFRP: THM 450 (E_f = 435 GPa; σ_u = 1200 MPa)
- Adhesive: Araldite 420 A/B (G_a = 730 MPa; σ_u = 26.0 MPa)

Mode I fatigue crack arrest – Nonprestressed reinforcement





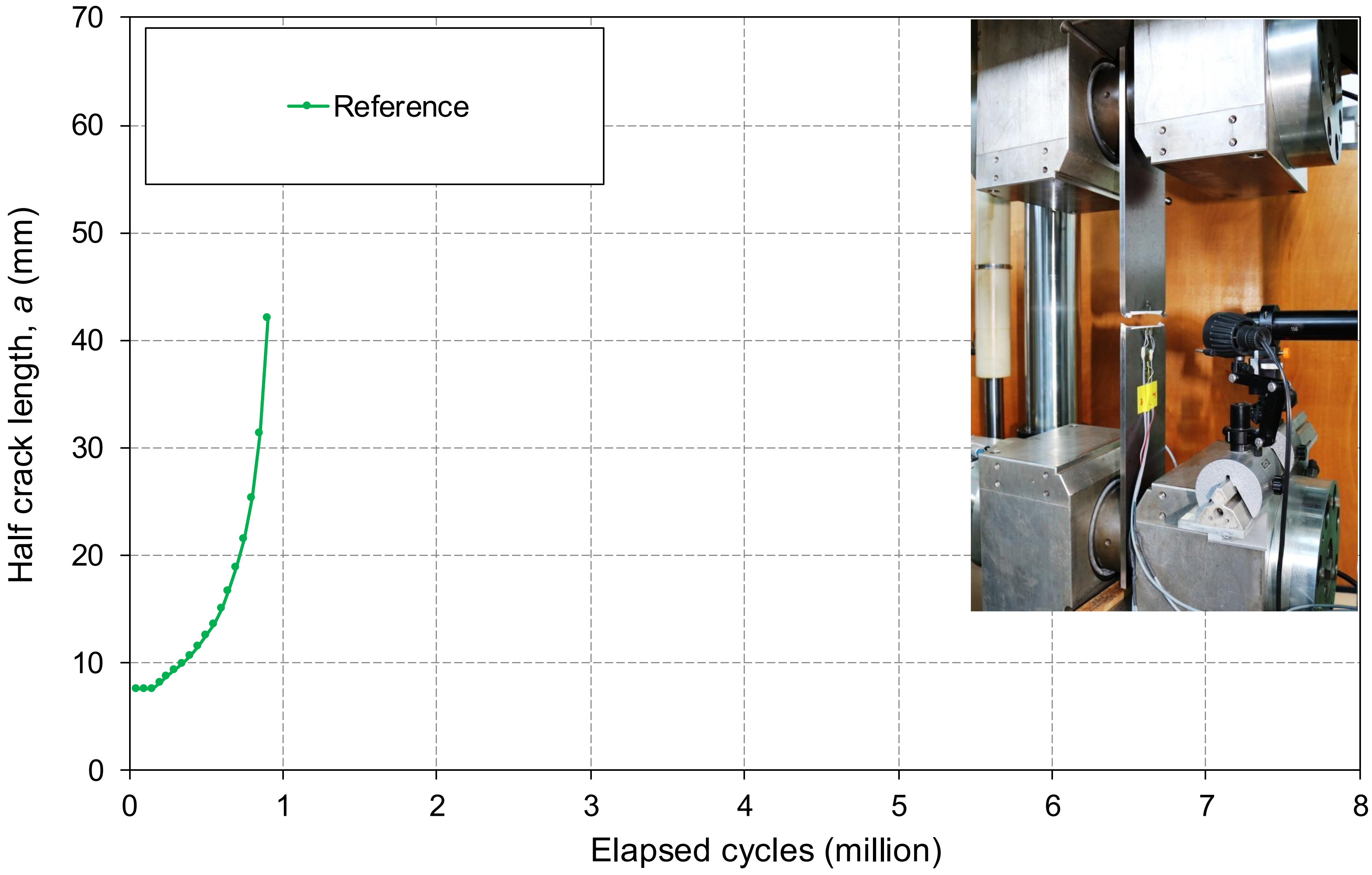
T_{max} = 140.6 kN σ_{max} = 93.7 MPa (22% σ_y)

T_{min} = 28.1 kN σ_{min} = 18.7 MPa (4% σ_y)

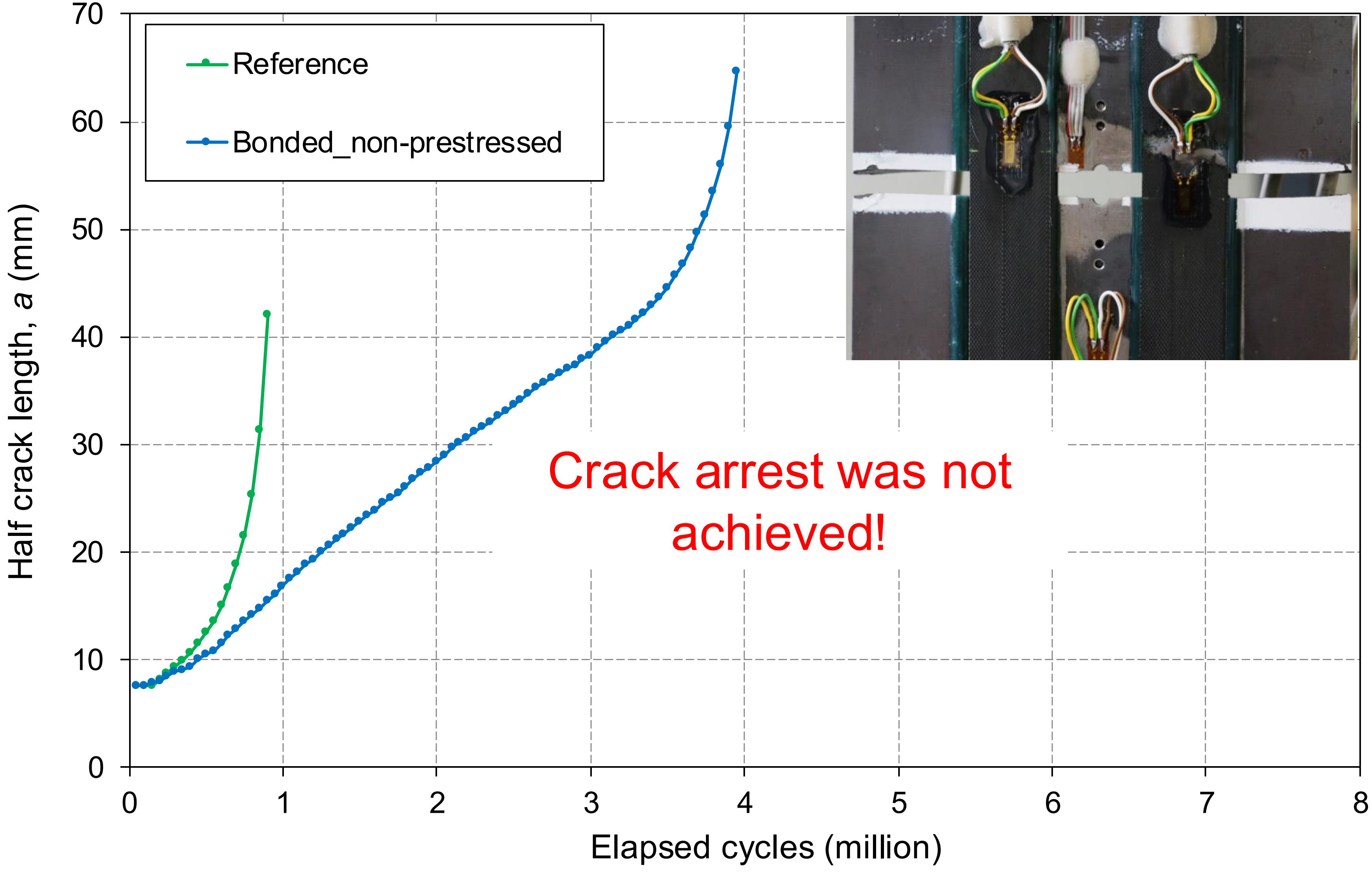
Load ratio (T_{min}/T_{max}) = 0.2

Loading frequency = 15 Hz

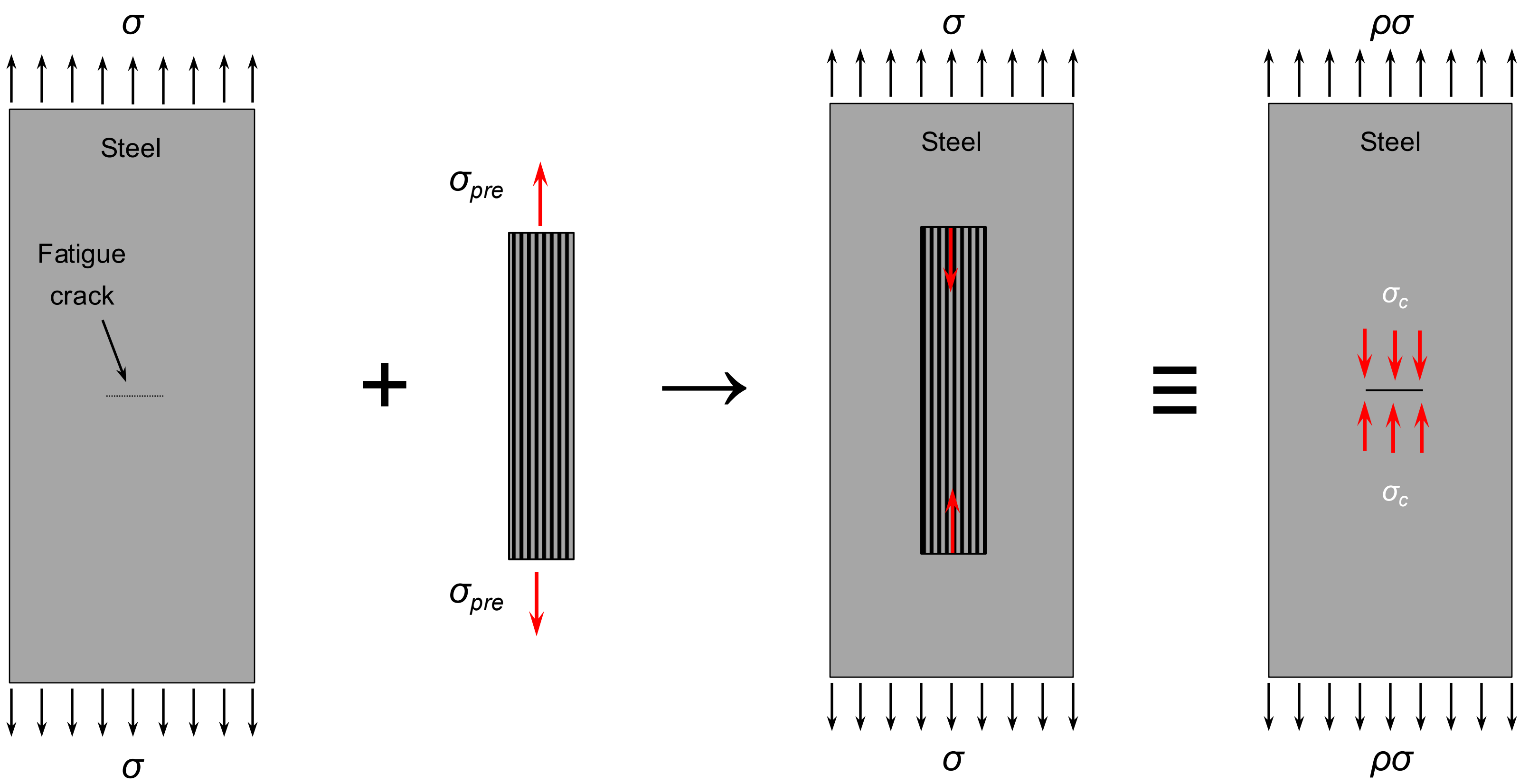
Mode I fatigue crack arrest – Nonprestressed reinforcement



Mode I fatigue crack arrest – Nonprestressed reinforcement



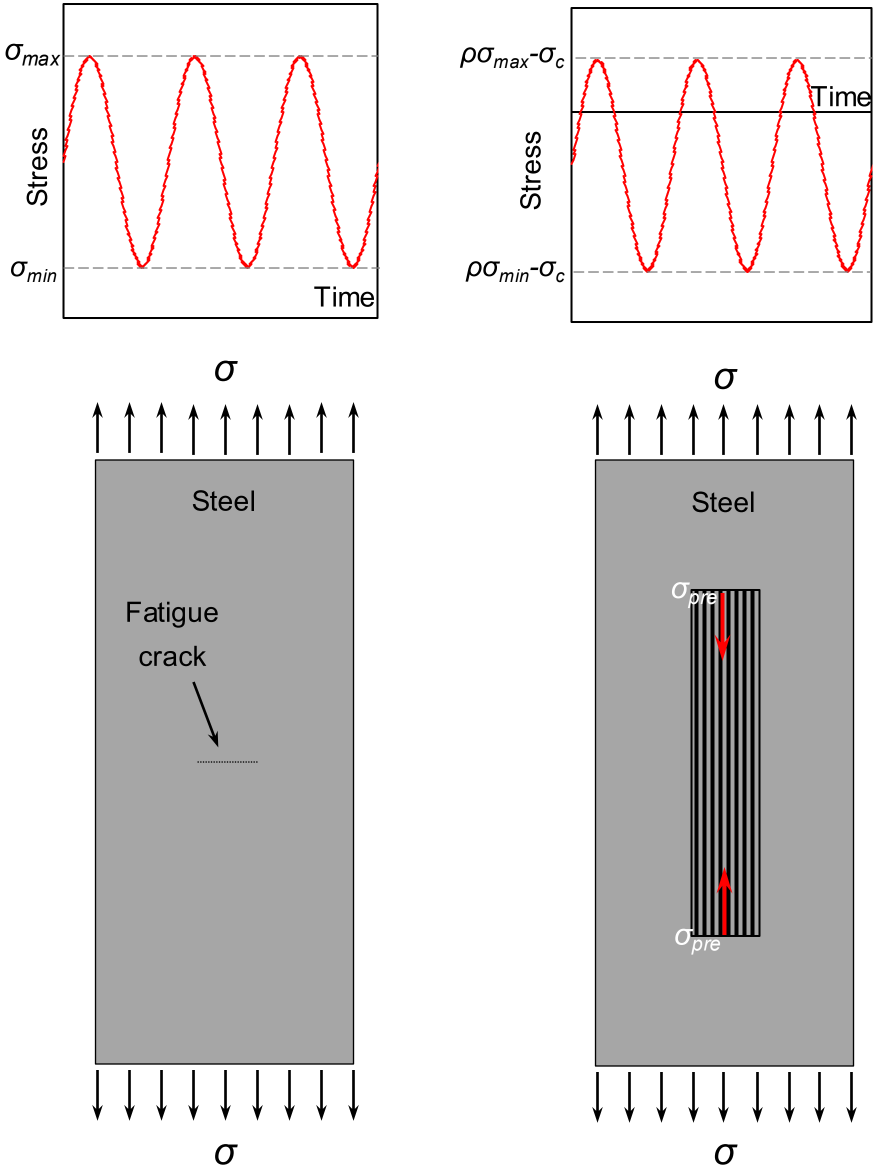
Mode I fatigue crack arrest – Why prestressing?



$$\rho = \frac{A_s E_s}{A_s E_s + A_f E_f}$$

σ_{pre}=? for the crack to be completely arrested (infinite fatigue life)

Mode I fatigue crack arrest – Why prestressing?



Based on linear elastic fracture mechanics (LEFM), we can derive σ_{pre}:

Criterion: $\Delta K_{I,eff} < \Delta K_{I,th}$

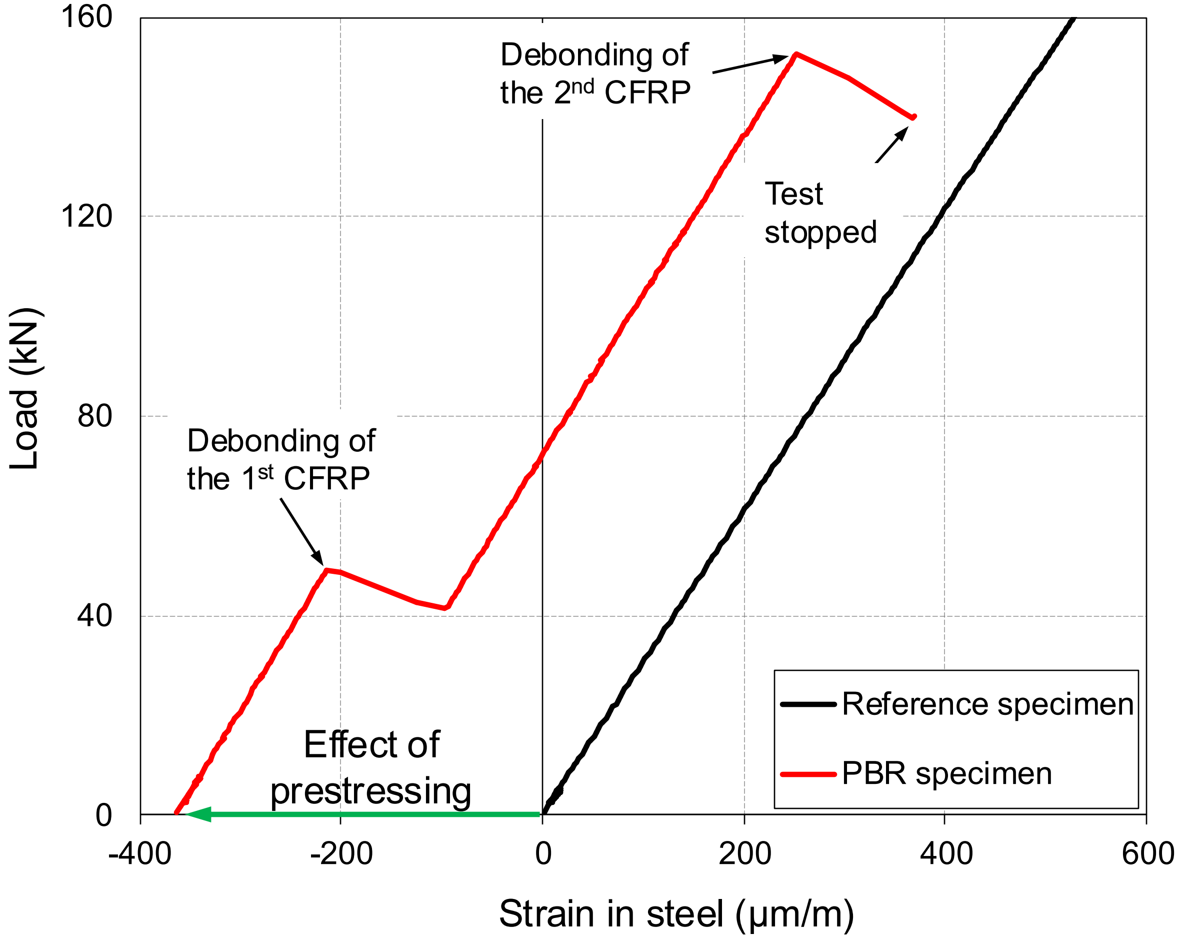
$$R_r < \frac{\dfrac{\Delta K_{I,th}}{U\rho\sigma_{\max} f(a,w)} + R - 1}{\dfrac{\Delta K_{I,th}}{U\rho\sigma_{\max} f(a,w)}}$$

$$\sigma_c = \frac{\rho}{1-R_r}\left(\sigma_{\min} - R_r\sigma_{\max}\right)$$

$$\sigma_{pre} = \frac{\sigma_c A_s E_s}{\rho A_f E_f}$$

U = crack closure parameter

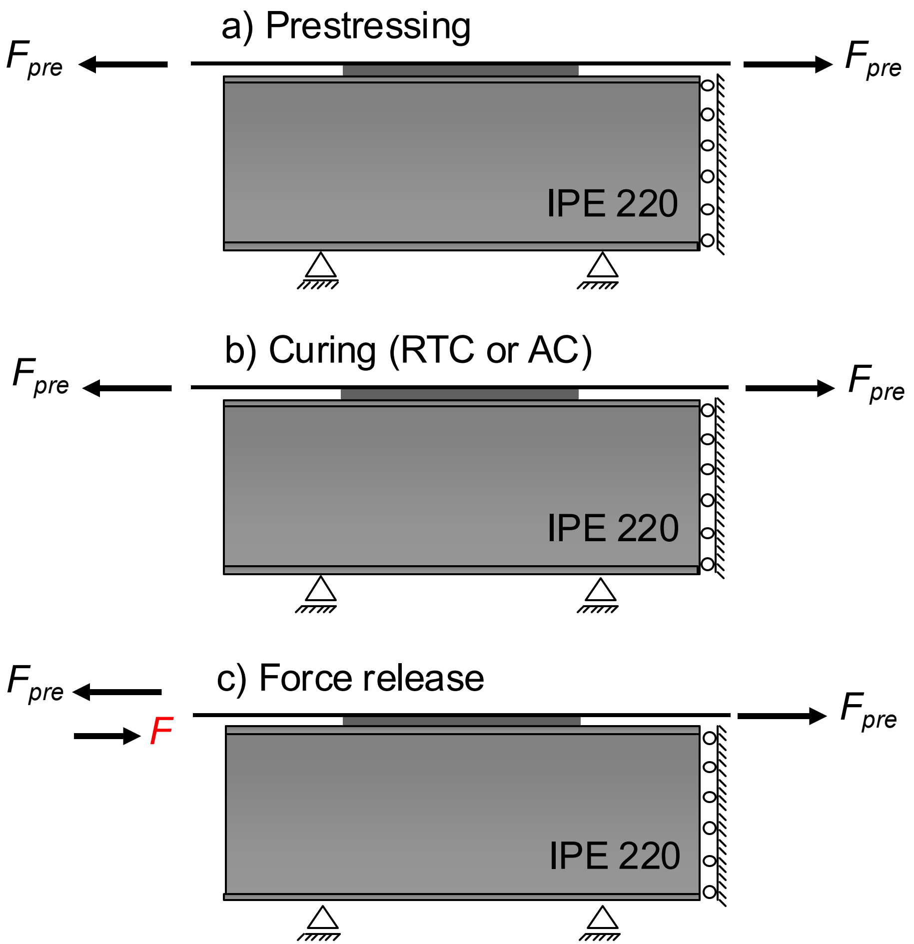
Mode I fatigue crack arrest – Prestressed bonded reinforcement



The required σ_{pre} is too much! What is the limit?!

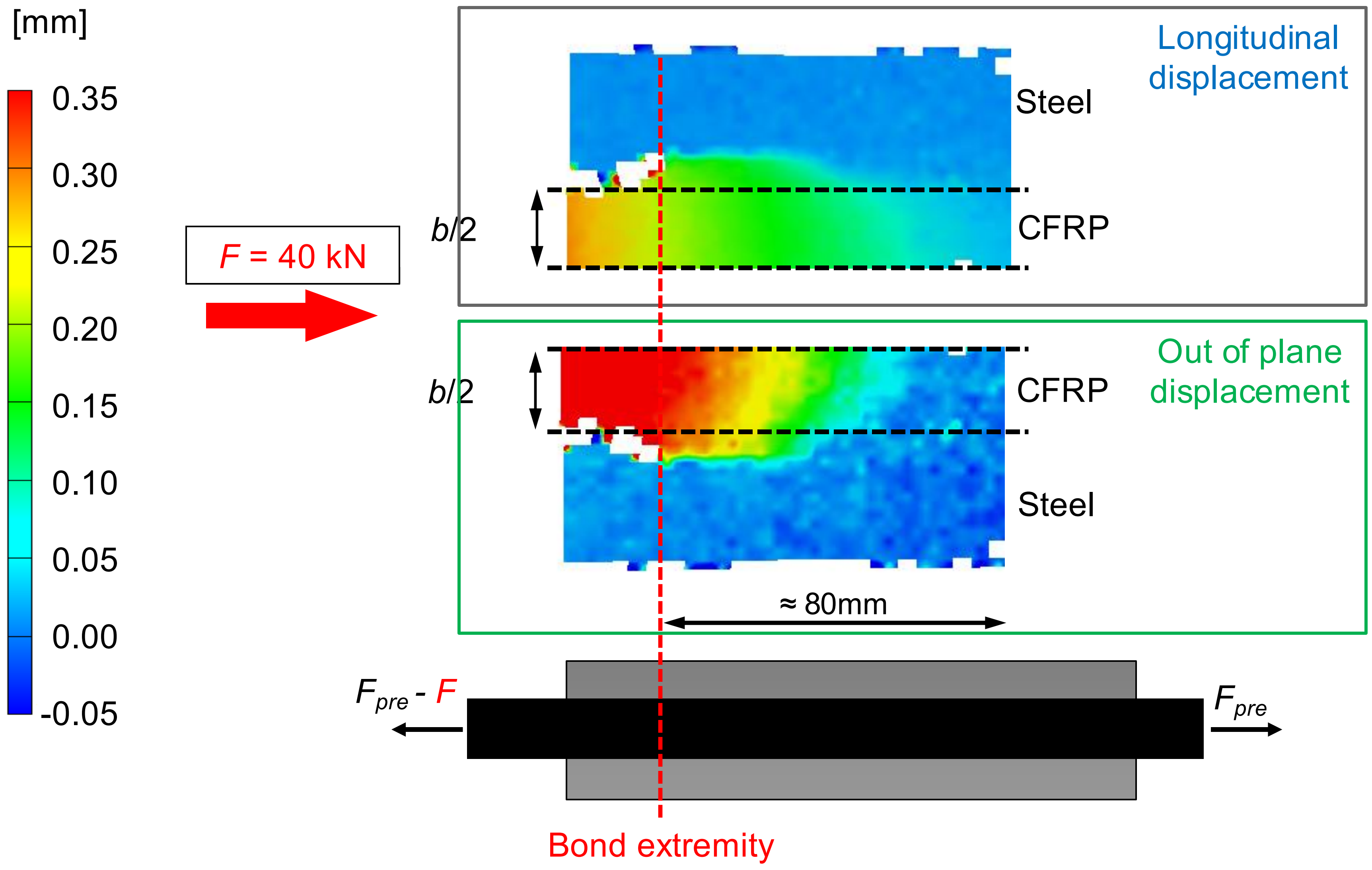
Mode I fatigue crack arrest – Bond performance

Prestress release test

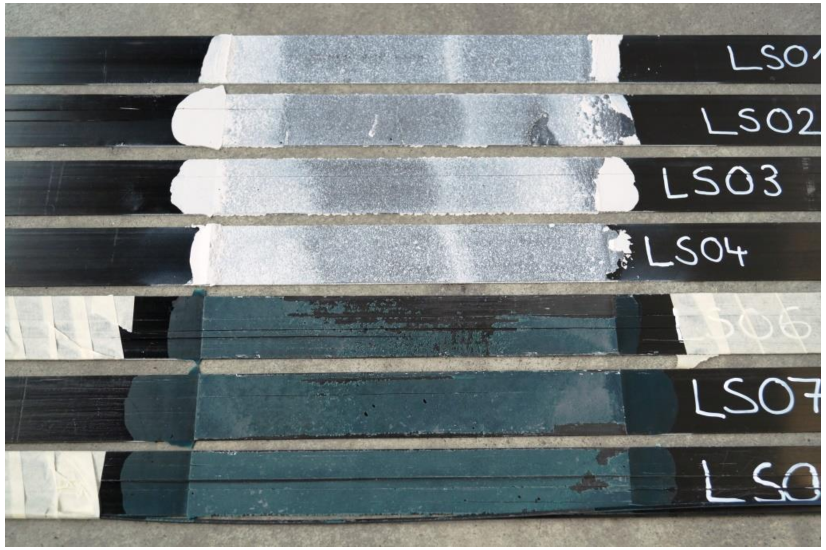


Mode I fatigue crack arrest – Bond performance

Prestress force release



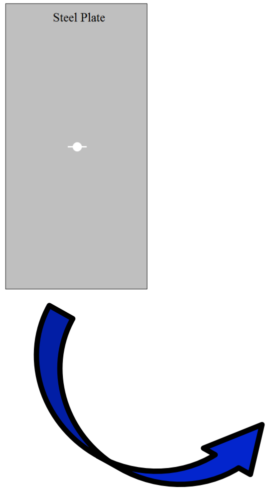
Mode I fatigue crack arrest – Bond performance



The required σ_{pre} (for crack arrest) is way more than the bond capacity!

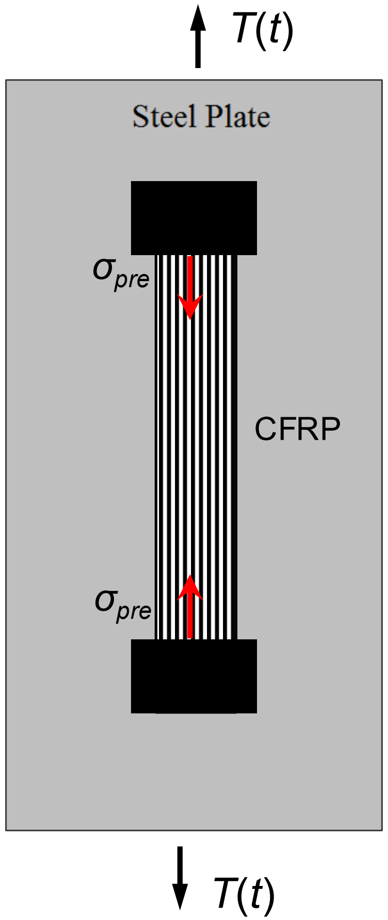
Mode I fatigue crack arrest – Solution to end load introduction

Prone to fatigue crack growth

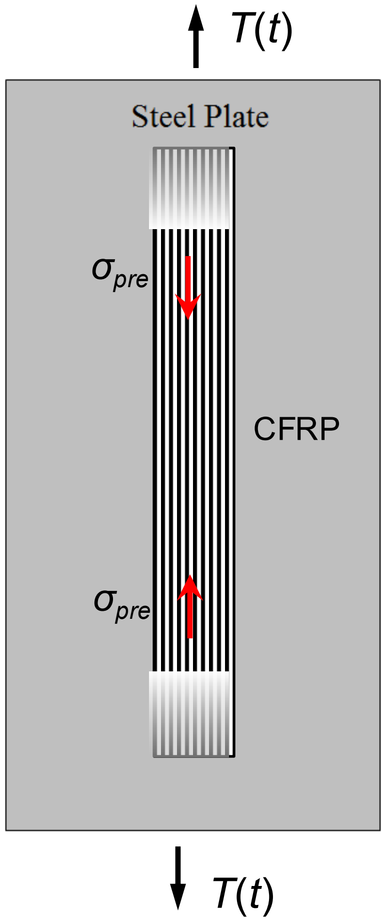


Strenghening

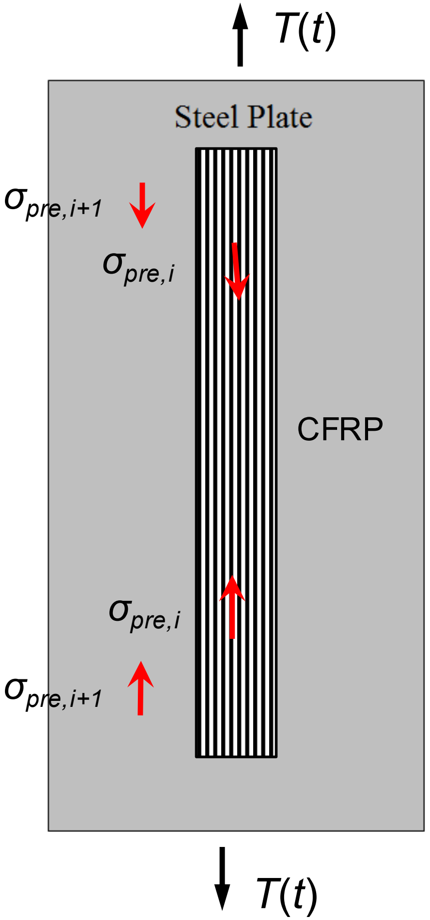
Fatigue crack arrest



Mechanical anchorages

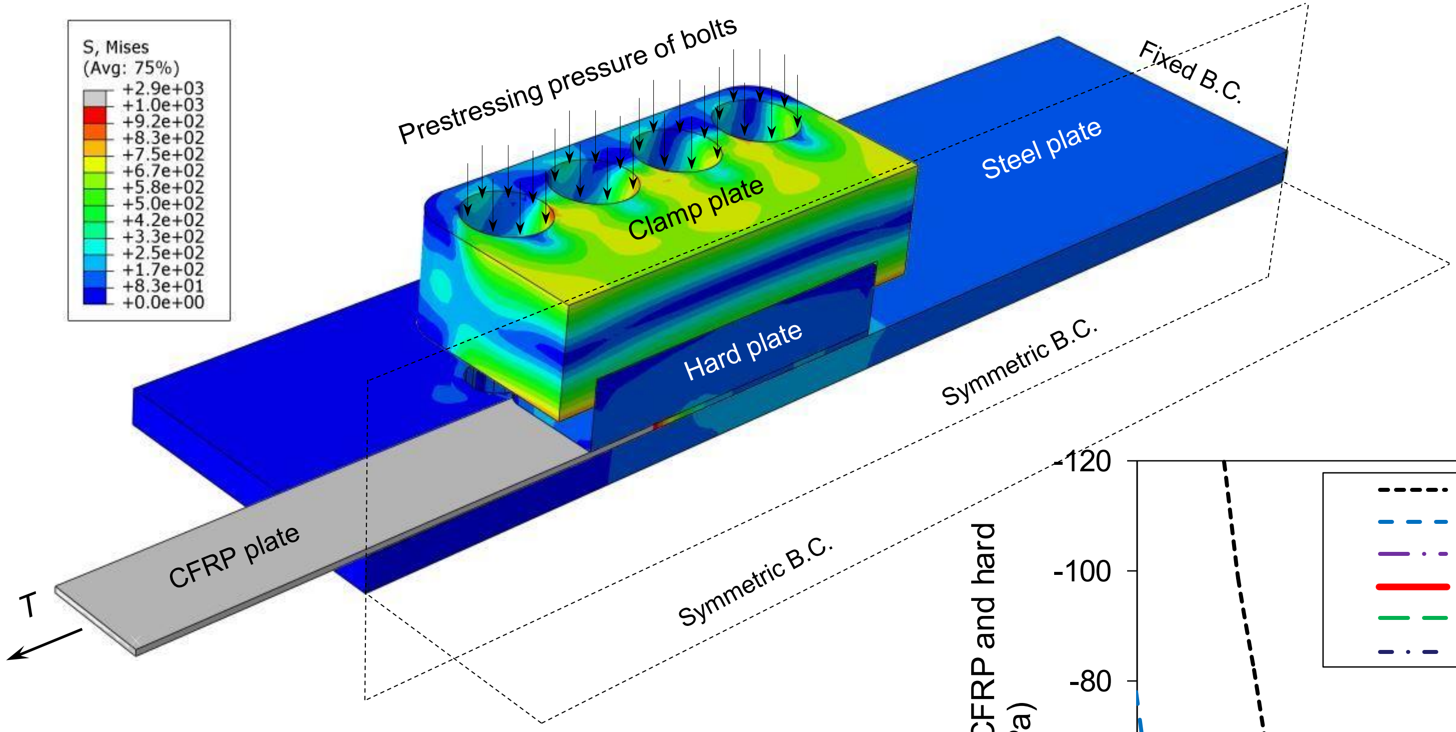


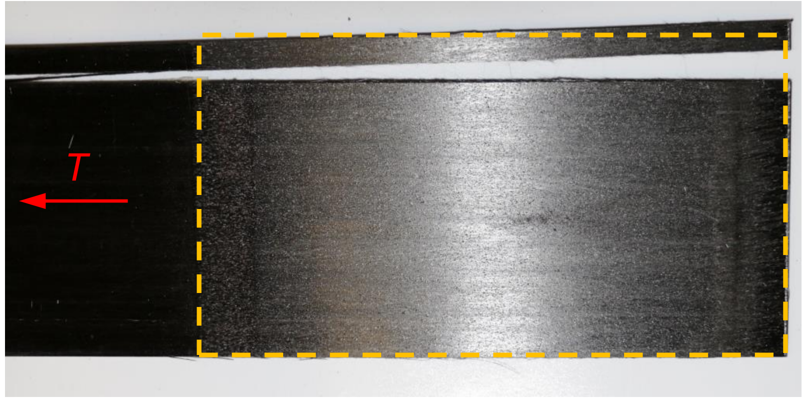
Tapering of ends and/or reduction of glue, fiber stiffnesses (for ex. Meier, U. et al., US-Patent N° 5713169, 1998)



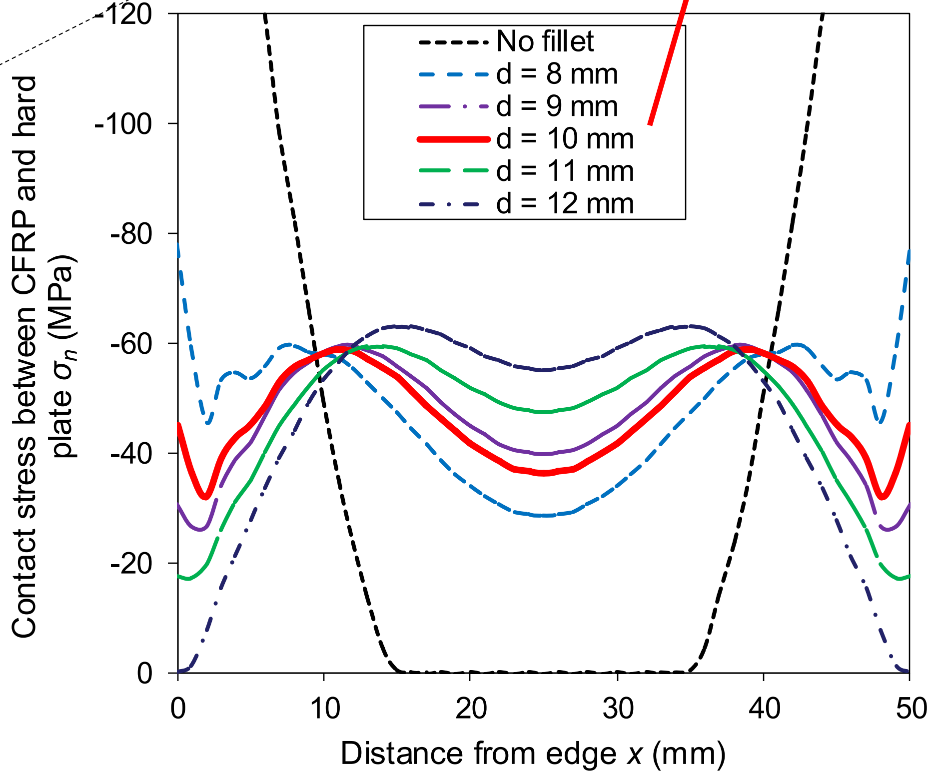
Sequential gluing/prestressing of ends (for ex. Meier and al., US Patent N° 6464811, 2000)

Mode I fatigue crack arrest – Prestressed unbonded retrofit (PUR)





with angle 1.5°



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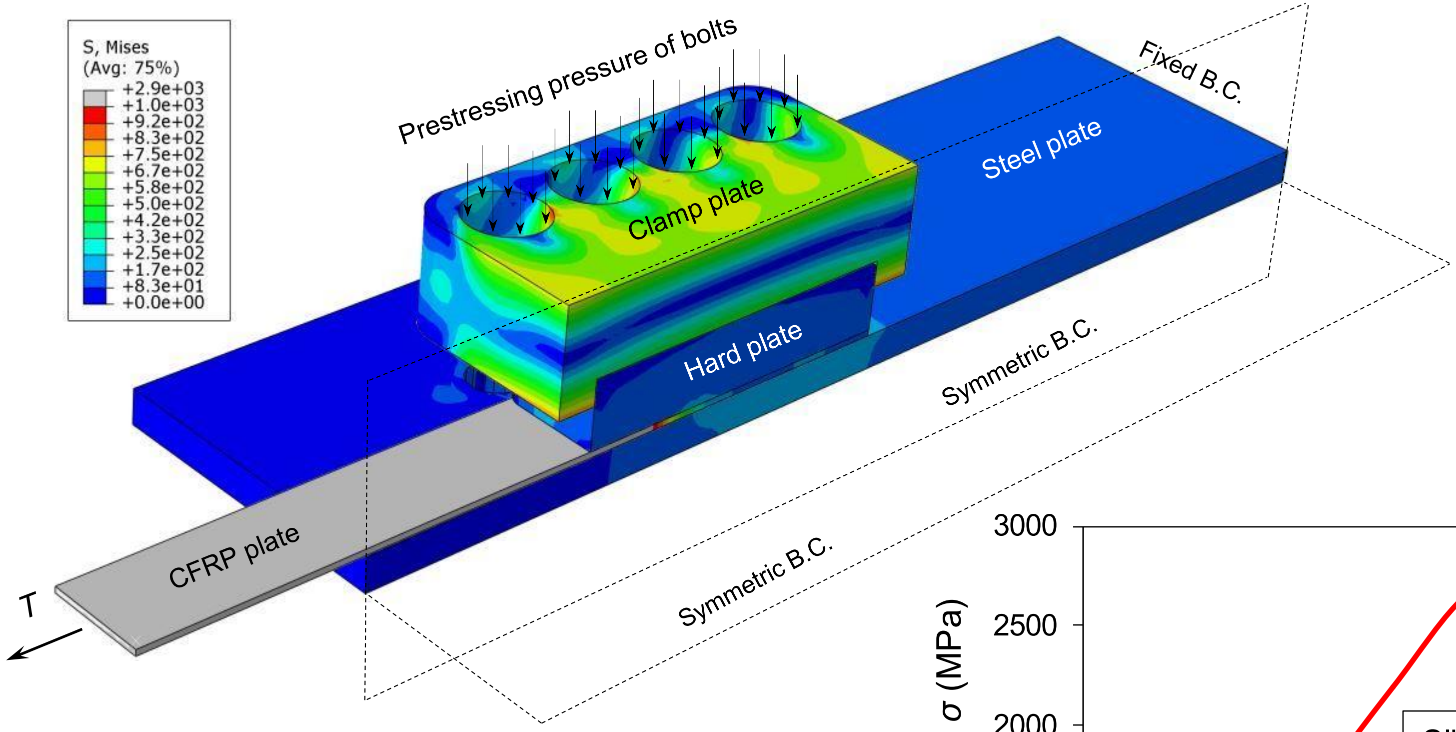
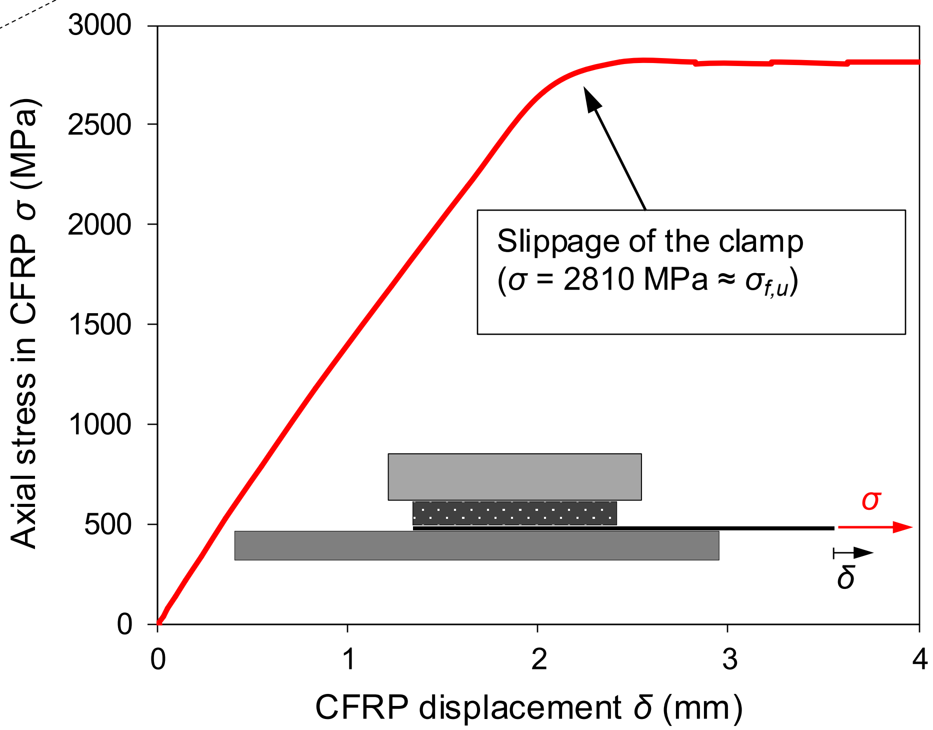
Mode I fatigue crack arrest – Prestressed unbonded retrofit (PUR)

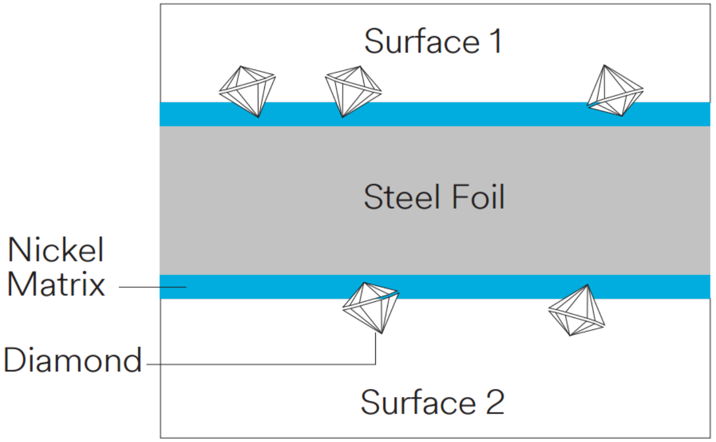


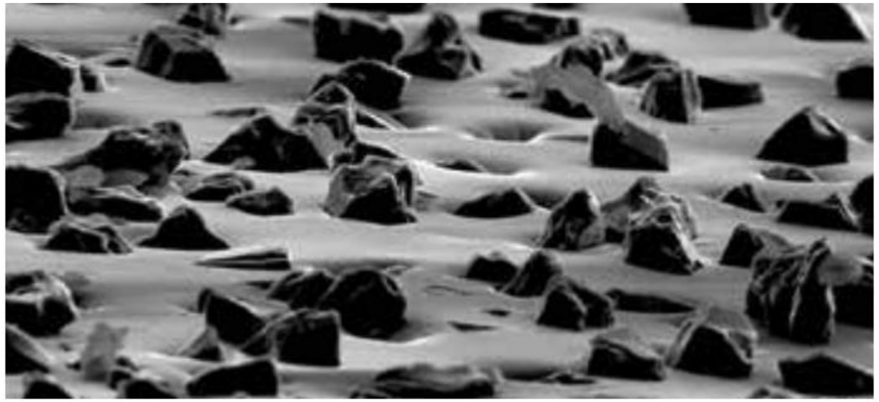


- Also round fillets with radius 2 mm in longitudinal direction
- Added diamond friction shims from 3M (resulting $\mu \geq 0.69$)

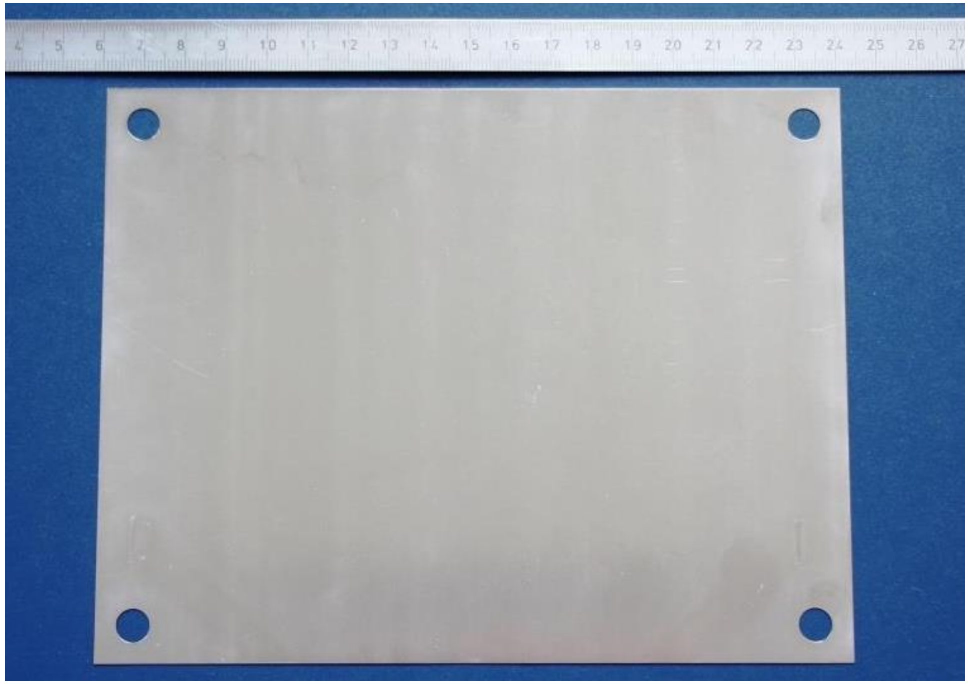
12.5 Diamond friction shims from 3M (resulting $\mu \geq 0.69$)

3M™ Friction Shim Diagram

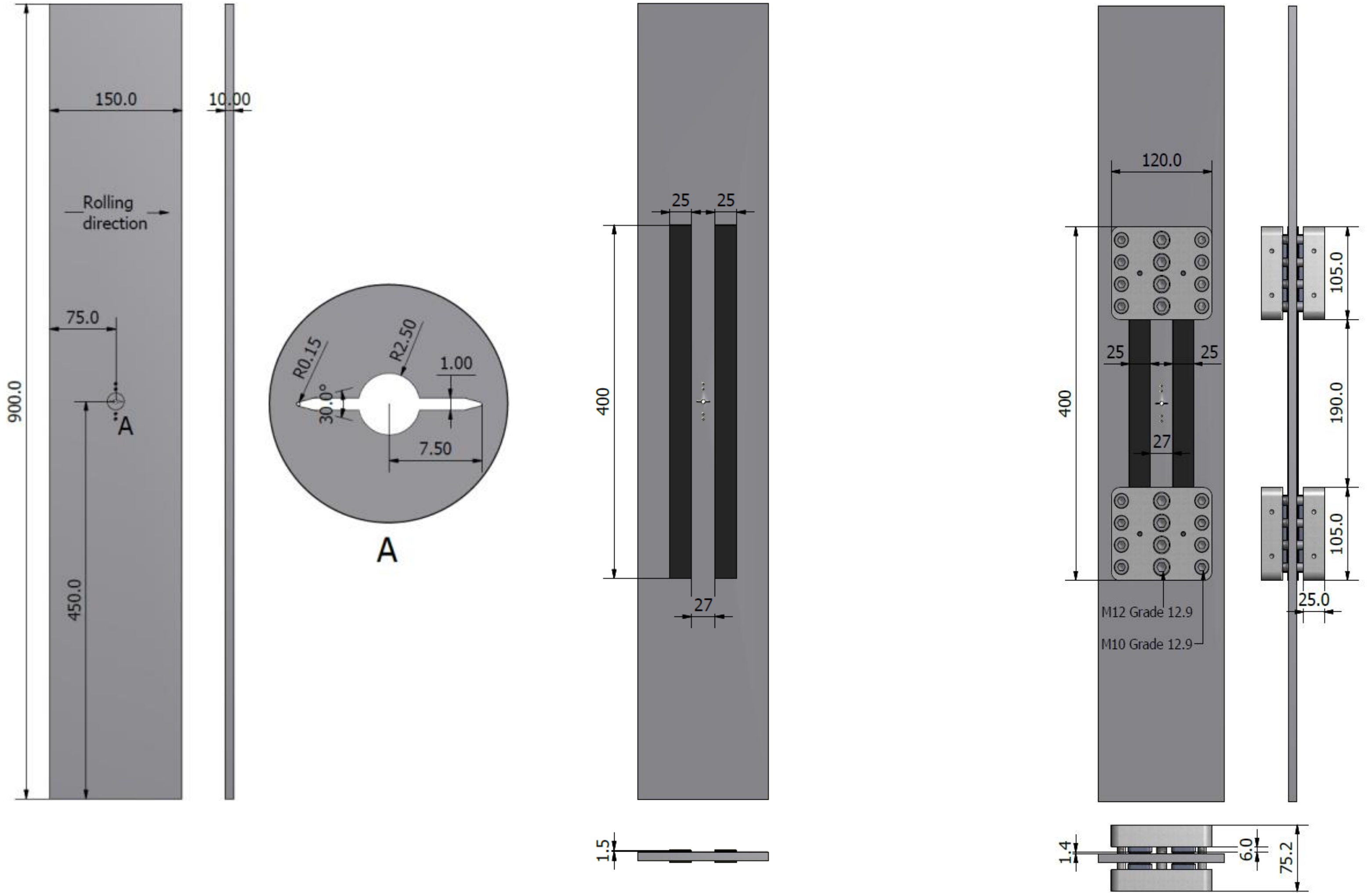




3M™ Friction Shims and SEM microphoto of nickel-diamond coating



Mode I fatigue crack arrest – Possible when using PUR system?



Reference

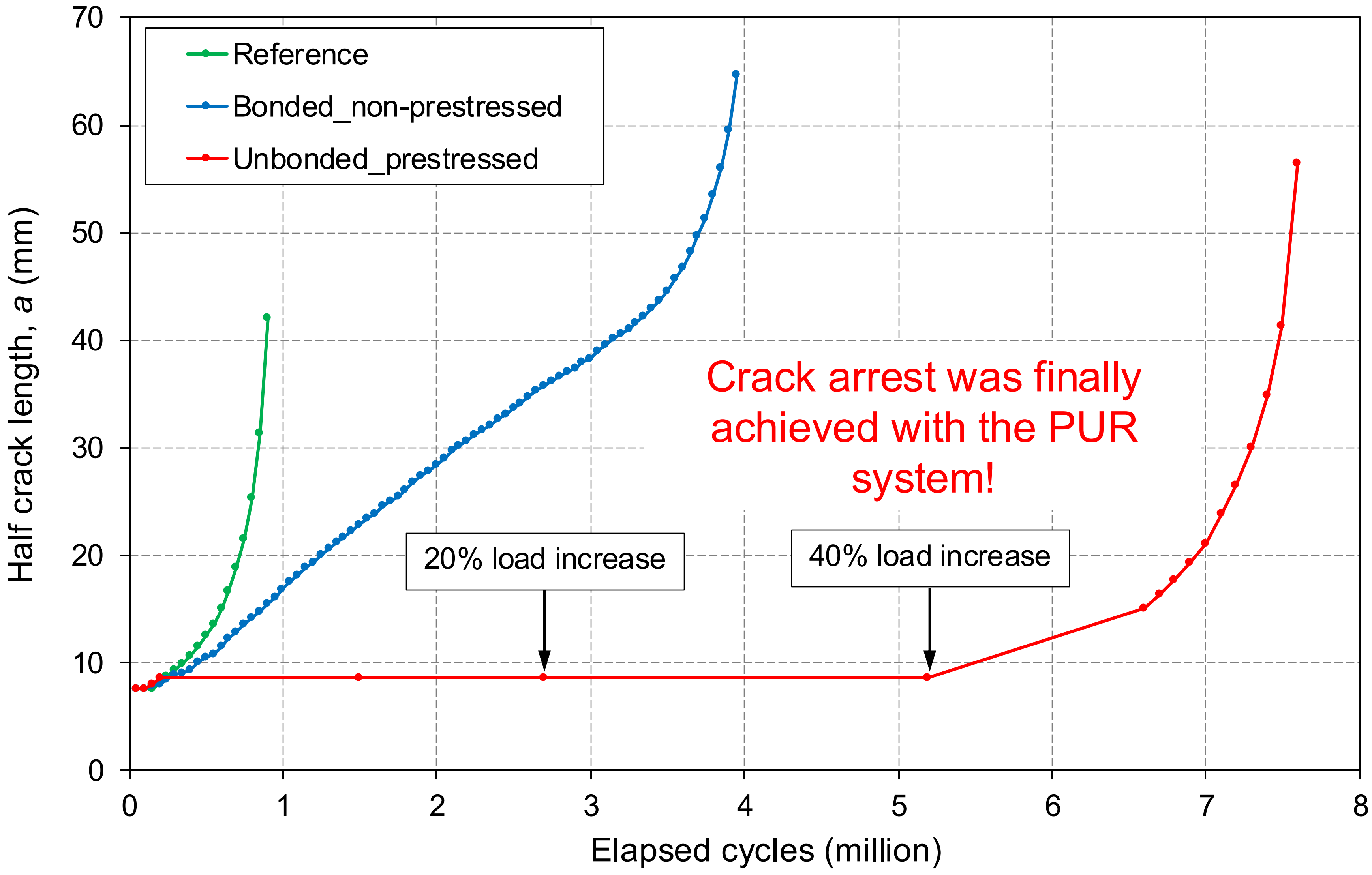
NPBR-UHM

PUR-NM

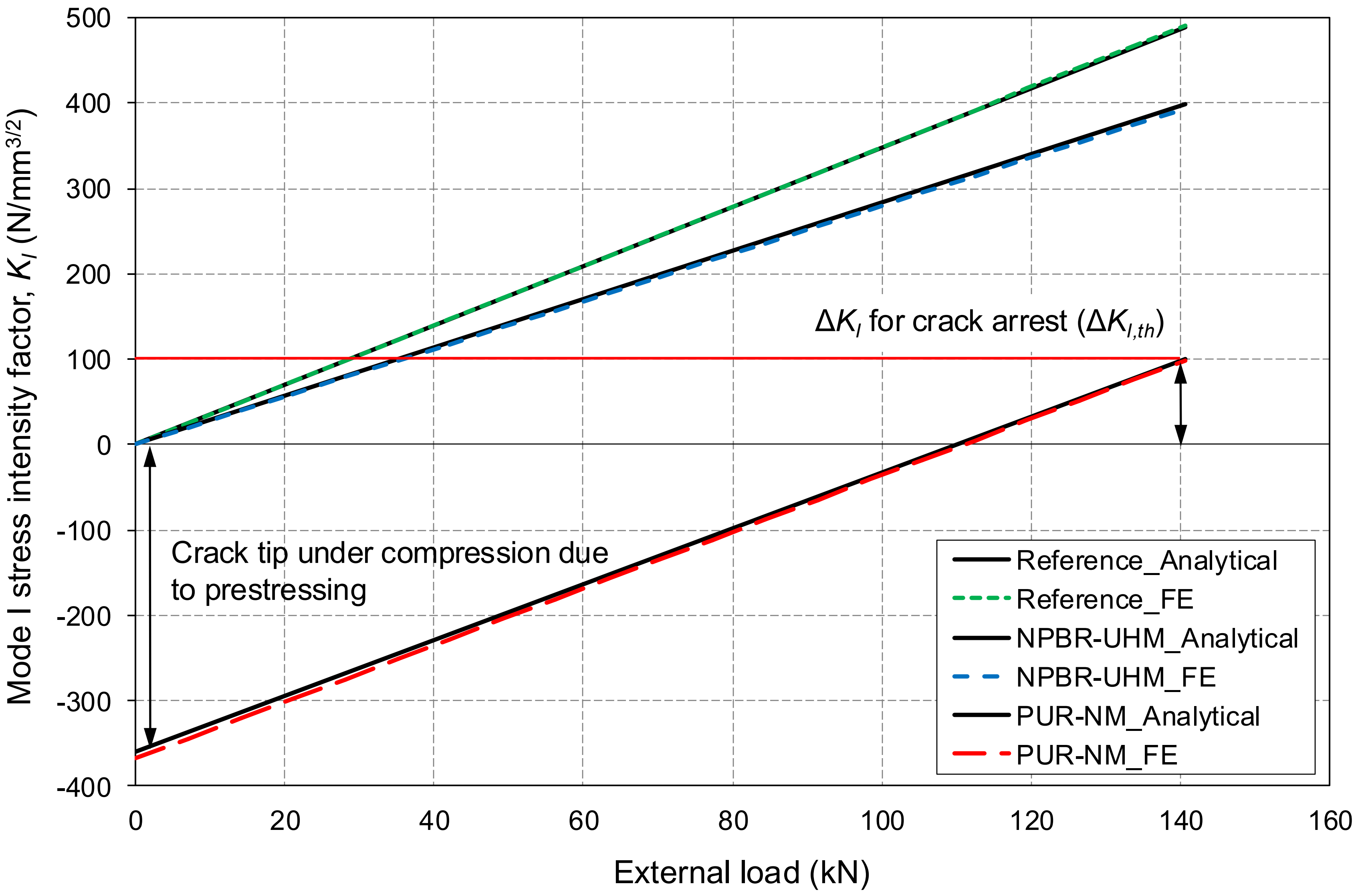
NM CFRP: S&P 150/2000 (E_f = 156 GPa; σ_u = 2905 MPa)

Anchorages tested up to 20,000,000 cycles (on specimens and beams)

Mode I fatigue crack arrest – Possible when using PUR system?



12.5 Mode I fatigue crack arrest – FE vs. analytical results

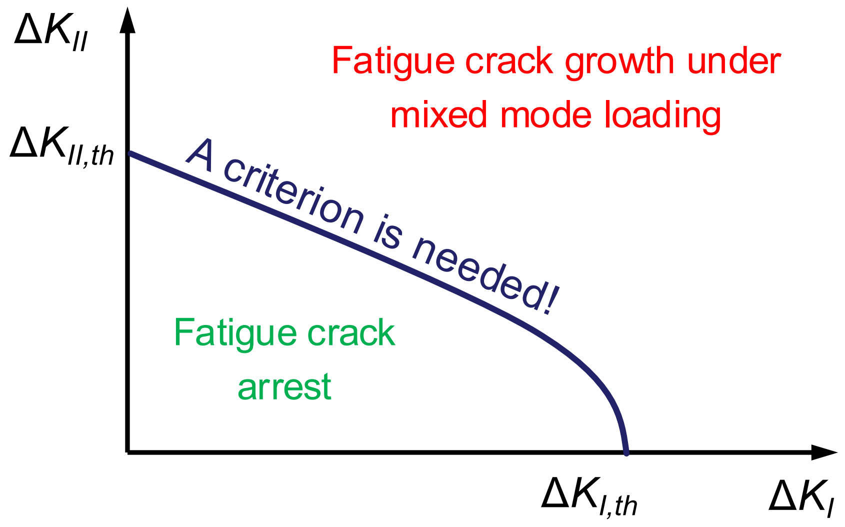


Mixed mode I/II fatigue crack arrest

- Mode I fatigue problem:

$$\Delta K_I \leq \Delta K_{I,th} \Rightarrow \text{Fatigue crack arrest}$$

- Mixed mode I/II fatigue problem:



Mixed mode I/II fatigue crack arrest – Background

Mixed mode I/II fatigue threshold for bare (unstrengthened) mild steel

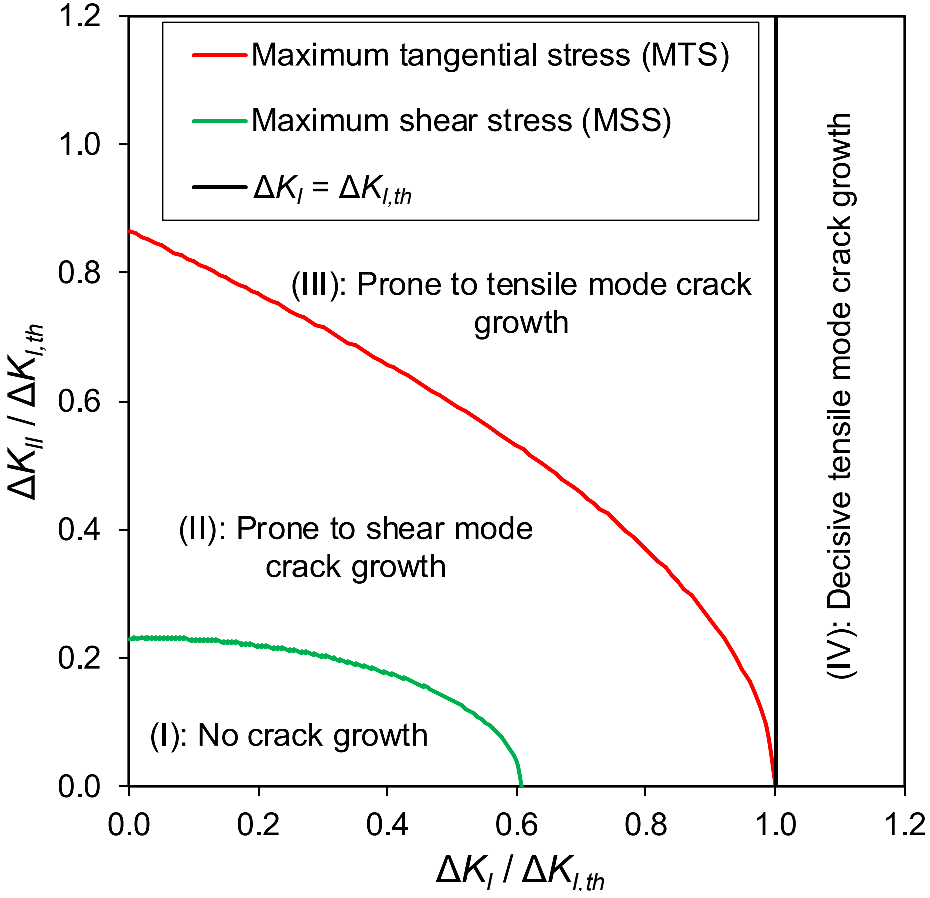
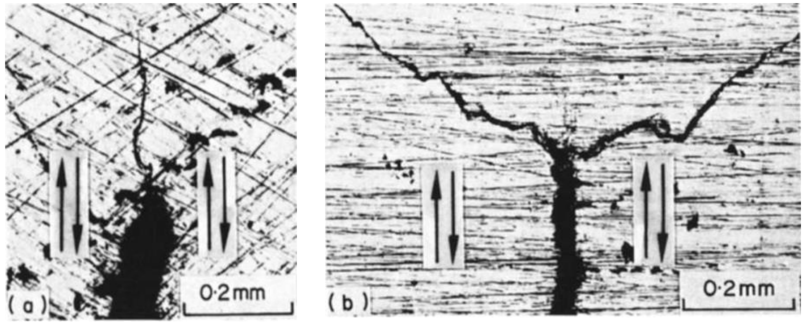


Diagram adopted from: Pook (1985)

Shear mode cracking

Tensile mode cracking



Photos from: Otsuka et al. (1975)

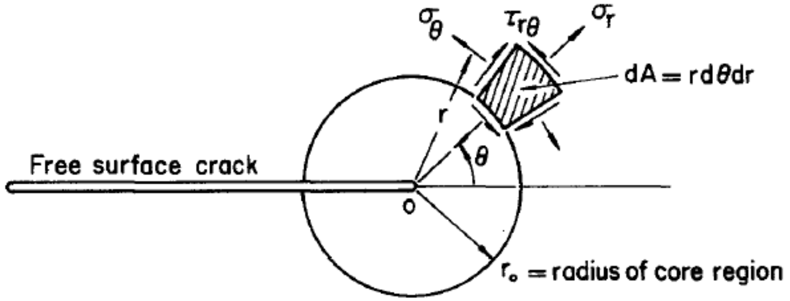


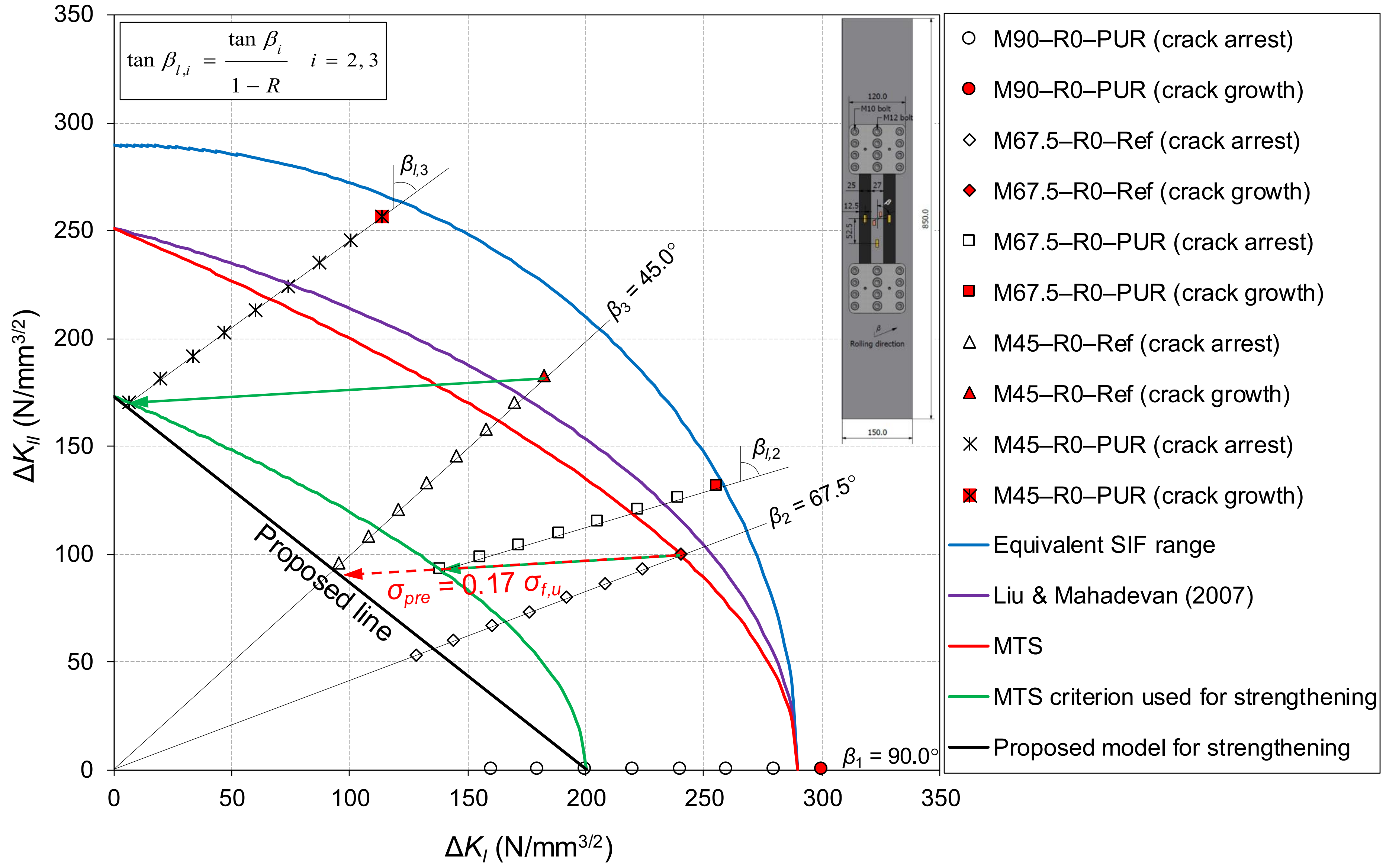
Photo from: Sih (1974)

For MTS criterion: $\Delta\sigma_\theta = \frac{1}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left[\Delta K_I \cos^2\frac{\theta}{2} - \frac{3}{2}\Delta K_{II} \sin\theta\right]$

For MSS criterion: $\Delta\tau_{r\theta} = \frac{1}{2\sqrt{2\pi r}} \cos\frac{\theta}{2}\left[\Delta K_I \sin\theta + \Delta K_{II}(3\cos\theta - 1)\right]$

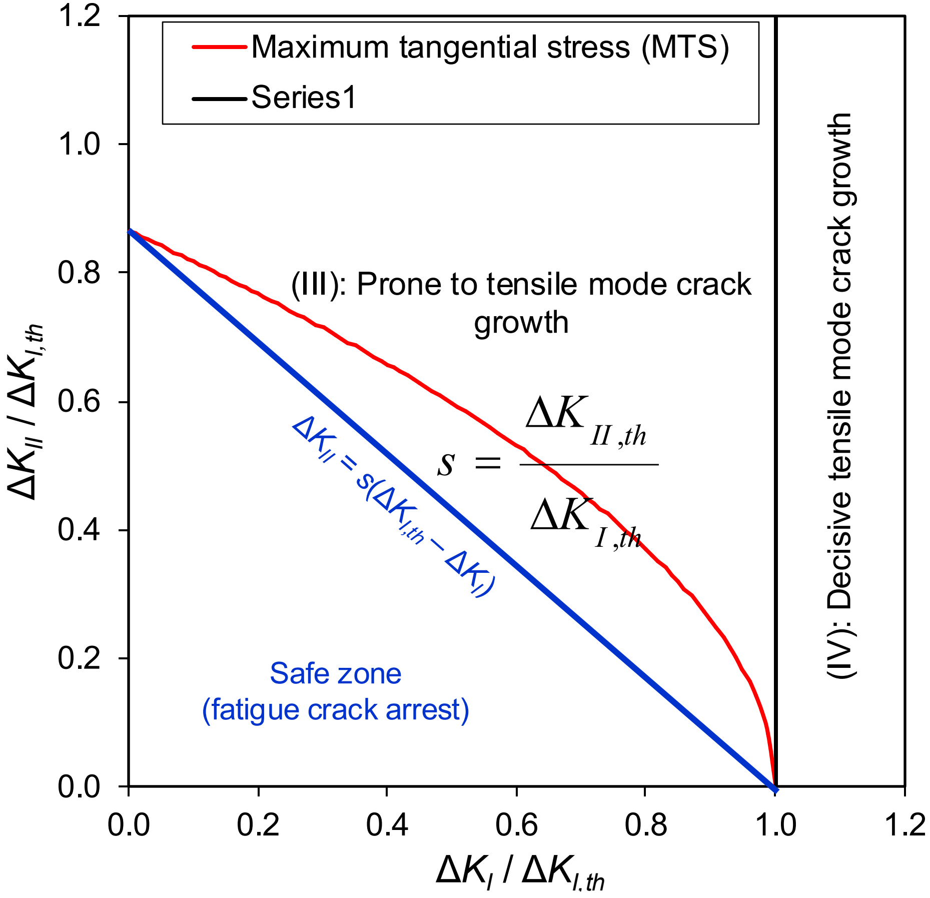
Pook (1985): MTS can be used for engineering applications.

Mixed mode I/II fatigue crack arrest – Experimental results



Mixed mode I/II fatigue crack arrest – Proposed criterion

After experimental verification, simplified linear criterion



Can write down the required prestressing level to stop the crack:

$$\sigma_{pre} = \frac{\sigma_{\max} A_s (R - R_r)}{A_f (1 - R_r)}$$

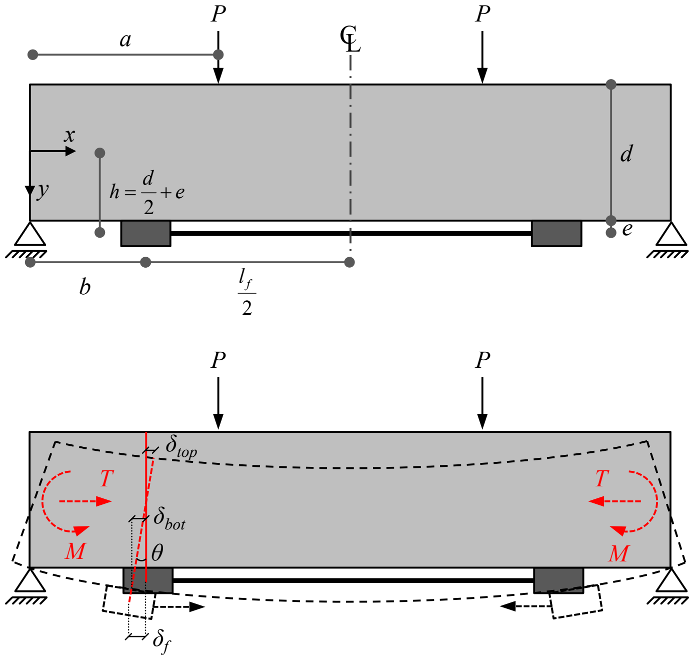
With:

$$R_r = \frac{\rho\sigma_{\min} - \sigma_c}{\rho\sigma_{\max} - \sigma_c}$$

$$\rho = \frac{A_s E_s}{A_s E_s + A_f E_f}$$

See annex for complete solution

FPUR System – Analytical modeling and experimental verification

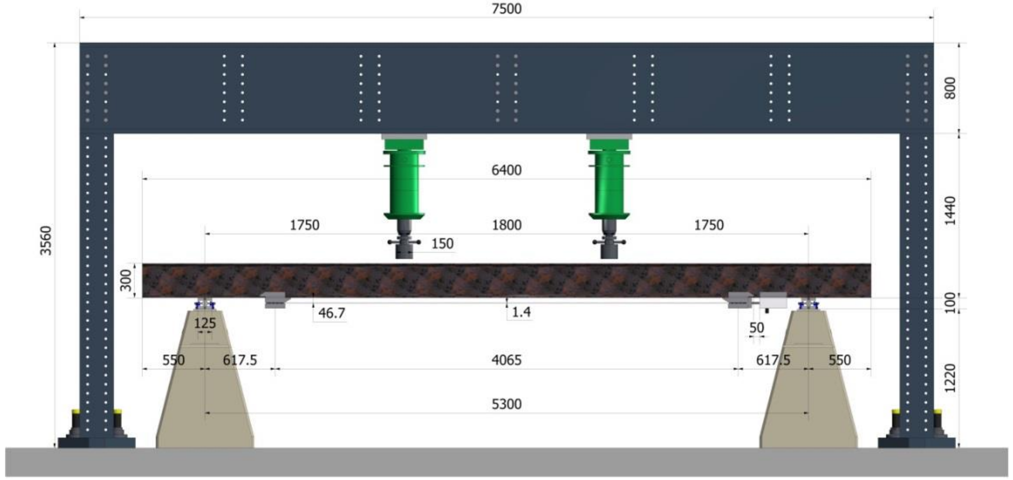


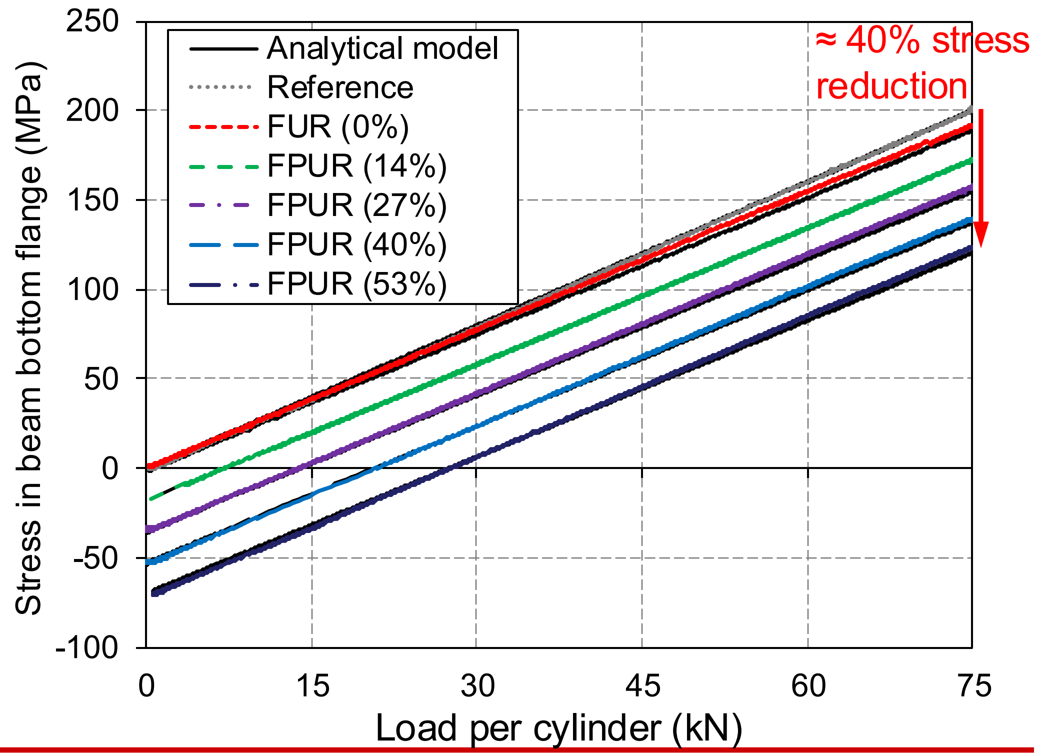
$$\sigma_{bot} = -\frac{T_f}{A_s} - \frac{(M_f - Pa)d}{2I_s}$$

$$\sigma_{top} = -\frac{T_f}{A_s} + \frac{(M_f - Pa)d}{2I_s}$$

$$T_f = T_{pre} + T$$

$$M_f = T_f h \qquad T = \frac{\frac{Ph}{E_s I_s l_f}\left[a l_f - (a-b)^2\right] + (\alpha_s - \alpha_f)\Delta T}{\frac{1}{E_f A_f} + \frac{1}{E_s A_s} + \frac{h^2}{E_s I_s}}$$





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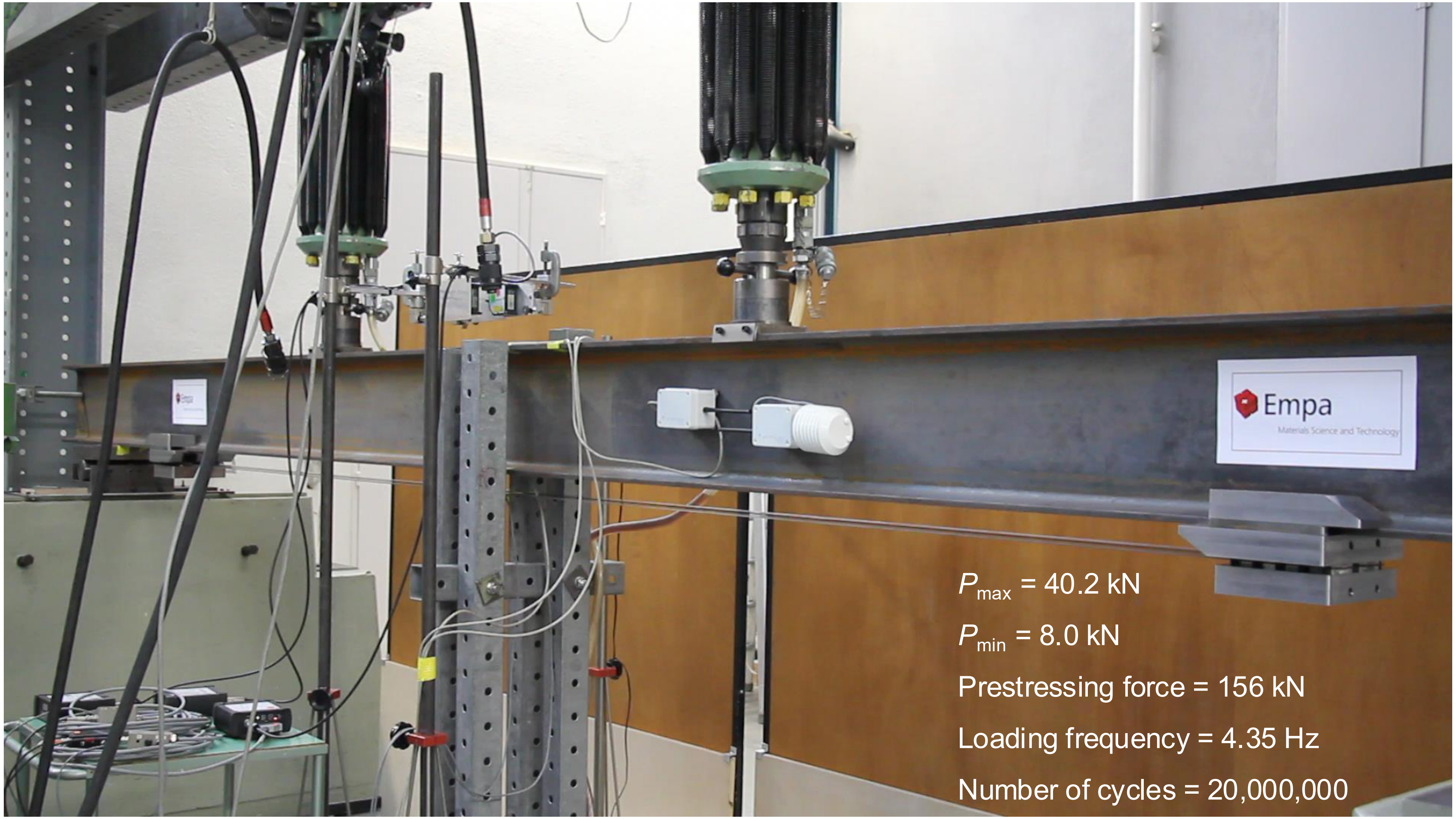
FPUR System – Fatigue performance



FPUR System – Field application

Diamond Creek roadway bridge, Victoria, Australia (year of construction: 1898)

Australian Government
Australian Research Council

Empa
Materials Science and Technology

SWINBURNE UNIVERSITY OF TECHNOLOGY

MONASH University

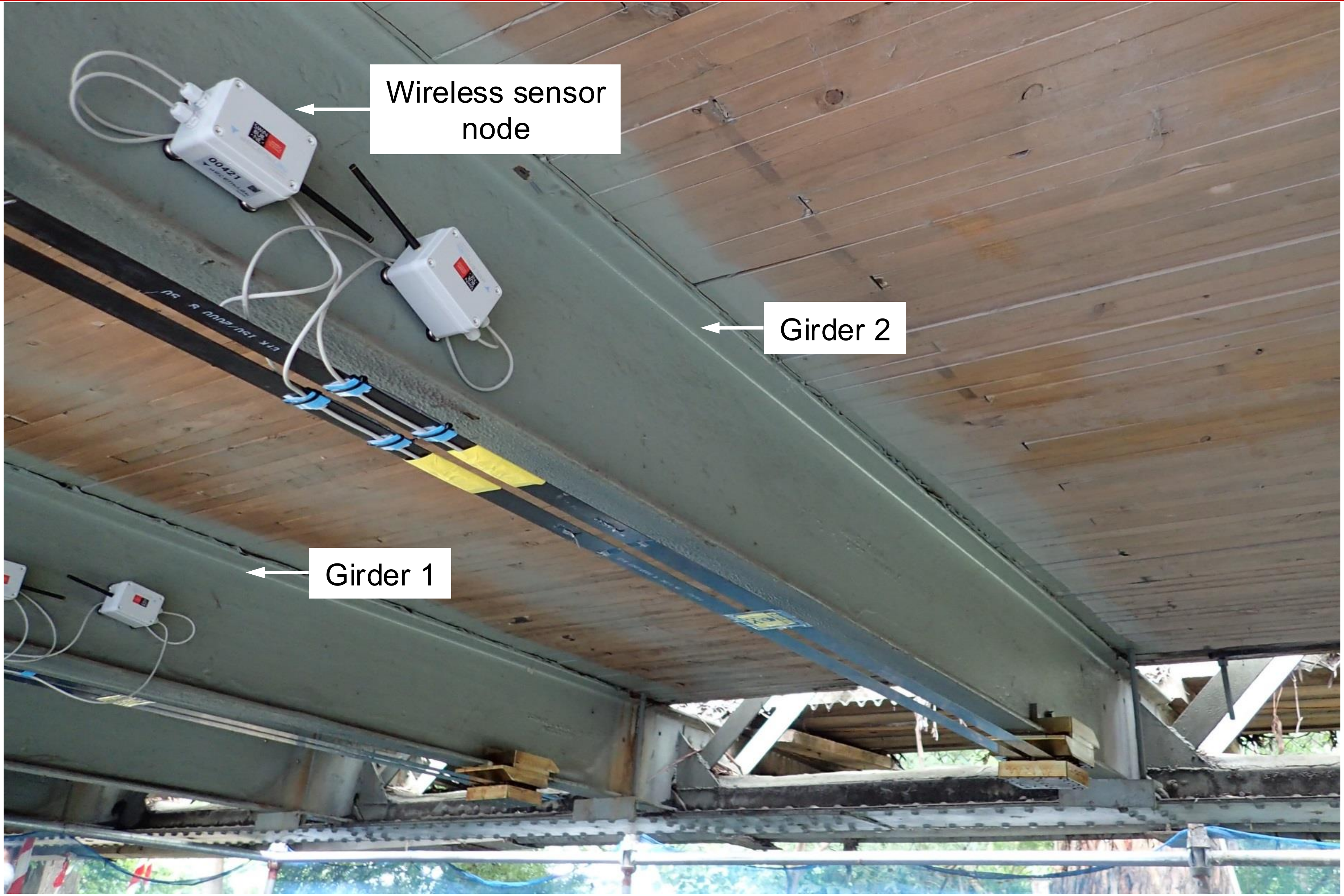
vicroads

S&P
A Simpson Strong-Tie® Company

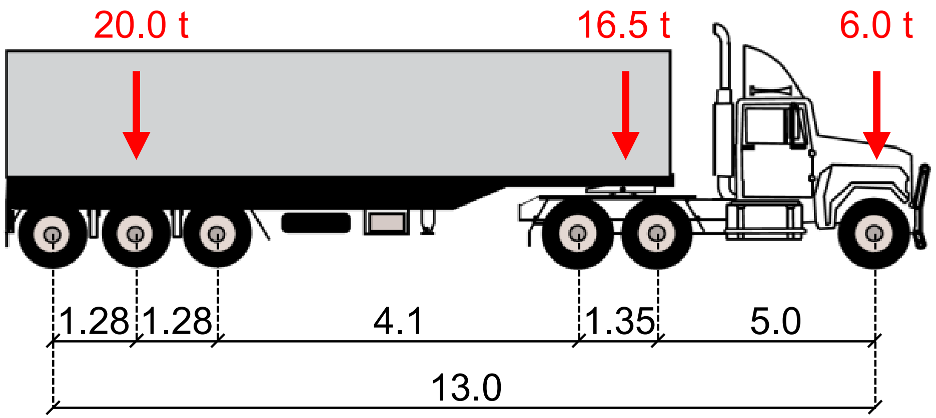
aeramix

SIMPSON Strong-Tie

FPUR System – Field application

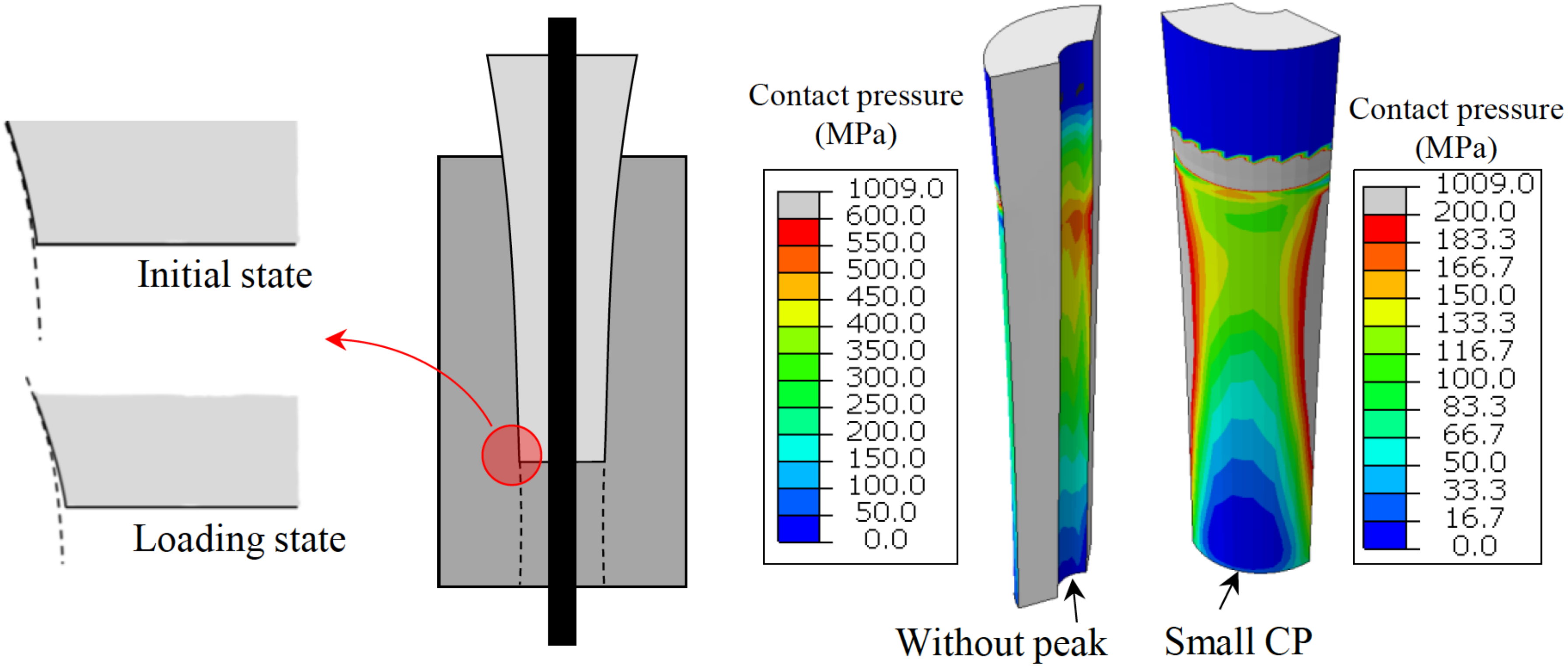


FPUR System – Field application

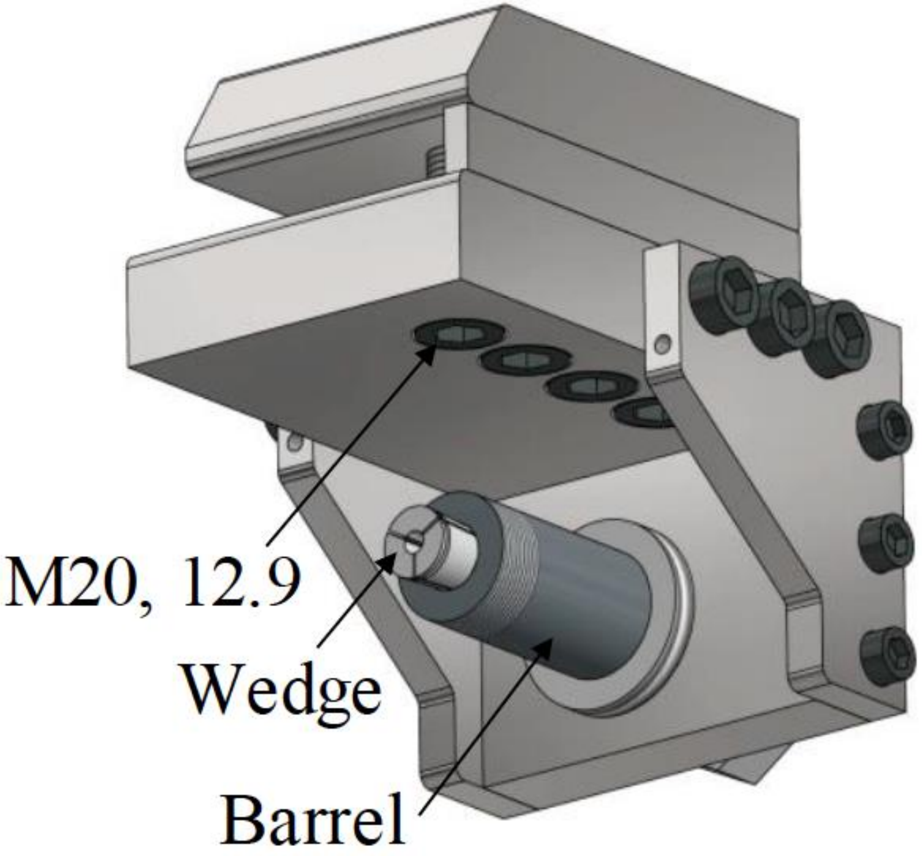


12.5 Other example: Development of mechanical wedge–barrel anchors for CFRP rods

Effect of curved profile on differential angle, on contact pressure



12.5 Other example: Development of mechanical wedge–barrel anchors for CFRP rods



12.6 Acknowledgements

- The material presented contains information from
  - Documents from E. Brühwiler (course CIVIL-436 – edition 2020)
  - Thesis works from Ardalan Hosseini, Hossein Heydarinouri, and E. Ghafoori (incl. colleagues M. Motavalli, X.L. Zhao, R. Al-Mahaidi, G. Terrasi)
    - Empa, Dübendorf, Switzerland
    - Swinburne University of Technology, Australia
    - The Hong Kong Polytechnic Univ.
- The teachers gratefully acknowledge the sharing of material

12.6 References

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[2] J.-A. Calgaro, R. Lacroix, *Maintenance et réparation des ponts*, 1997.

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[4] B. Adey, J. de Castro, E. Brühwiler, *Carbon fibre shear strengthening of rectangular concrete beams*, 1998.

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[7] M. Deuring, W. Steiner, *Verstärkungen durch CFK-Lamellen, SIA n044*, 1996.

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[10] Norme SIA 166: Armatures collées. SIA Zurich, 2004.Exercise 13: building or bridge? reinforcement with glued CFRP lamellas

[11] Hosseini, A., Ghafoori, E., Motavalli, M., Nussbaumer, A., Zhao, X.L., Al-Mahaidi, R. and Terrasi, G., 2019. Development of prestressed unbonded and bonded CFRP strengthening solutions for tensile metallic members. *Engineering Structures*, 181, pp.550-561

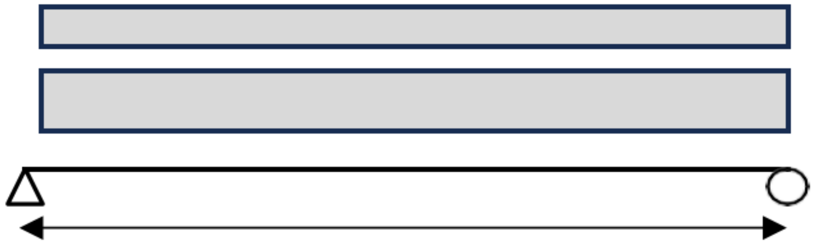
[12] Hosseini, A., Nussbaumer, A., Motavalli, M., Zhao, X.L. and Ghafoori, E., 2019. Mixed mode I/II fatigue crack arrest in steel members using prestressed CFRP reinforcement. *International Journal of Fatigue*, 129, pp 345-361

Exercise 12

- Reinforced concrete office building from the 1960’s, 18 m high, which is changing use
- The owner wants freedom in organizing the office spaces
- General exam shows part of one floor slab has insufficient resistance to bending, 9 x 8.5 m

- Aim of exercise is to check the structural safety of slab and design its external strengthening

- Relevant material properties (not all), dimensions (nominal) and actions on the slab are given

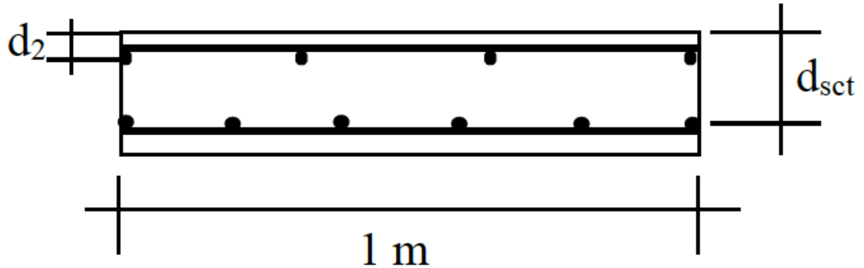


q_k = 5 kN/m (service load)

g_k = 6.5 kN/m (self-weight)

Slab span

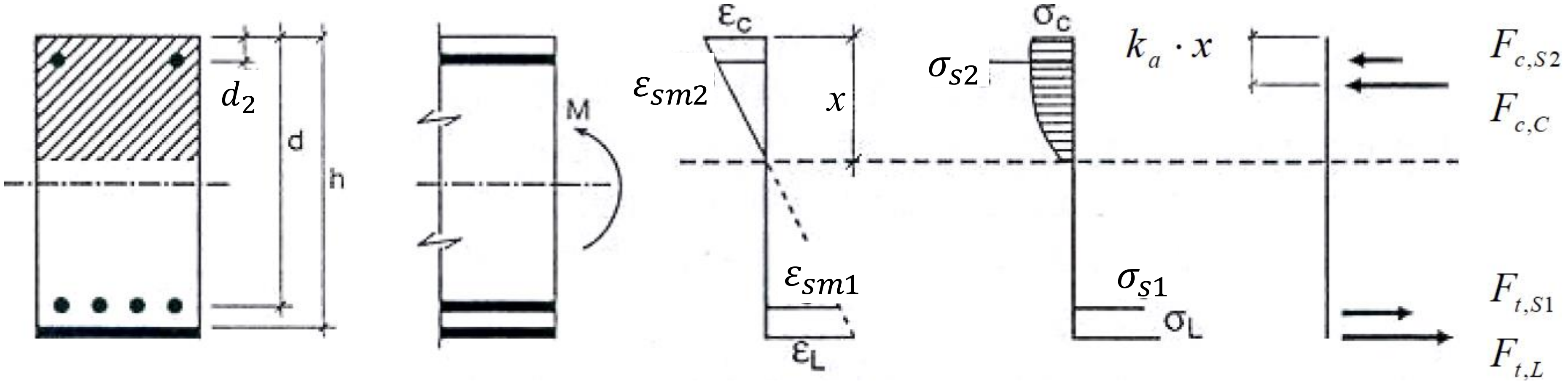
- Cross-section of the slab (of unit length 1 m):



h = 220 mm
d = 185 mm
d_2 = 34 mm
top 4ø8 : A_{S2} = 201 mm²
bottom 6ø14 : A_{S1} = 924 mm²

ANNEXES

12.3.1 Cross sectional analysis (2)



- Conditions of compatibility :
  - Concrete: $$\varepsilon_{cm} = \frac{\varepsilon_L}{h-x} x + \varepsilon_{c0}$$
  - Rebars layers: $$\varepsilon_{sm1} = \frac{\varepsilon_L}{h-x}(d-x) + \varepsilon_{s10}$$ $$\varepsilon_{sm2} = \frac{\varepsilon_{Ll}}{h-x}(x-d_2) + \varepsilon_{s20}$$
  - Laminates: $$\varepsilon_{Lm} = \varepsilon_{L0} + \varepsilon_L$$

Notes:

ε_{c0}, ε_{si0} Initial strains in concrete, each rebars layer

ε_{L0} Strain following prestressing in the lamina at time t = 0

12.3.1 Cross sectional analysis (3)

- Internal forces:
  - Tension in the laminates: $F_{t,L} = E_L \cdot A_L \cdot \varepsilon_L$
  - Tension in rebars layer 1 (bottom): $F_{t,S1} = E_s \cdot A_{S1} \cdot \varepsilon_{S1,\ \max}$
  - Compression in rebars layer 2 (top): $F_{c,S2} = E_s \cdot A_{S2} \cdot \varepsilon_{S2,\ \max}$
  - Compression in concrete (top): $F_{c,c} = \alpha_R \cdot b \cdot x \cdot f_c$
- Equilibrium conditions (of moments wrt $F_{c,c}$ position):

$$\sum N = 0 \qquad F_{t,L} + F_{t,S1} - F_{c,S2} - F_{c,c} = 0$$

$$\sum M = 0 \qquad M_R - F_{t,L}(h - k_a x) - F_{t,S1}(d - k_a x) - F_{c,S2}(k_a x - d_2) = 0$$

12.3.1 Cross sectional analysis (4)

- Internal forces in beam calculated as:

$\varepsilon_{cm} \leq 2‰:$

$$\alpha_R = \varepsilon_{cm}\left(\frac{6-\varepsilon_{cm}}{12}\right)$$

$$k_a = \frac{8-\varepsilon_{cm}}{4(6-\varepsilon_{cm})}$$

$\varepsilon_{cm} \geq 2‰:$

$$\alpha_R = \frac{3\varepsilon_{cm}-2}{3\varepsilon_{cm}}$$

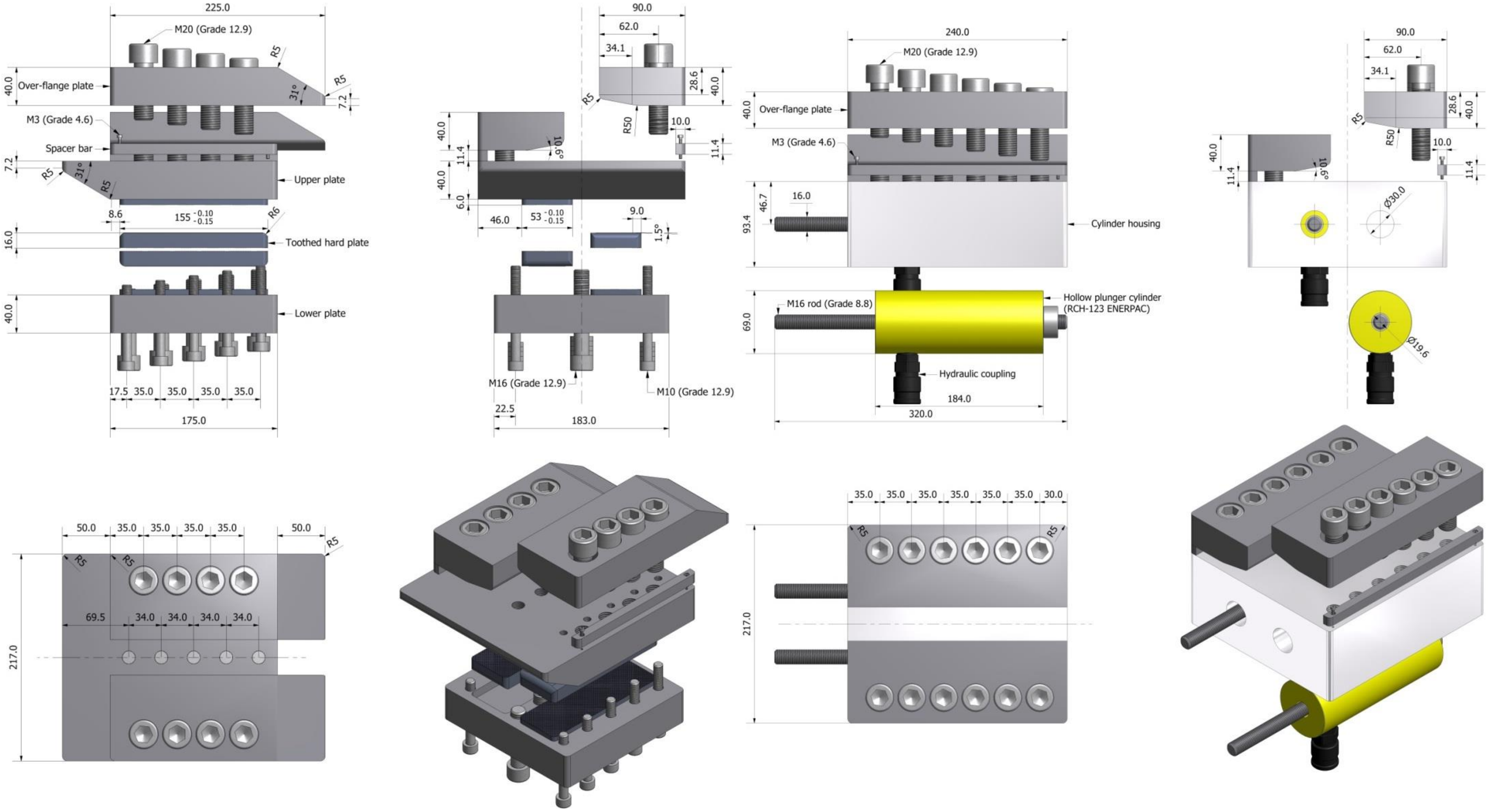
$$k_a = \frac{\varepsilon_{cm}(3\varepsilon_{cm}-4)+2}{2\varepsilon_{cm}(3\varepsilon_{cm}-2)}$$

α_R filling parameter

k_a position parameter.

- Neutral axis x determination: Iteratively
- Note: for slabs, in first approximation, one can use $\alpha_R = 0.8$
- Ultimate flexural moment: $M_R = F_{t,L}(h - k_a x) + F_{t,S1}(d - k_a x) - F_{c,S2}(k_a x - d_2)$
- Note: for slabs, in first approximation, one can use $k_a = \alpha_R/2 = 0.4$

Flat prestressed unbonded retrofit (FPUR) system – Development



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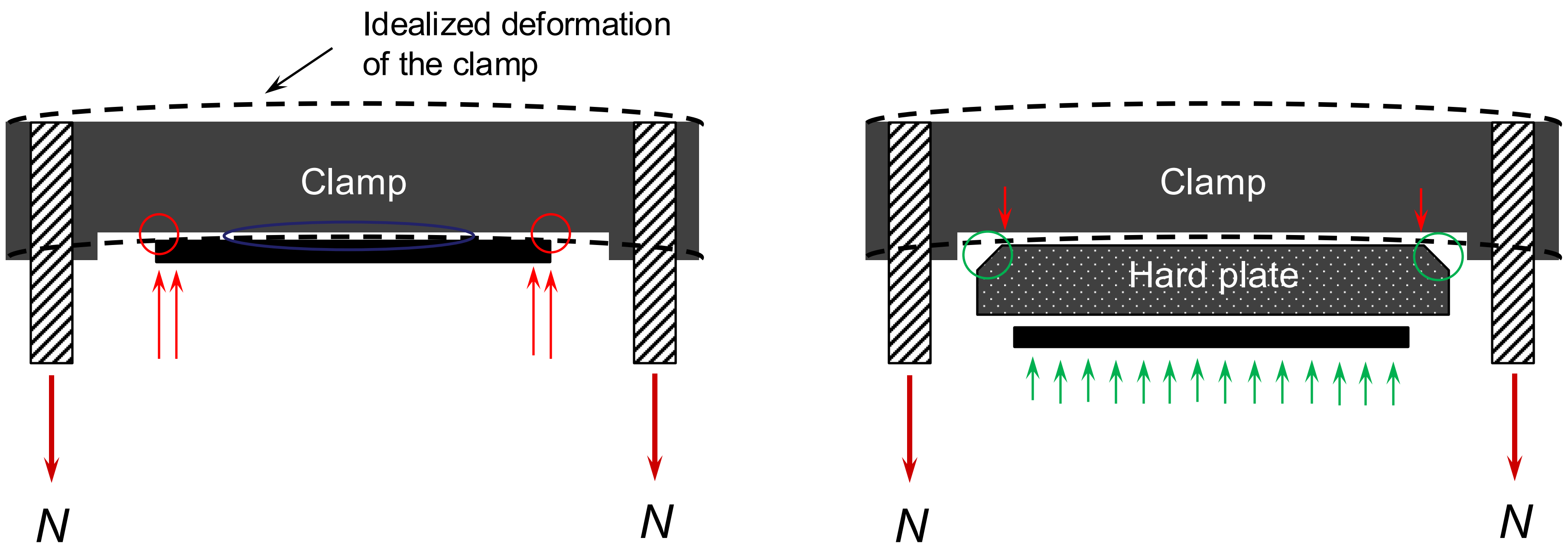
Prestressed unbonded retrofit (PUR)



12.5 Mixed mode I/II fatigue crack arrest – Analytical formulation

Based on linear elastic fracture mechanics (LEFM), we can write:

$$\Delta K_I = \Delta\sigma_y f(a,w) = \begin{cases} \rho\Delta\sigma \sin^2\beta f(a,w) & R_r > 0 \\ (\rho\sigma_{\max} - \sigma_c)\sin^2\beta f(a,w) & R_r \le 0 \end{cases}$$

$$\Delta K_{II} = \Delta\tau_{xy} f(a,w) = \rho\Delta\sigma \sin\beta\cos\beta f(a,w)$$

- For nonprestressed strengthening:

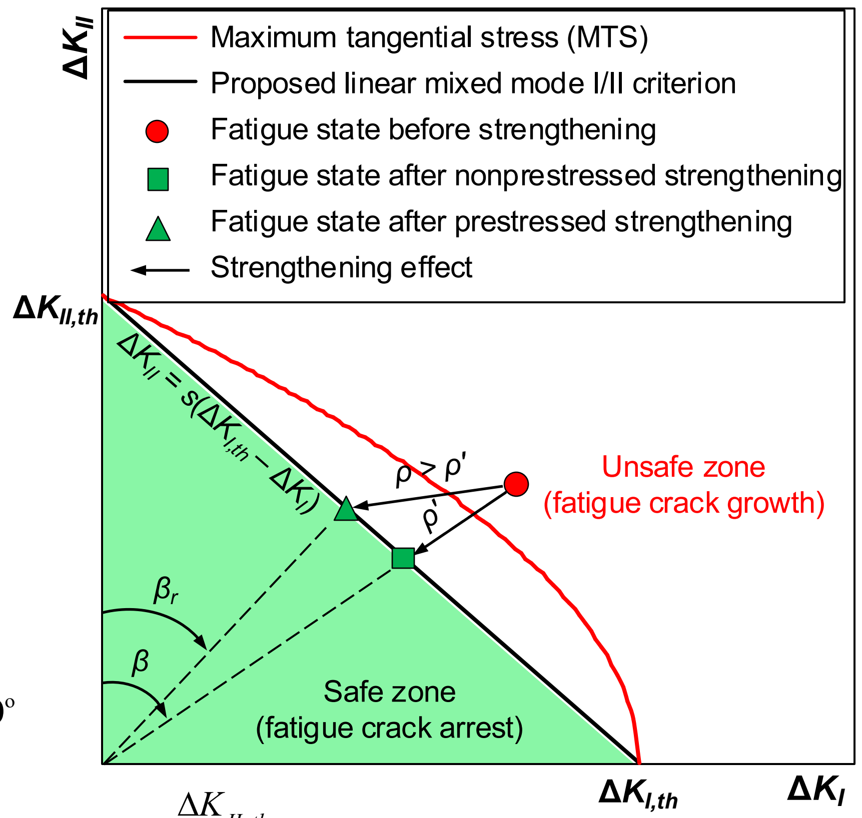
$$\rho = \frac{s\Delta K_{I,th}}{\sigma_{\max}\sin^2\beta f(a,w)(1-R)(s+\cot\beta)} \quad \text{for } R_r > 0,\ 0 < \beta \le 90^\circ$$

- For prestressed strengthening:

$$R_r = 1 + \frac{s\tan\beta}{\left[1 + \frac{s\Delta K_{I,th}}{(R-1)\rho\sigma_{\max}\sin\beta\cos\beta f(a,w)}\right]} \quad \text{for } R_r \le 0,\ 0 < \beta \le 90^\circ$$

$$\sigma_{pre} = \frac{\sigma_{\max} A_s (R - R_r)}{A_f (1 - R_r)}$$

Or $\Delta K_{II,d} \le \Delta K_{II,th}(1 - \Delta K_{I,d}/\Delta K_{I,th})$

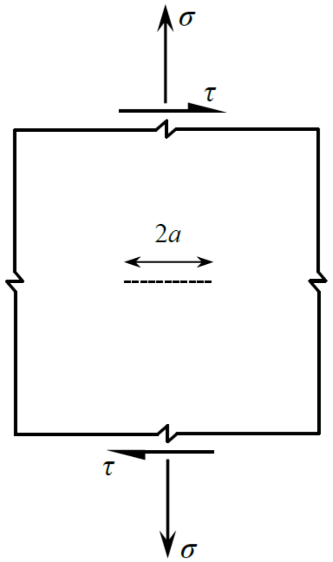


$$s = \frac{\Delta K_{II,th}}{\Delta K_{I,th}}$$

$$\tan\beta_r = \frac{\rho\sigma_{\max} - \sigma_c}{\rho(\sigma_{\max} - \sigma_{\min})}\tan\beta$$

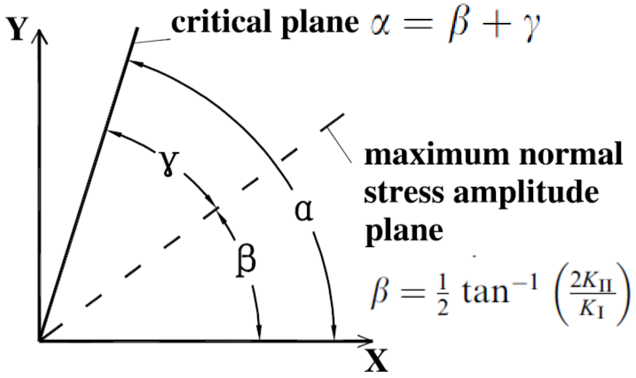
$$\rho = \frac{A_s E_s}{A_s E_s + A_f E_f} \qquad R_r = \frac{\rho\sigma_{\min} - \sigma_c}{\rho\sigma_{\max} - \sigma_c}$$

Liu and Mahadevan's model



$$K_{\mathrm{I}} = \sigma\sqrt{\pi a}$$

$$K_{\mathrm{II}} = \tau\sqrt{\pi a}$$



$$\sqrt{\left(\frac{k_1}{K_{\mathrm{I,th}}}\right)^2 + \left(\frac{k_2}{K_{\mathrm{II,th}}}\right)^2 + A\left(\frac{k^H}{K_{\mathrm{I,th}}}\right)^2} = B$$

$$\begin{cases} k_1 = \frac{K_{\mathrm{I}}}{2}(1+\cos 2\alpha) + K_{\mathrm{II}}\sin 2\alpha \\ k_2 = -\frac{K_{\mathrm{I}}}{2}\sin 2\alpha + K_{\mathrm{II}}\cos 2a \\ k^{\mathrm{H}} = \frac{K_{\mathrm{I}}}{3} \end{cases}$$

Material parameters for fatigue limit criterion

Material property	$s = \frac{t_{-1}}{f_{-1}} \leqslant 1$	$s = \frac{t_{-1}}{f_{-1}} > 1$
γ	$\cos(2\gamma) = \frac{-2+\sqrt{4-4(1/s^2-3)(5-1/s^2-4s^2)}}{2(5-1/s^2-4s^2)}$	$\gamma = 0$
A	$A = 0$	$A = 9(s^2-1)$
B	$B = [\cos^2(2\gamma)s^2 + \sin^2(2\gamma)]^{\frac{1}{2}}$	$B = s$

From: Liu, Y. and Mahadevan, S., 2007. Threshold stress intensity factor and crack growth rate prediction under mixed-mode loading. Engineering fracture mechanics, 74(3), pp.332-345..