Strengthening of Metallic Members using CFRP Materials

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Outlines

- Introduction & Motivation
- Flexural Strengthening
- Lateral Torsional Buckling (LTB) Strengthening
- Fatigue Strengthening of Healthy Metallic Members
- Case Studies:
  - ✓ Fatigue Strengthening of Münchenstein Railway Bridge **Girders**
  - ✓ Fatigue Strengthening of Aabach Railway Bridge **Connections**

Introduction

Market

Europe

- 22% bridges are metallic
- 70% are older than 50 years

Switzerland

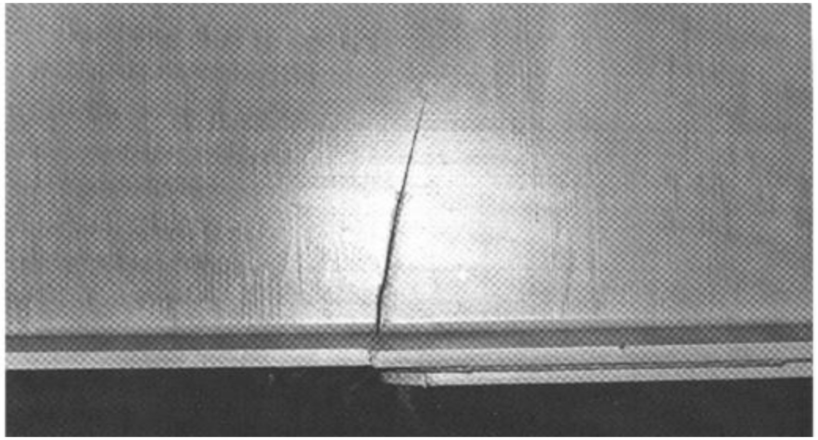
- Swiss Federal Railways (SBB) has 5’051 railway bridges
- 25% of bridges older than 80 years are metallic riveted

Problems in Metallic Bridges

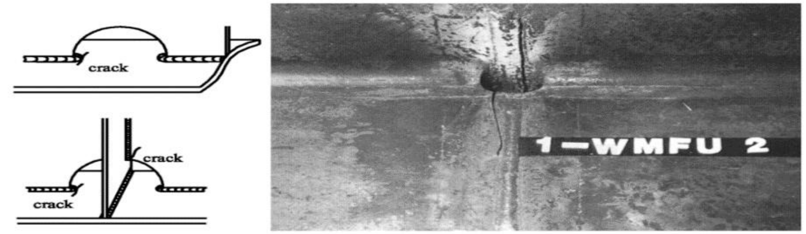
- Insufficient fatigue crack safety
- Need for upgrade to carry larger loads/traffic
- Most commonly used structural metals:
  Steel, wrought irons, cast irons

Chajes et al. „*Fracture: Field testing of the I-95 bridge.*“ In Third Annual Bridge Workshop: Fatigue and Fracture; Center of Innovative Bridge Engineering: Ames, IA,USA, 2004

Examples of fatigue cracked bridges



Kuehn et al. „*Assessment of Existing Steel Structures: Recommendations for Estimation of Remaining Fatigue Life*“*;* the Publications Office of the European Union: Luxembourg, 2008



Kuehn et al. „*Assessment of Existing Steel Structures: Recommendations for Estimation of Remaining Fatigue Life*“*;* the Publications Office of the European Union: Luxembourg, 2008

Fisher, J.W. *“Fatigue and Fracture in Steel Bridges”*; Wiley-Interscience: Hoboken, USA, 1984

Daniel Hoan Memorial Bridge, Milwaukee, Wisconsin, Failure on the 13th of December 2000

Examples of fatigue cracked bridges

Photos taken by Elyas Ghafoori, April. 2017

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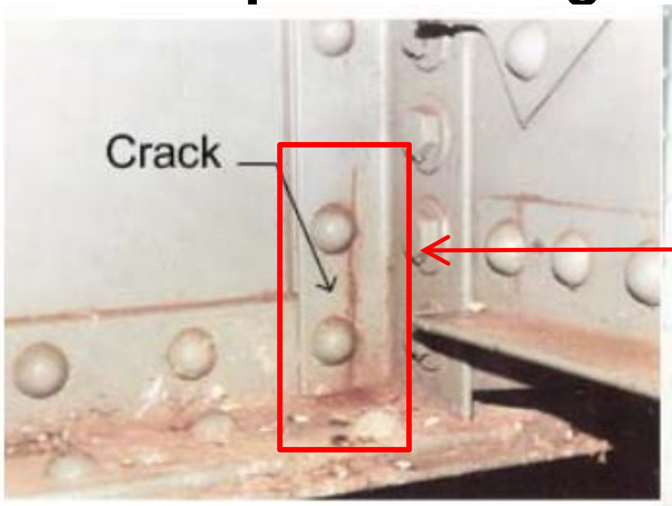
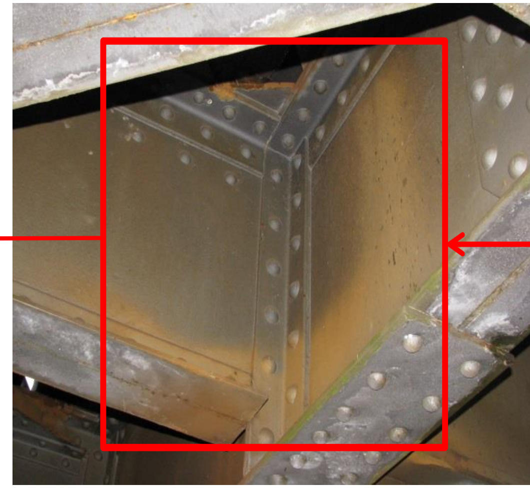
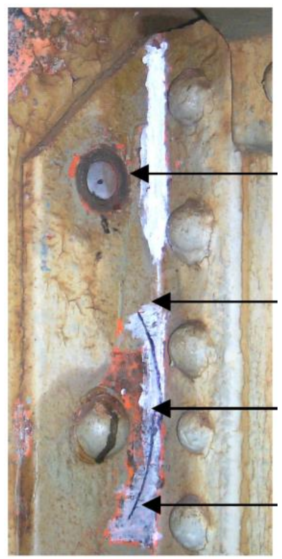
Examples of fatigue cracked bridges





Rivet failure: rivet head pop-out

Rivet failure: rivet head pop-out



Rivet failure: rivet head pop-out

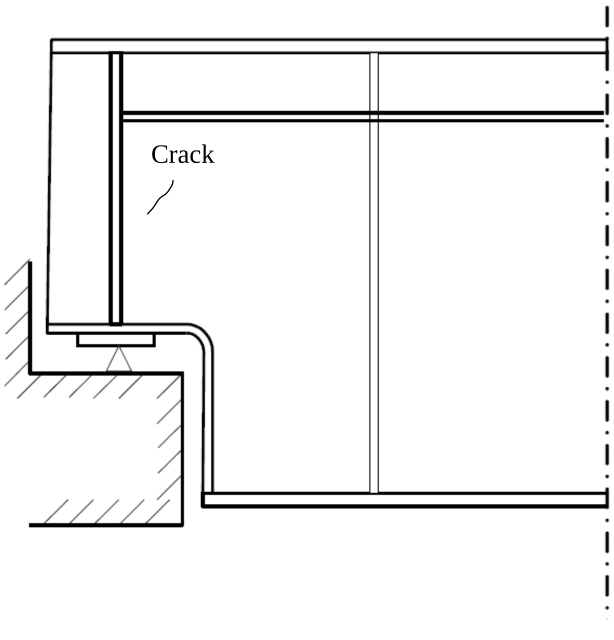
Crack propagation

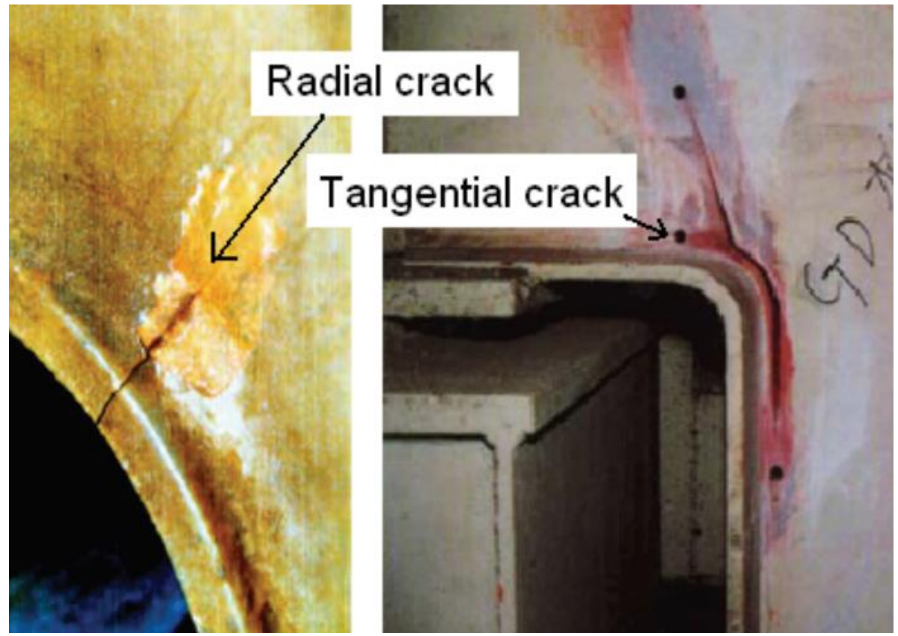
Crack initiation in the fillet

Crack propagation

Examples of fatigue cracked bridges

Typical fatigue cracks that can be found near supports of metallic girders (due to change of stiffness) in metallic bridges





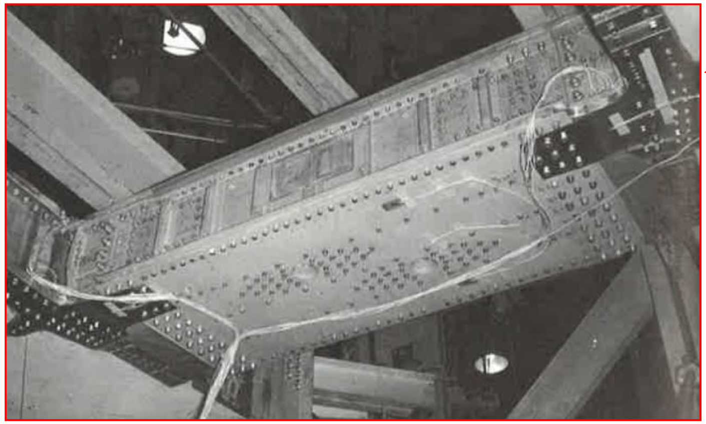
A metallic bridge in Sweden

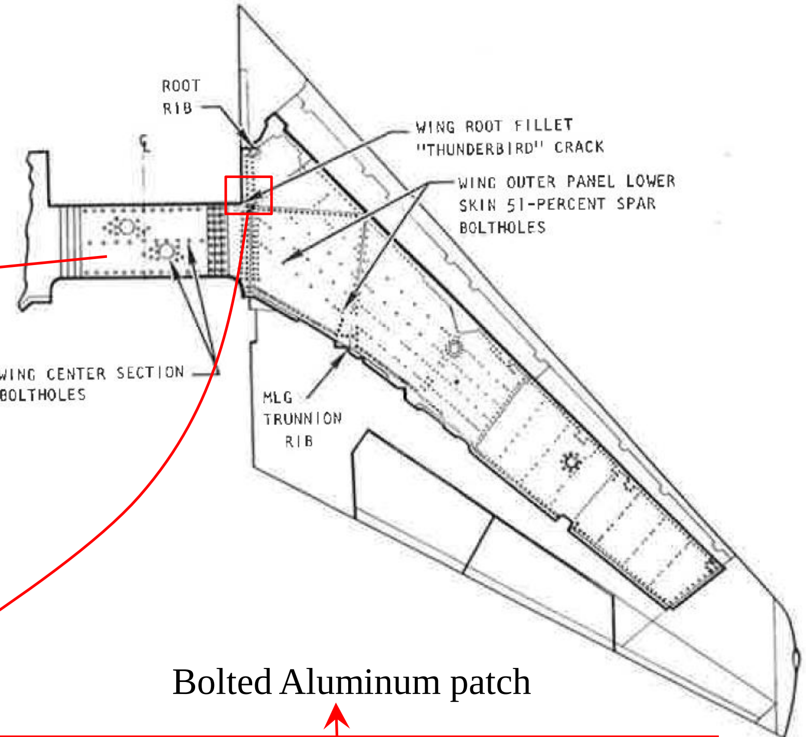
Ref. Buildings 2012, 2: p. 476-456)

Introduction

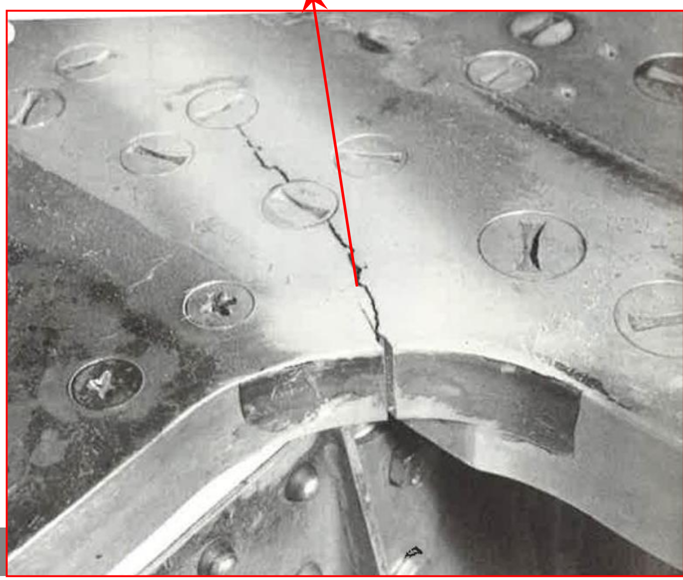
Retrofit of metallic aircrafts

Retrofit of F-100 wing structure



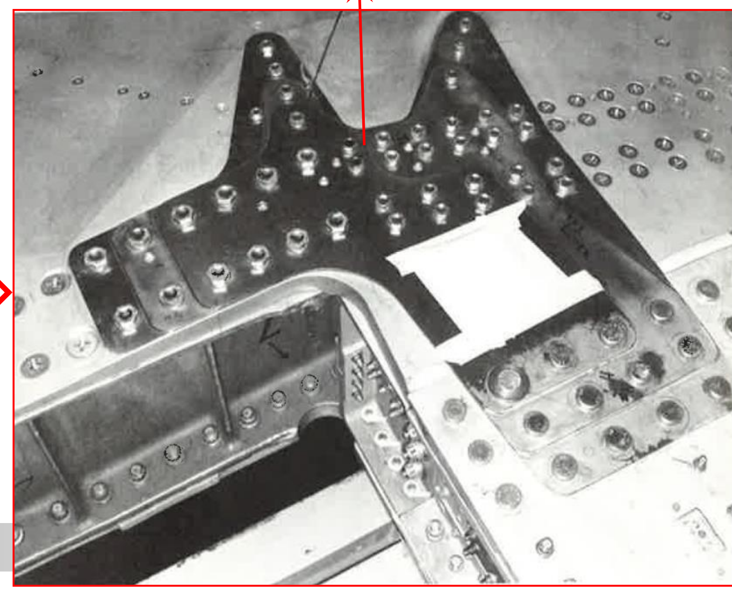


Fatigue crack in wing root fillet



Retrofit

Bolted Aluminum patch



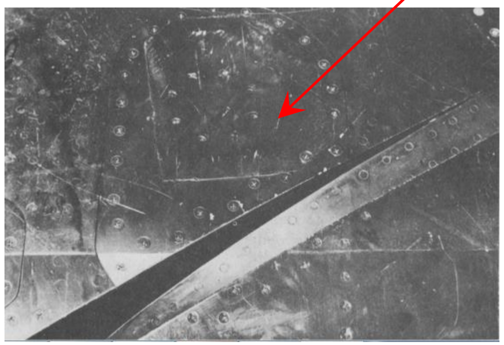
Baker, A.A., Repair of Cracked or Defective Metallic Aircraft Components with Advanced Fibre Composites: an Overview of Australian Work, Composite Structures 2 (1984) 153-181.

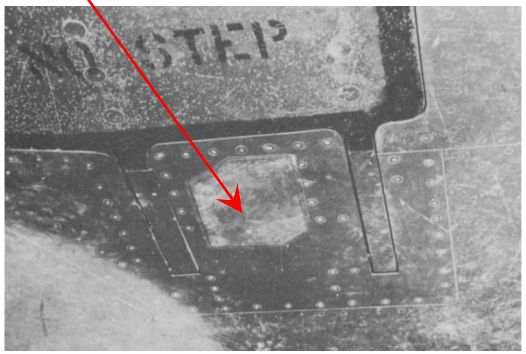
Introduction

Retrofitting of aircrafts with bonded composite materials

Cracking	Material	Component	Aircraft	Comments
Stress-corrosion	7075T6	Wing plank[a]	Hercules	Over 300 repairs since 1975
Fatigue	Mg Alloy MSR	Landing wheel[a]	Macchi	Life doubled, at least
Fatigue	AU4SG	Fin skin	Mirage	In service since 1978
Fatigue	AU4SG	Lower wing skin[ab]	Mirage	Over 150 repairs since 1979
Fatigue	2024T3	Upper wing skin	Nomad (fatigue test)	Over 105 900 simulated flying hours
Fatigue	2024T3	Door frame	Nomad (fatigue test)	Over 106 619 simulated flying hours
Stress-corrosion	7075T6	Console truss	F111	Service since 1980
Lightning burn	2024T3	Fuselage skin	Orion	Service since 1980[c]

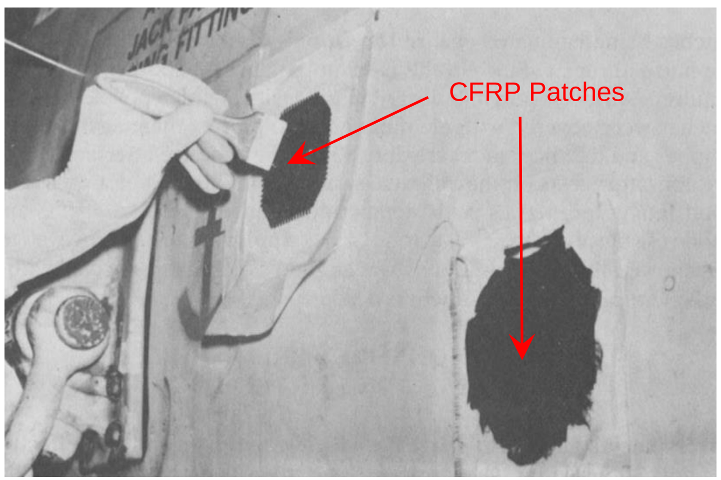
BFRP Patches





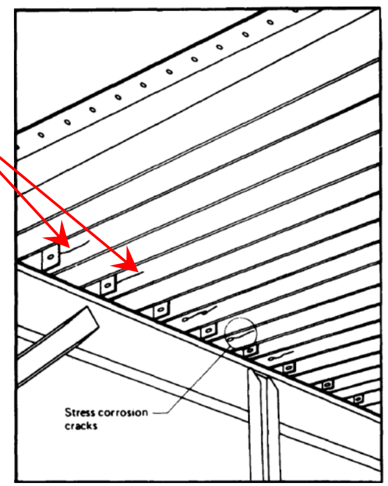
BFRP patch bonded to the wing skin of a Mirage aircraft

CFRP patch bonded to the fuselage of an Orion aircraft

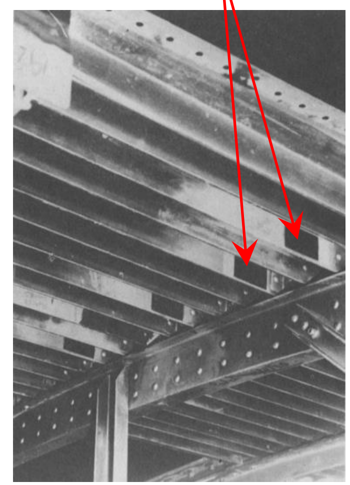


CFRP Patches

Cracks



CFRP Patches



Schematic view of the underside of a Hercules upper wing plank showing location of typical stress-corrosion cracks.

Baker, A.A., Repair of Cracked or Defective Metallic Aircraft Components with Advanced Fibre Composites: an Overview of Australian Work, Composite Structures 2 (1984) 153-181.

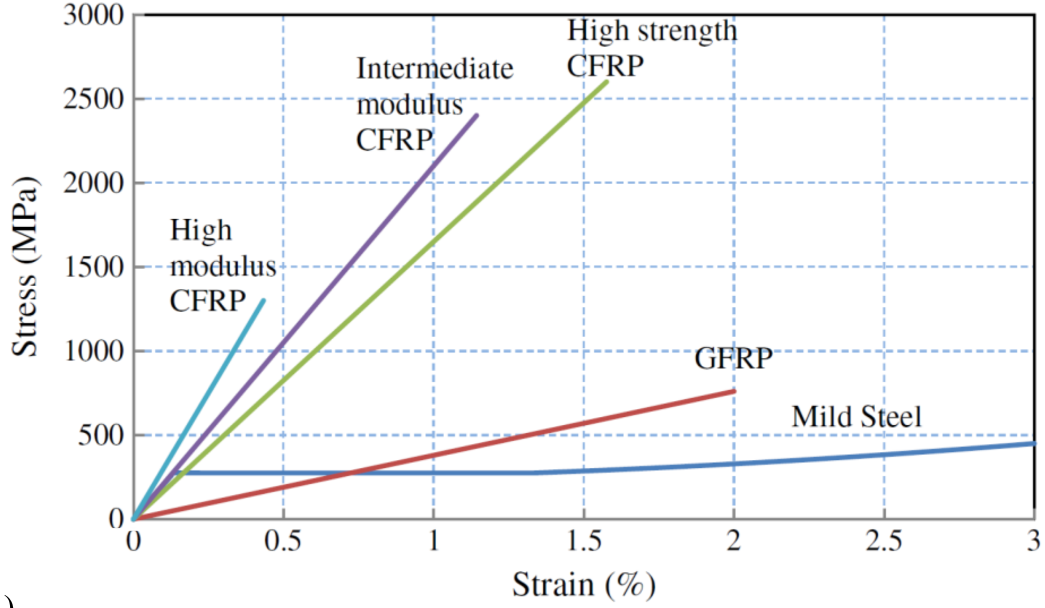
Introduction: Why CFRP Laminates?

Traditional Strengthening Solutions:
- Steel: heavy

CFRP:
- Excellent fatigue behavior
- High fatigue-to-weight ratio

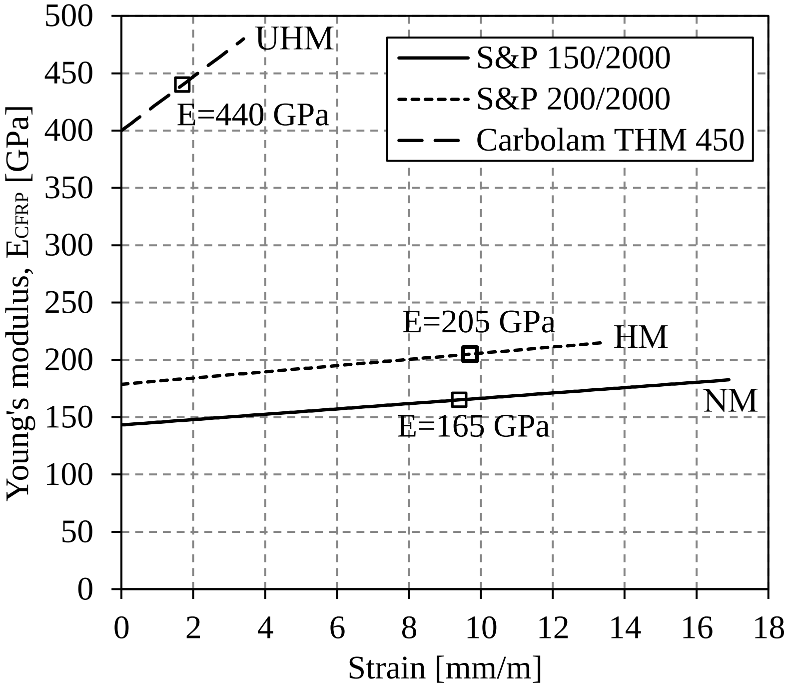
Classifications of the CFRP laminates according to their Young's modulus relative to that of steel:

Laminate type	Laminate modulus
Low modulus (LM)	< 100 GPa ($E_{CFRP} < 0.5\ E_{steel}$)
Normal modulus (NM)	100 –200 GPa ($0.5E_{steel} \leq E_{CFRP} < E_{steel}$)
High modulus (HM)	200–400 GPa ($E_{steel} \leq E_{CFRP} < 2E_{steel}$)
Ultra-high modulus (UHM)	≥400 GPa ($E_{CFRP} \geq 2\ E_{steel}$)

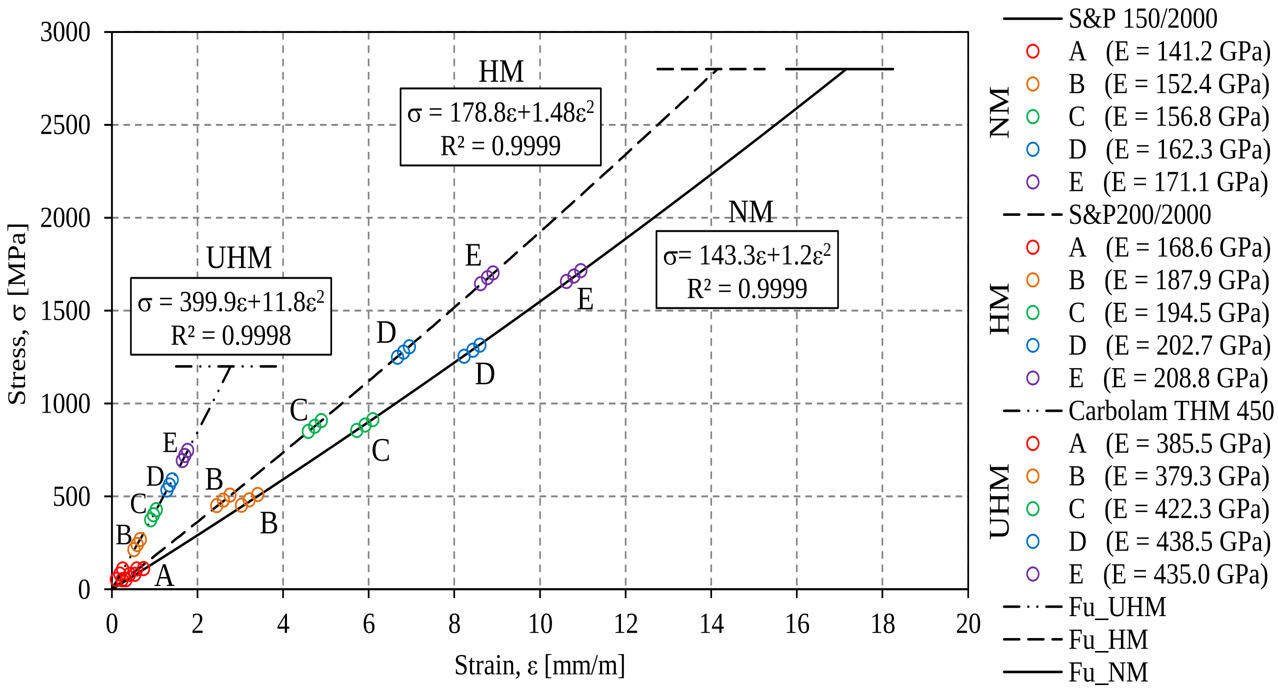


More details in: Ghafoori E., Motavalli M. Normal, high and ultra-high modulus CFRP laminates for bonded and un-bonded strengthening of steel beams. Materials and Design, 2015. 67: p. 232–243.

Introduction: Change in CFRP Young's Modulus



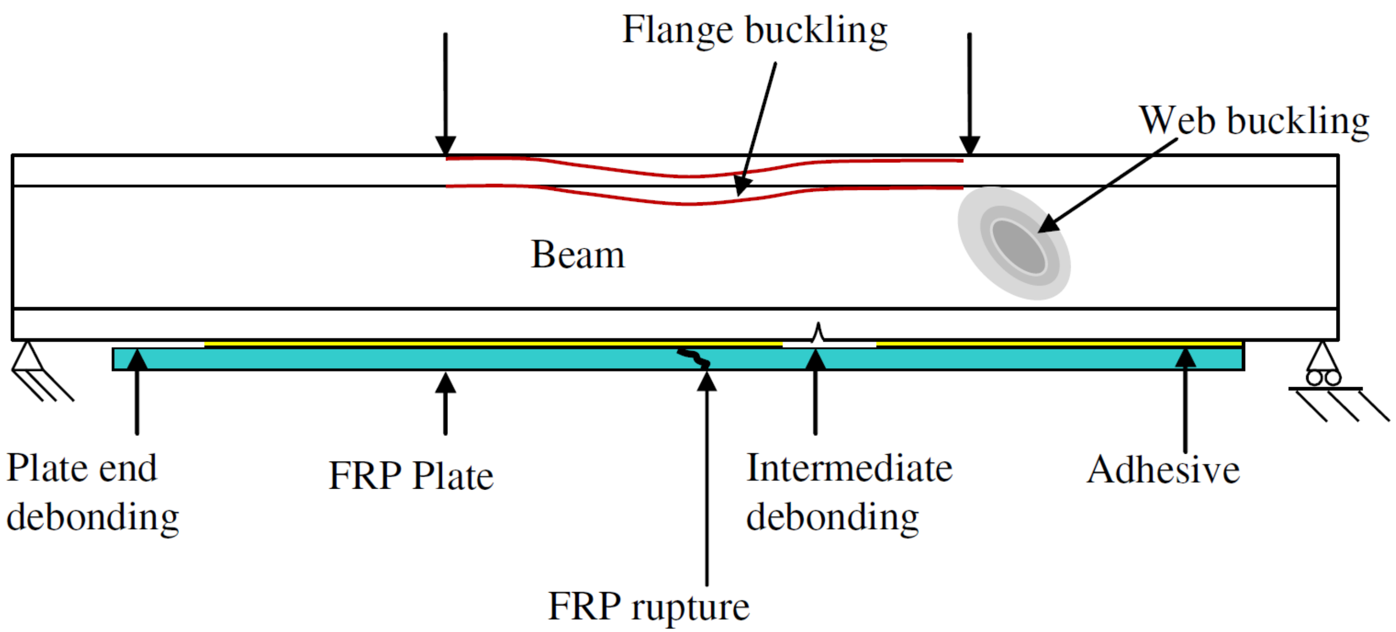
The measured Young's modulus of the NM, HM, and UHM CFRP laminates as a function of the applied strain. The square markers show the Young's moduli provided by the manufacturers.



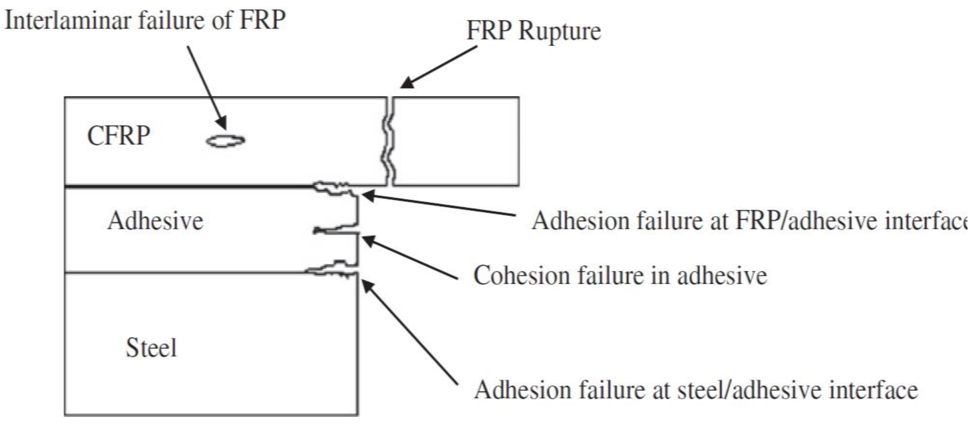
The measured Young's modulus for the NM, HM, and UHM CFRP laminates at different strain levels, indicating a non-linear elastic behavior for the CFRP laminates.

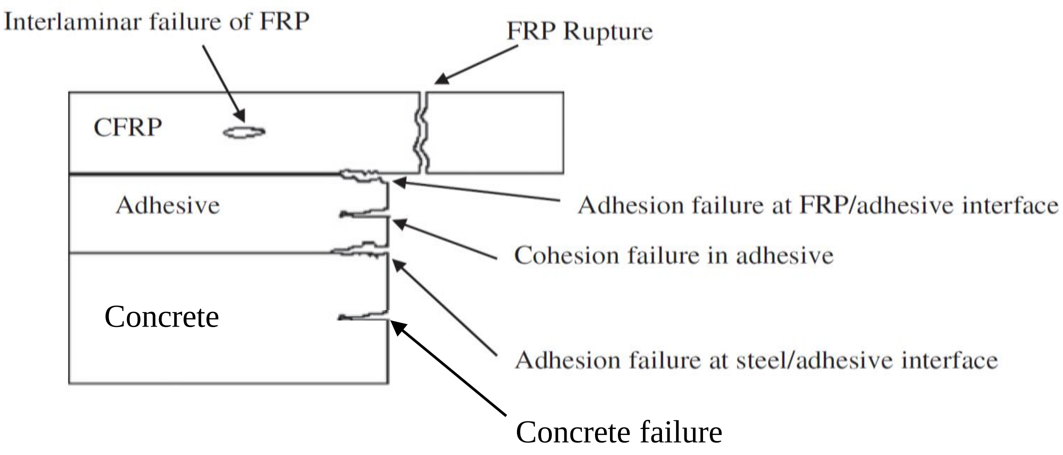
More details in: Ghafoori E., Motavalli M. Normal, high and ultra-high modulus CFRP laminates for bonded and un-bonded strengthening of steel beams. Materials and Design, 2015. 67: p. 232–243.

Introduction: Some of Typical Failure Modes of Steel Beams Bonded with CFRP Plate



Introduction: Possible Failure Modes of CFRP-to-Concrete/Steel Bonded Joints

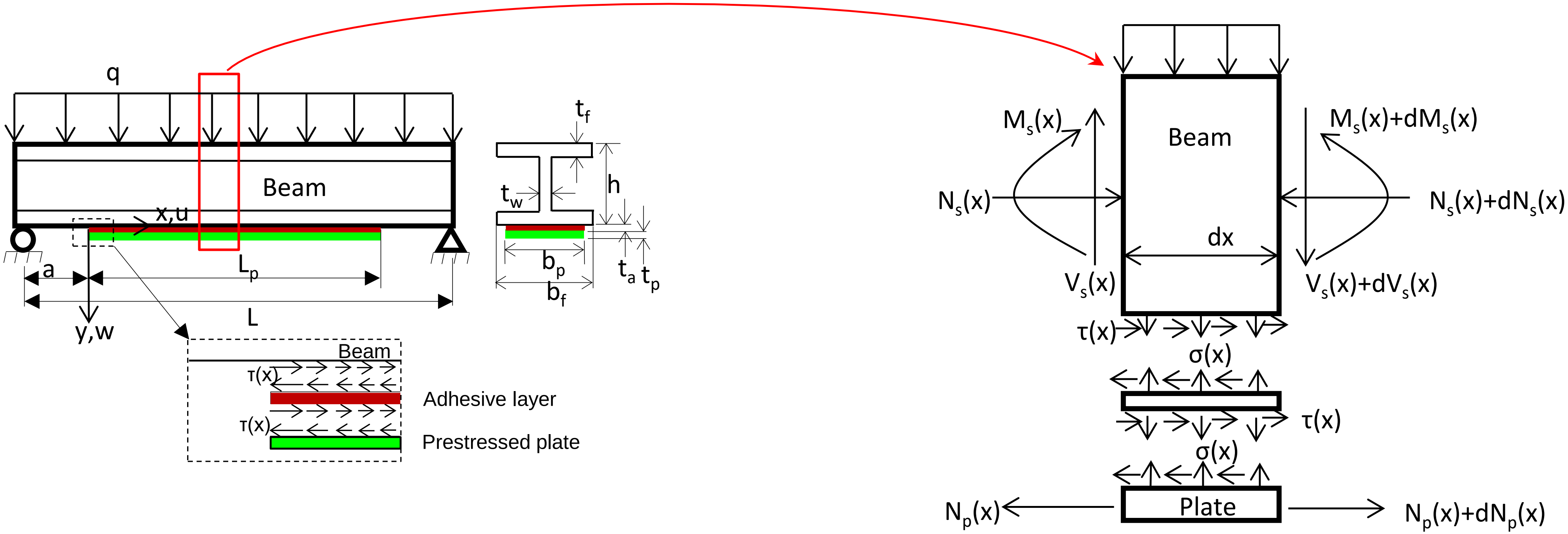




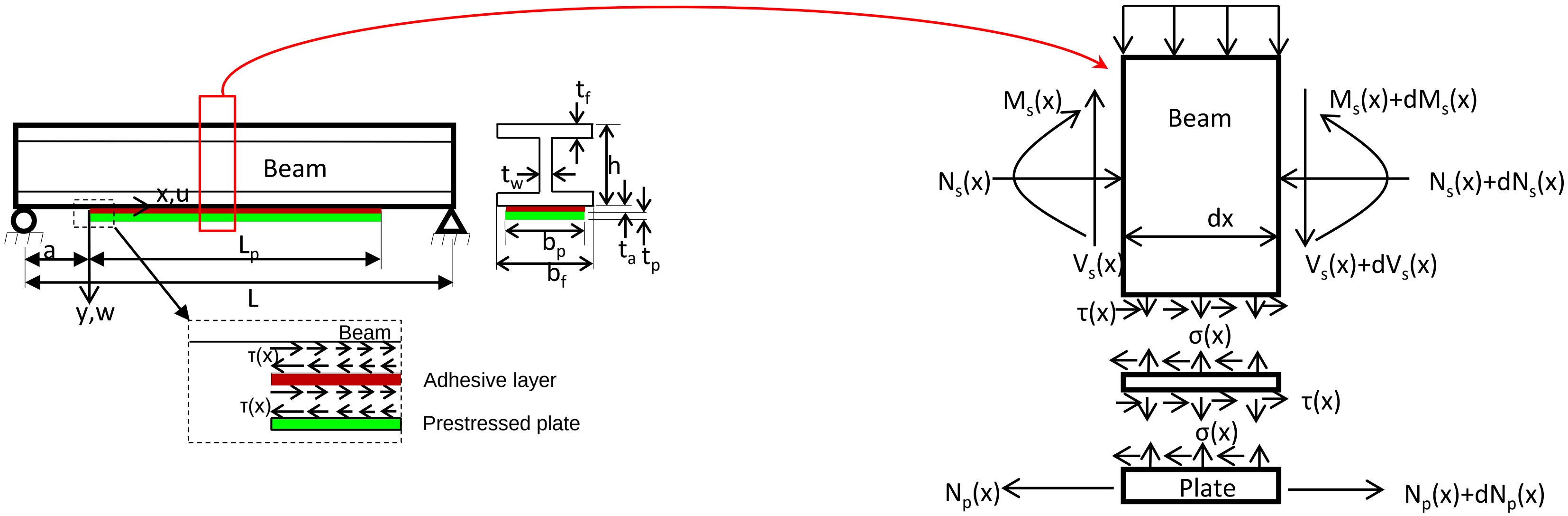
- The main difference between FRP–steel and FRP–concrete bonded joints is that in the former, failure will likely occur in the adhesive layer and in the latter failure is expected to occur in the concrete. Therefore, by providing an adequate bond length, the optimal strength of a bond joint is dependent on the fracture energy of the adhesive for the former and the fracture energy of the concrete for the latter.
- In FRP-strengthened steel structures, interfacial failure should happen within the adhesive layer in the form of **cohesion** failure to maximize the effectiveness of FRP strengthening.
- Inappropriate surface preparation of the steel substrate prior to the bond application may result in an adhesion failure at the steel-to-adhesive interface.

Flexural Strengthening

Steel Beam Strengthened by a Prestressed Bonded Plate



More details in: Ghafoori E., Motavalli M., Zhao X.L., Nussbaumer A., Fontana M. Fatigue design criteria for strengthening metallic beams with bonded CFRP plates. Engineering Structures, 2015. 101: p. 542-557



$$N_s(x) = N_p(x) = N(x) \tag{1}$$

$$\varepsilon_s(x) = \frac{du_s(x)}{dx} = \varepsilon_s^N(x) + \varepsilon_s^M(x) = -\frac{du_s^N(x)}{dx} + \frac{hM_s(x)}{2E_sI_s}, \tag{2}$$

$$\varepsilon_p(x) = \frac{du_p(x)}{dx} = \frac{\Delta N_p(x)}{E_pA_p}, \tag{3}$$

$$\Delta N_p(x) = N_p(x) - N_0, \tag{4}$$

$$\tau(x) = \frac{G_a}{t_a}\left(u_p(x) - u_s(x)\right), \tag{5}$$

$$\frac{d\tau(x)}{dx} = \frac{G_a}{t_a}\left(\frac{du_p(x)}{dx} - \frac{du_s(x)}{dx}\right), \tag{6}$$

(2) & (3) into (6) =>
$$\frac{d\tau(x)}{dx} = \frac{G_a}{t_a}\left(\frac{N_p(x) - N_0}{E_pA_p} - \frac{hM_s(x)}{2E_sI_s} + \frac{N_s(x)}{E_sA_s}\right), \tag{7}$$

$$\frac{d^2\tau(x)}{dx^2} = \frac{G_a}{t_a}\left(\frac{1}{E_pA_p}\frac{dN_p(x)}{dx} - \frac{h}{2E_sI_s}\frac{dM_s(x)}{dx} + \frac{1}{E_sA_s}\frac{dN_s(x)}{dx}\right). \tag{8}$$

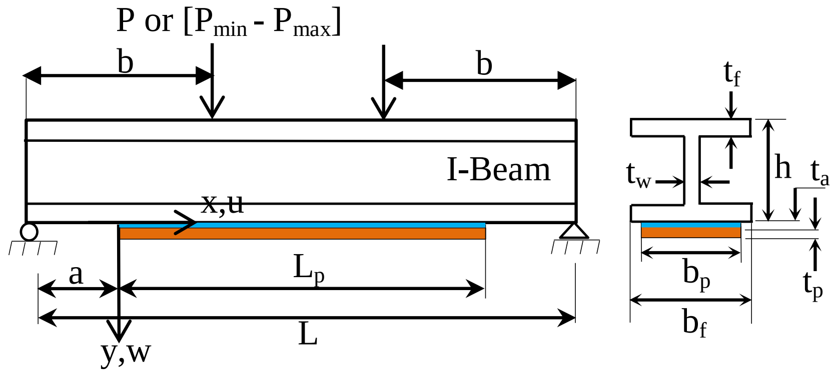
Force equilibrium in x direction:
$$\frac{dN_s(x)}{dx} = \frac{dN_p(x)}{dx} = b_p\tau(x), \tag{9}$$

Moment equilibrium:
$$\frac{dM_s(x)}{dx} = V_s(x) - \frac{b_ph}{2}\tau(x) \tag{10}$$

$$\frac{d^2\tau(x)}{dx^2} - \frac{G_ab_p}{t_a}\left(\frac{1}{E_sI_s} + \frac{1}{E_pI_p} + \frac{h^2}{4I_sE_s}\right)\tau(x) = -K\frac{h}{2E_sI_s}V_T(x). \tag{11}$$

$$\frac{d^2\tau(x)}{dx^2} - \alpha\tau(x) = \beta(x). \tag{12}$$

More details in: Ghafoori E., Motavalli M., Zhao X.L., Nussbaumer A., Fontana M. Fatigue design criteria for strengthening metallic beams with bonded CFRP plates. Engineering Structures, 2015. 101: p. 542-557



Beam strengthened by the bonded CFRP laminate in a four-point bending set-up.

By applying the boundary conditions for the above four-point bending set-up:

$$\tau(x) = \begin{cases} \dfrac{G_a}{t_a \lambda}\left(\dfrac{N_0}{E_p A_p} + \dfrac{hPa}{2E_s I_s}\right) e^{-\lambda x} + m_1 P\left(1 - e^{-\lambda \mu}\cosh(\lambda x)\right) & 0 \le x \le b-a \\ \left(\dfrac{G_a}{t_a \lambda}\left(\dfrac{N_0}{E_p A_p} + \dfrac{hPa}{2E_s I_s}\right) + m_1 P \sinh(\lambda \mu)\right) e^{-\lambda x} & b-a \le x \le L_p/2 \end{cases} \quad (13)$$

$$\lambda = \sqrt{\frac{G_a b_p}{t_a}\left(\frac{1}{E_s I_s} + \frac{1}{E_p I_p} + \frac{h^2}{4E_s I_s}\right)}; \qquad m_1 = \frac{G_a}{2t_a \lambda^2}\frac{h}{E_s I_s} \quad (14)$$

From (1) & (7) =>

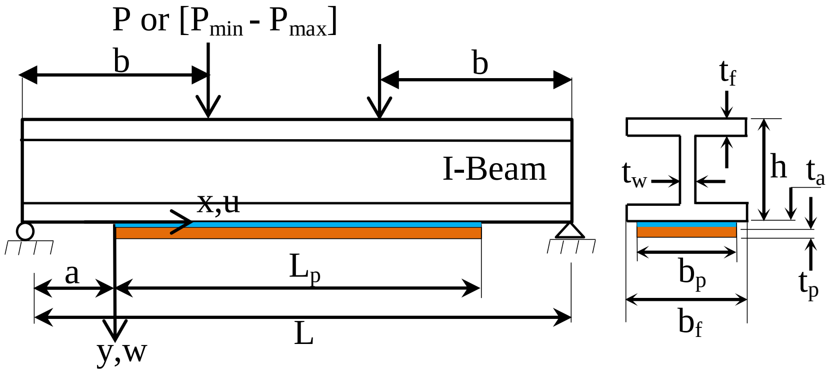
$$N(x) = \frac{b_p}{\lambda^2}\left(\frac{d\tau(x)}{dx} + m_1 \lambda^2 M_T(x) + \frac{G_a N_0}{t_a E_p A_p}\right) \quad (15)$$

(16)

Stress in bottom flange:

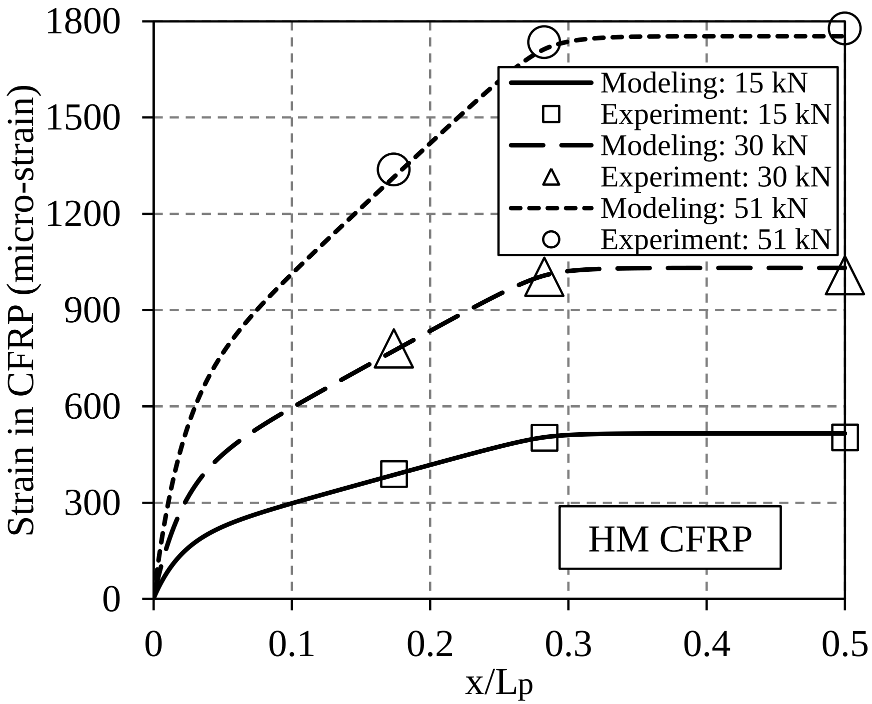
$$\sigma(x) = M_T(x)\frac{h}{2I_s} - \frac{b_p}{\lambda^2}\left(\frac{h^2}{4I_s} + \frac{1}{A_s}\right)\left(\frac{d\tau(x)}{dx} + m_1 \lambda^2 M_T(x) + \frac{G_a N_0}{t_a E_p A_p}\right) \quad (17)$$

More details in: Ghafoori E., Motavalli M., Zhao X.L., Nussbaumer A., Fontana M. Fatigue design criteria for strengthening metallic beams with bonded CFRP plates. Engineering Structures, 2015. 101: p. 542-557

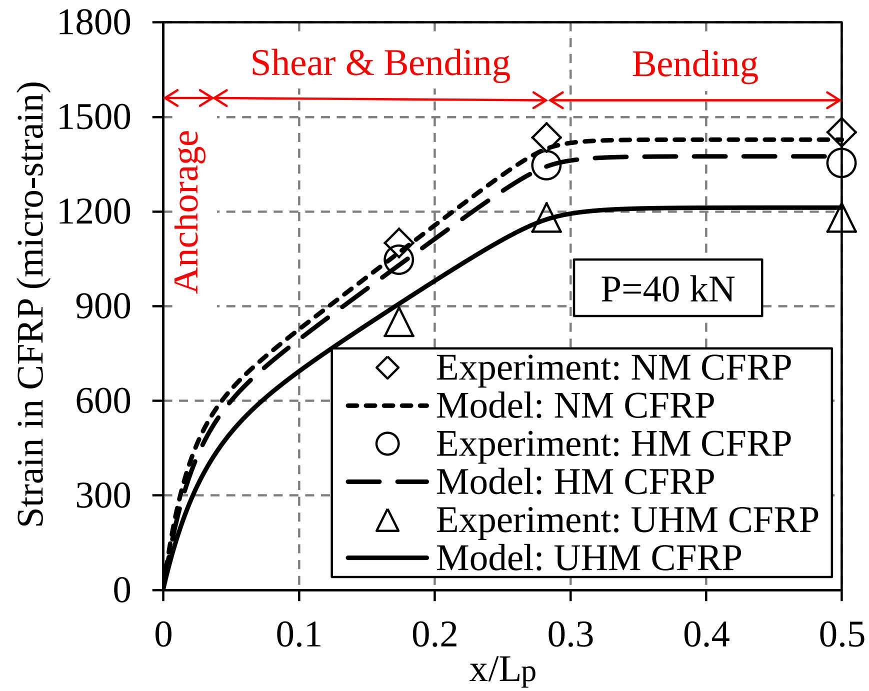


A simply supported beam with a free span of L=1200 mm and a CFRP plate length of L_p= 920 mm (i.e., a=140 mm) in a four-point bending set-up:

$b_f = 65\ mm,\ t_f = 6.2\ mm,\ t_w = 4.4\ mm,\ h = 120\ mm,\ t_p = 1.4\ mm,\ b_p = 50\ mm,$
$t_a = 1\ mm,\ E_s = 210\ GPa,\ G_a = 1040\ MPa.$

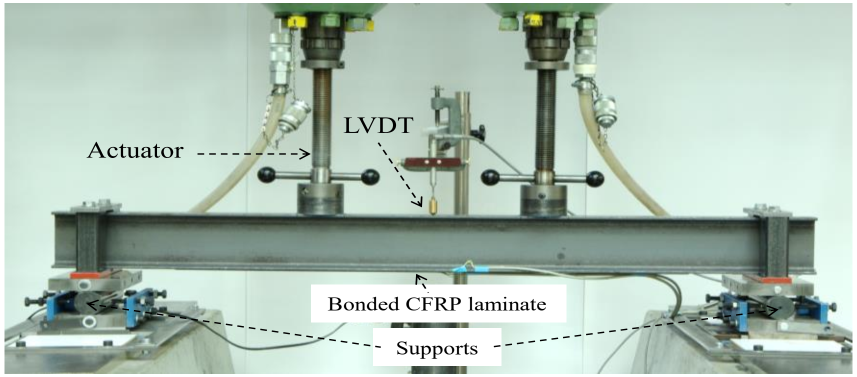


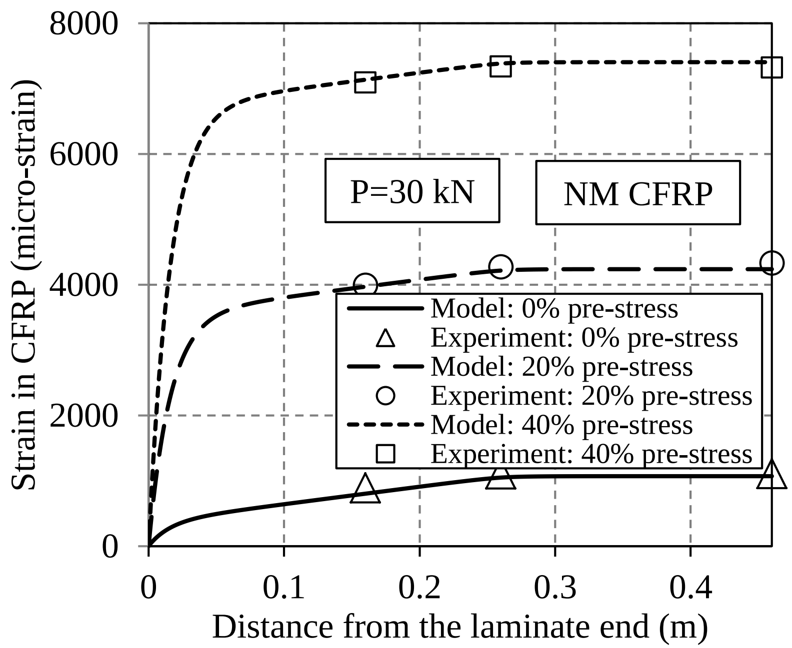
The calculated and measured strains along the CFRP laminates for the beam strengthened by the HM CFRP at actuator load levels of P=15 kN, 30 kN and 51 kN (within the elastic domain).



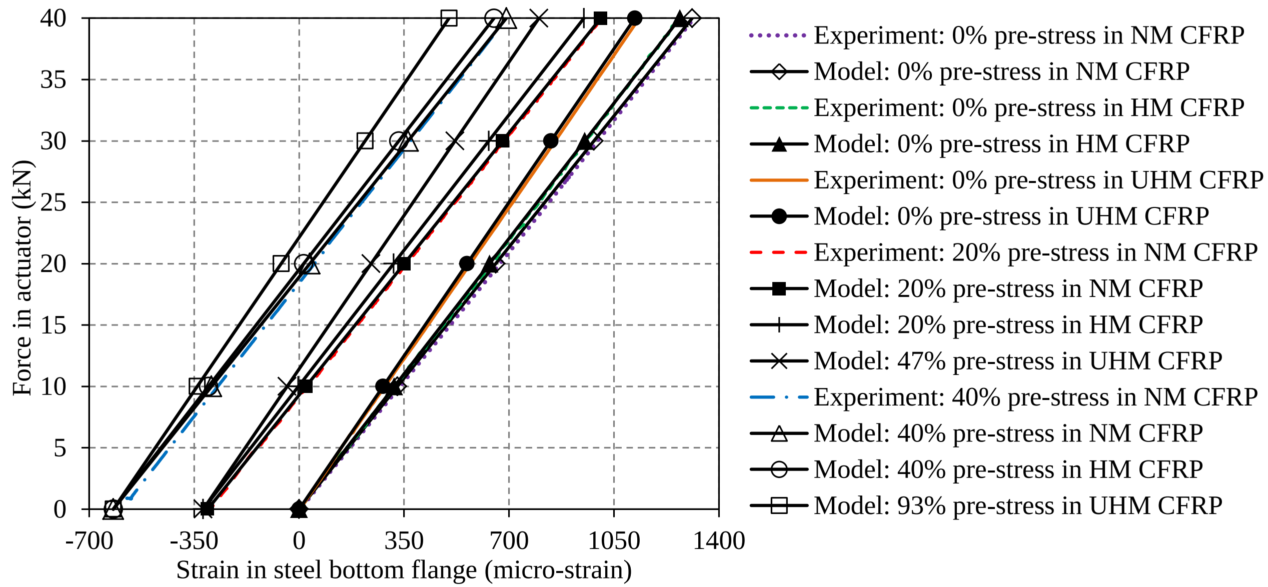
The calculated and measured strain along the CFRP laminates for the retrofitted beams with the NM, the HM and the UHM CFRP at an actuator load level of P=40 kN (within the elastic domain).

More details in: Ghafoori E., Motavalli M., Zhao X.L., Nussbaumer A., Fontana M. Fatigue design criteria for strengthening metallic beams with bonded CFRP plates. Engineering Structures, 2015. 101: p. 542-557



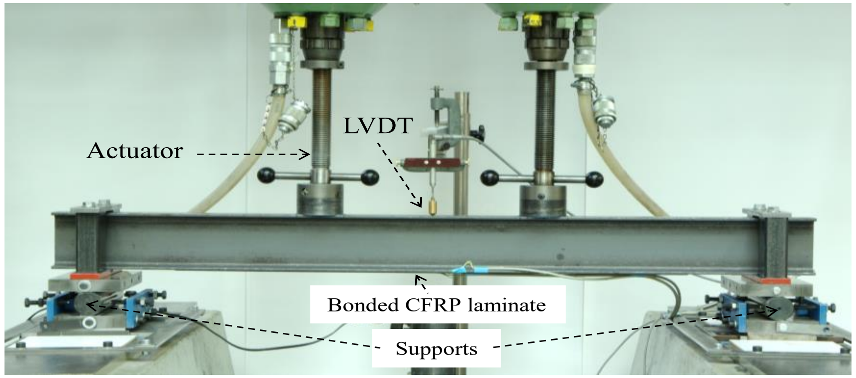


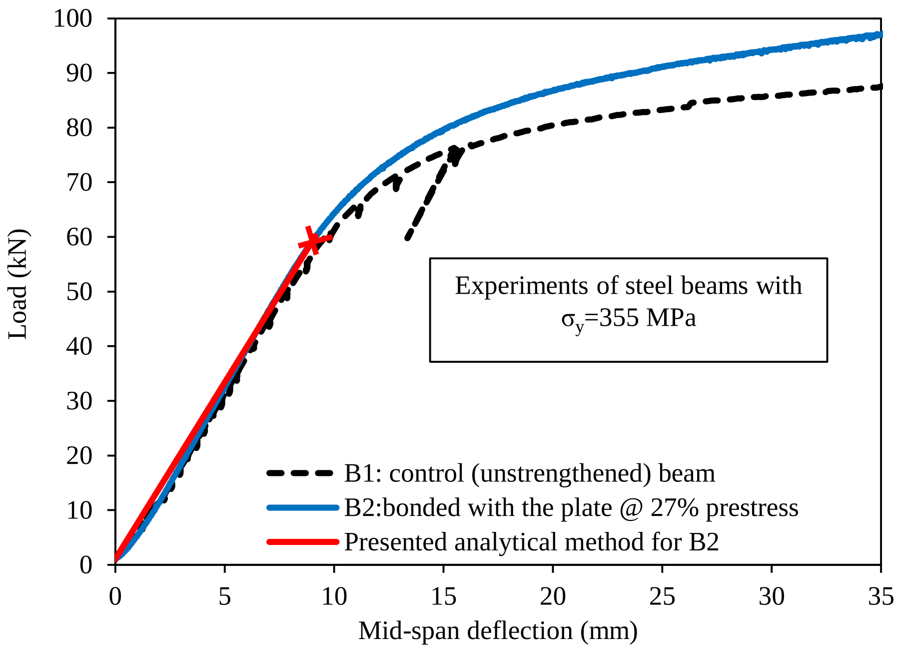
The calculated and measured strains along the CFRP laminates for the beams strengthened by the NM CFRP with 0%, 20% and 40% pre-stress levels subjected to an actuator load level of P=30 kN.



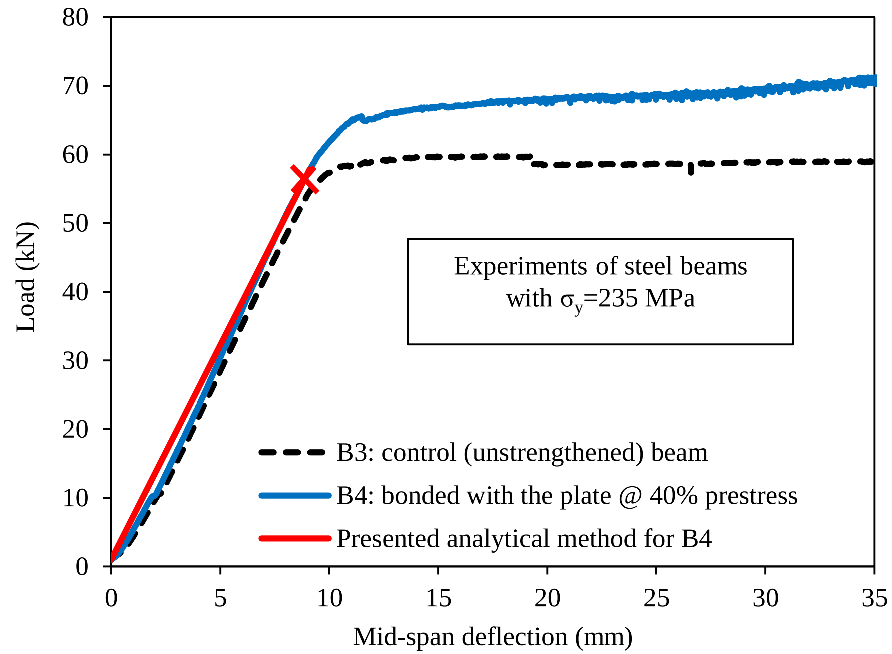
The strain in the bottom flange of the specimens strengthened by the NM, the HM and the UHM CFRP laminates with different pre-stress levels while the actuator load, P, increases from 0 to 40 kN.

More details in: Ghafoori E., Motavalli M., Zhao X.L., Nussbaumer A., Fontana M. Fatigue design criteria for strengthening metallic beams with bonded CFRP plates. Engineering Structures, 2015. 101: p. 542-557





Comparison of load-deflection behaviors of steel beams with σy=355 MPa, one unstrengthened and one strengthened with a 27% prestressed bonded CFRP plate, both loaded in a four-point bending set-up.



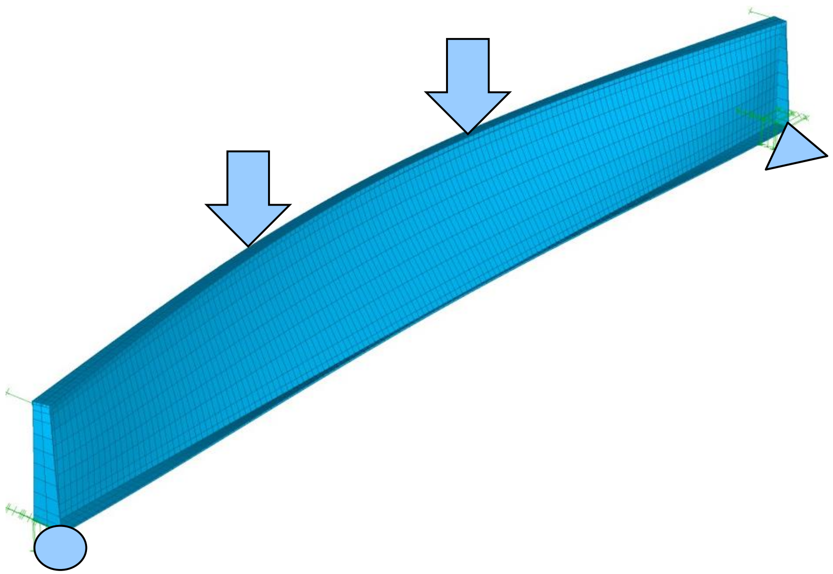
Comparison of load-deflection behaviors of two steel beams with σ_y=235 MPa, one unstrengthened and one strengthened with a 40% prestressed bonded CFRP plate, both loaded in a four-point bending set-up

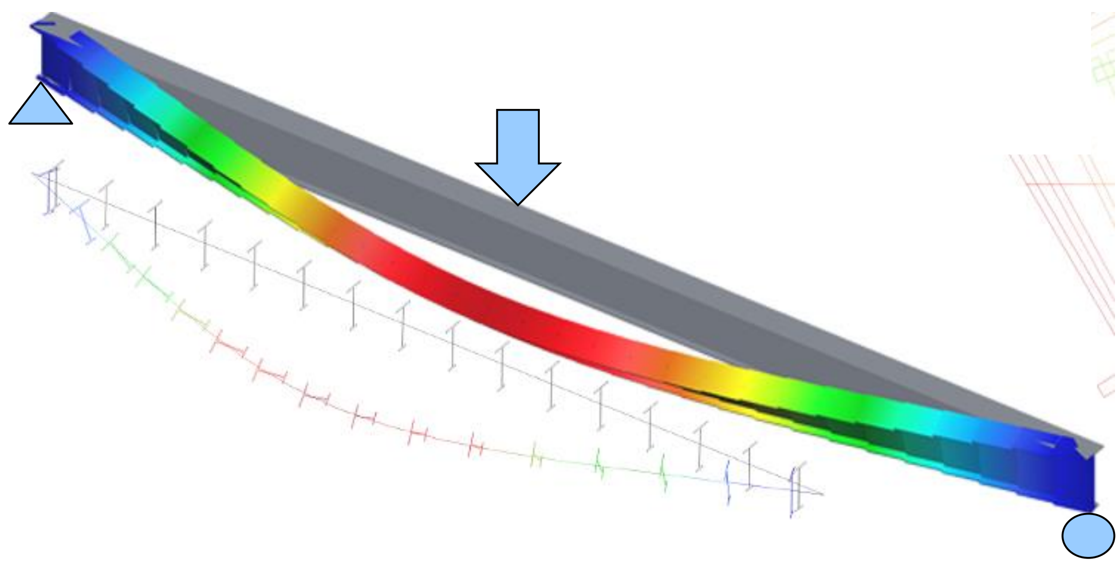
More details in: Ghafoori E., Motavalli M., Flexural and interfacial behavior of metallic beams strengthened by prestressed bonded plates, Composite Structures, 101 (2013), 22-34.

Strengthening against Lateral Torsional Buckling

Definition of Lateral Torsional Buckling (LTB)

- The LTB failure is often triggered in slender beams, which do not have sufficient lateral supports, due to eccentricities, and can occur at load levels that are below yield capacity.
- These eccentricities, in reality, can be due to the geometrical imperfections of the beam itself or the position of the loads.
- The eccentricity generates a bending moment about the longitudinal axis, which displaces the compression flange laterally away from the loading plane, while the tension flange tends to keep the beam straight, and thus, the beam cross section is twisted.
- This twisting in combination with the lateral displacement of the beam is called the LTB failure and could occur well before the yielding capacity of the steel cross section is reached.





More details in: Ghafoori E., Motavalli M. Lateral-torsional buckling of steel I-beams retrofitted by bonded and un-bonded CFRP laminates with different pre-stress levels: experimental and numerical study. Construction and Building Materials, 2015. 76: p. 194–206.

Mechanisms of Strengthening against LTB

Two retrofit mechanisms:

- Increasing out-of-plane **stiffness** of the beam using UHM CFRP laminates

  For the LTB failure, the specimen buckles out of the plane under flexural loading, and the CFRP laminates can affect the buckling capacity of the retrofitted beams by stiffening the steel cross section around the weak axis. Application of the ultra-high modulus CFRP laminates increases the out-of-plane stiffness of the specimens, and consequently, the buckling strength of the beams increases.

- Applying tension to the top flange of the beam using **pre-stressed** CFRP laminates

  Whether the prestressed CFRP laminate leads to tensile or compressive stresses in the top flange depends only on the profile geometry. Assuming that the prestressing is applied on the bottom surface of the bottom flange, the stresses in the top flange caused by the axial force and by the bending moment can be calculated as:

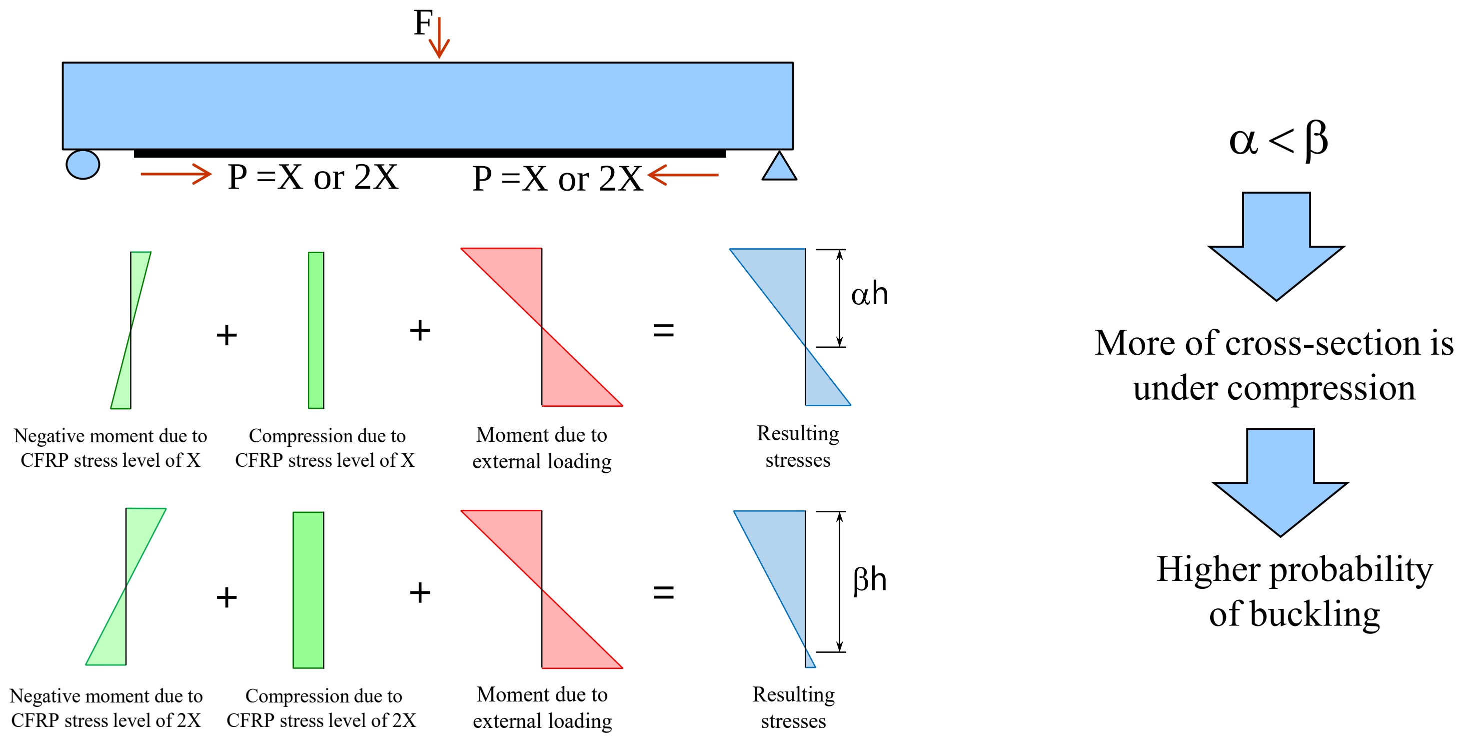
$$\sigma_{top} = \frac{ph/2}{I} \times \frac{h}{2} - \frac{P}{A} > 0 \Rightarrow h > 2.\sqrt{\frac{I}{A}}$$

Condition for top flange to be in tension

More details in: Ghafoori E., Motavalli M. Normal, high and ultra-high modulus CFRP laminates for bonded and un-bonded strengthening of steel beams. Materials and Design, 2015. 67: p. 232–243.

Important Notes on CFRP Strengthening against LTB

- When $h < 2.\sqrt{\frac{I}{A}}$, use of CFRP laminates with high pre-stress levels is NOT recommended! Instead, we can use UHM laminates.



Stress distribution in the beam cross-section for the two different pre-stress levels of X % and 2X %.

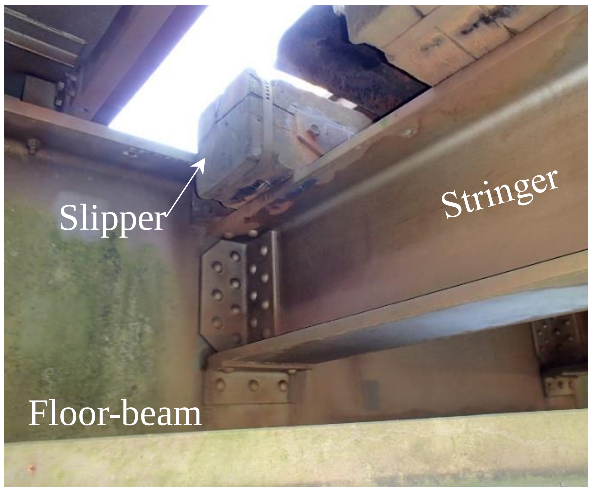
- Note: Application of CFRP laminates to the tension face of the steel beams increases the in-plane bending strength and also the lateral buckling strength; however, the former increases more significantly. This arrangement could change the failure mode of the steel beam from in-plane bending to the buckling failure mode after CFRP strengthening. This need to be check in advance!

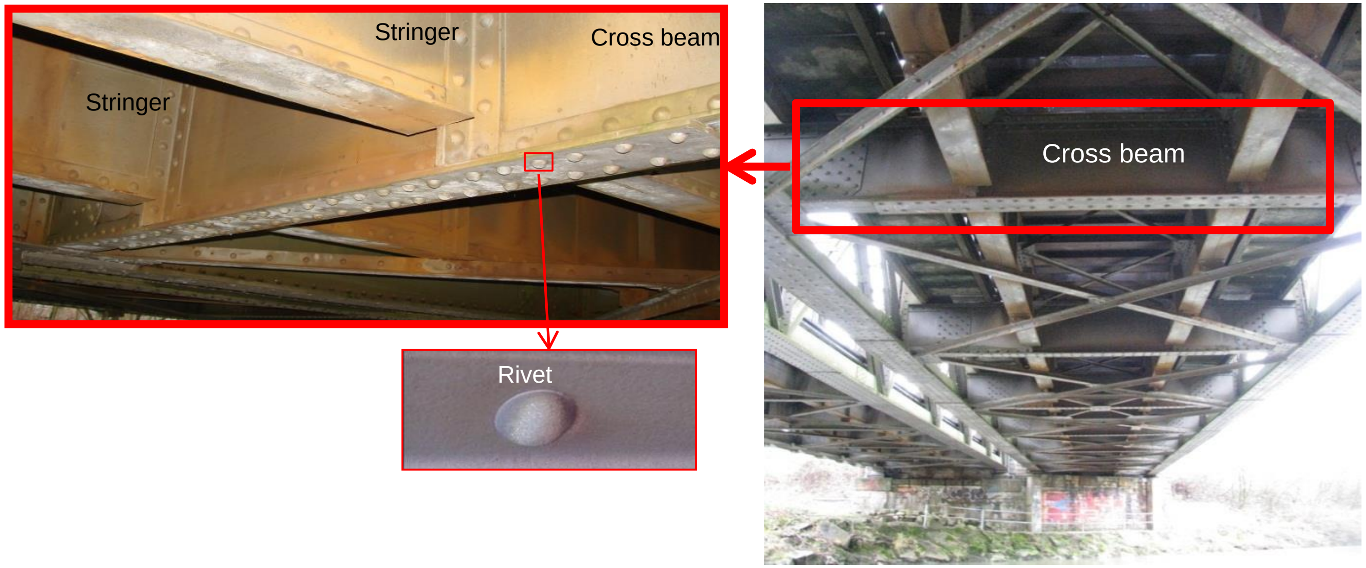
More details in: Ghafoori E., Motavalli M. Lateral-torsional buckling of steel I-beams retrofitted by bonded and un-bonded CFRP laminates with different pre-stress levels: experimental and numerical study. Construction and Building Materials, 2015. 76: p. 194–206.

Fatigue Strengthening

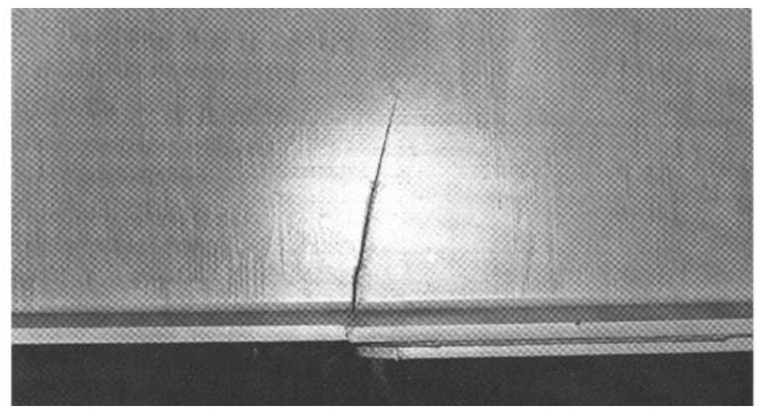
Fatigue Strengthening

- Healthy metallic members:



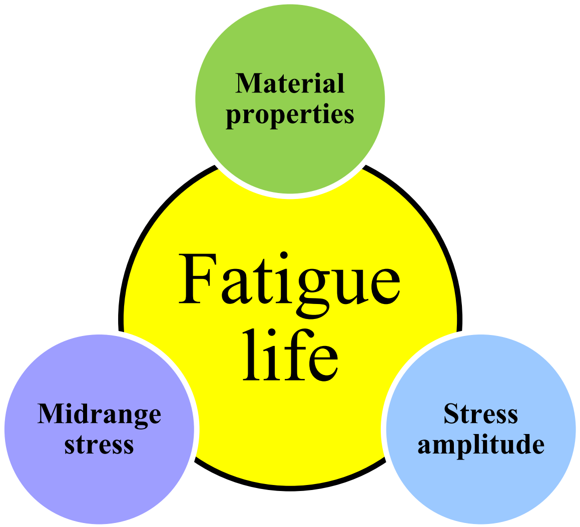


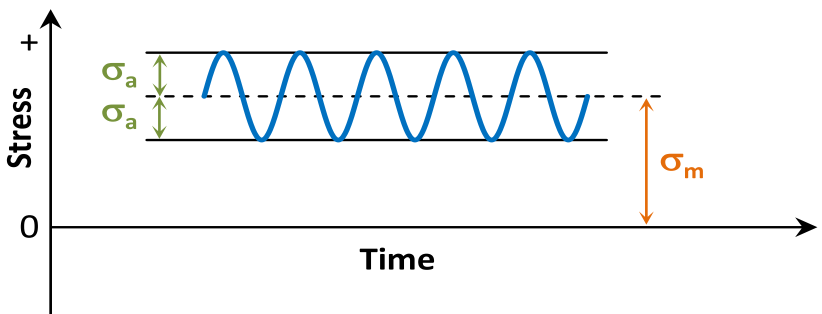
- Cracked metallic members:



Fatigue Strengthening of Healthy Metallic Members

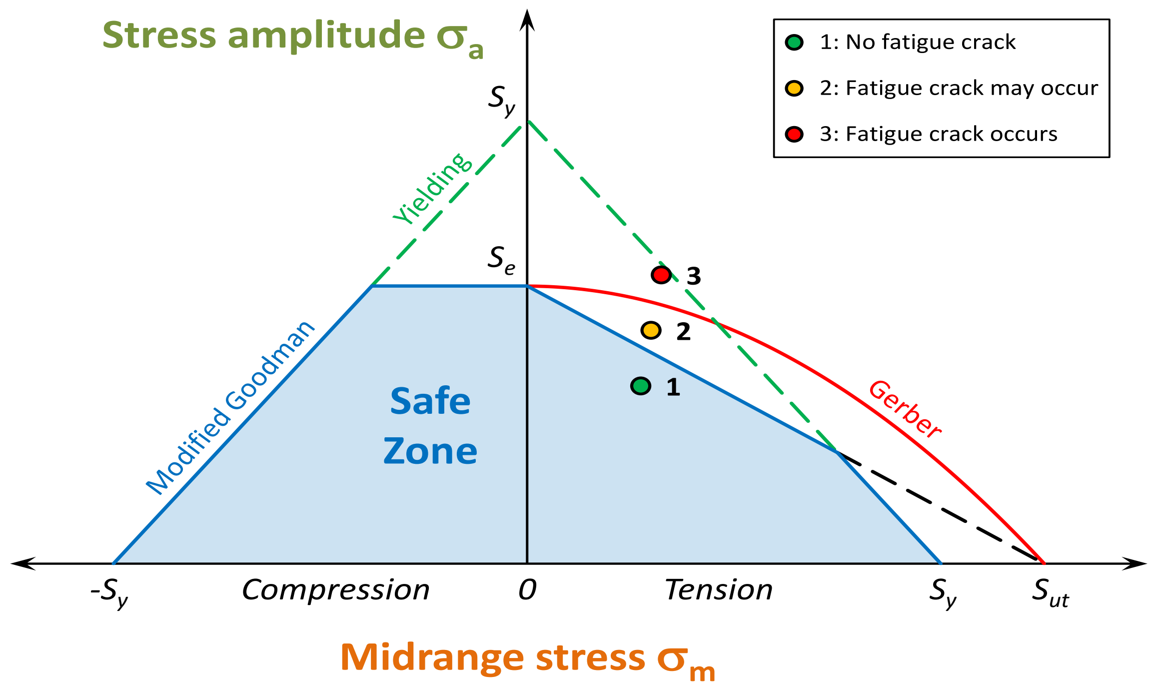
Fatigue Theory



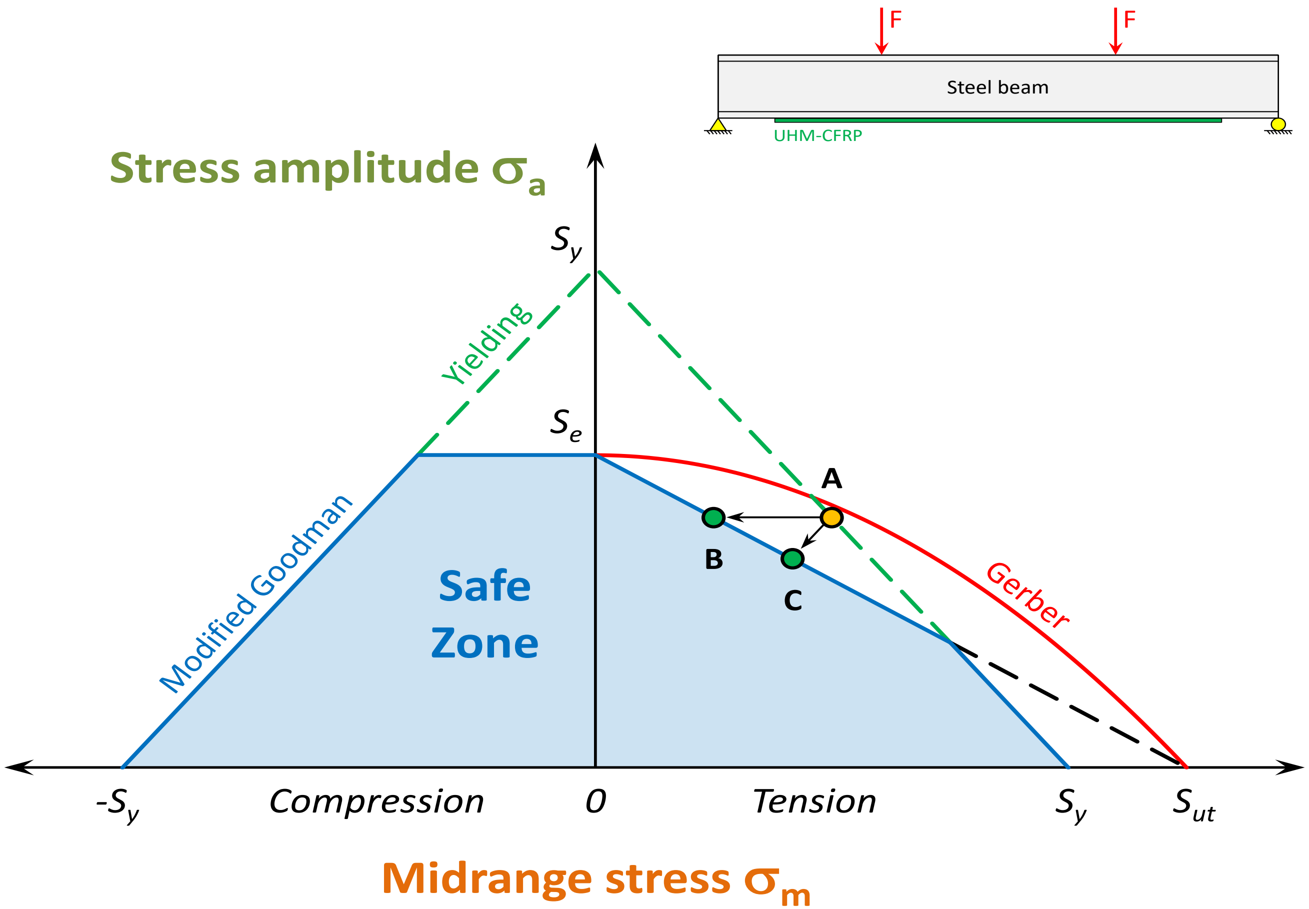


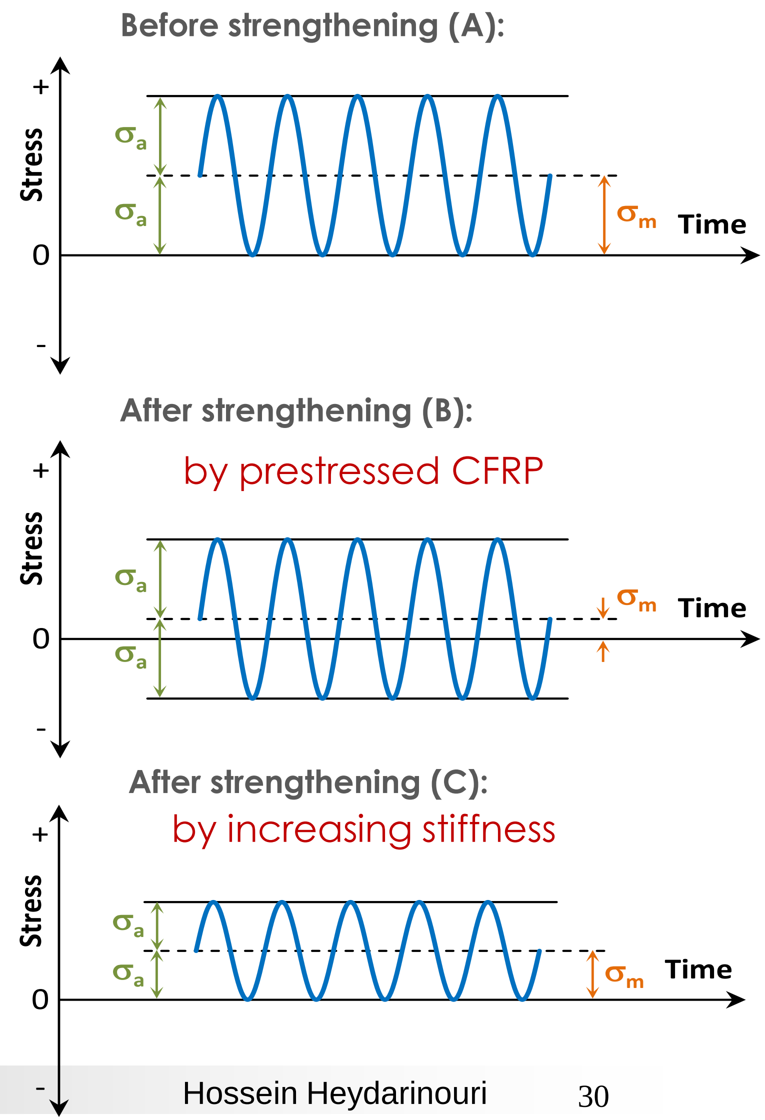
$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \qquad \sigma_a = \left| \frac{\sigma_{max} - \sigma_{min}}{2} \right|$$

S_y	Yield strength
S_e	Fatigue endurance limit
S_{ut}	Ultimate tensile strength



Fatigue Theory



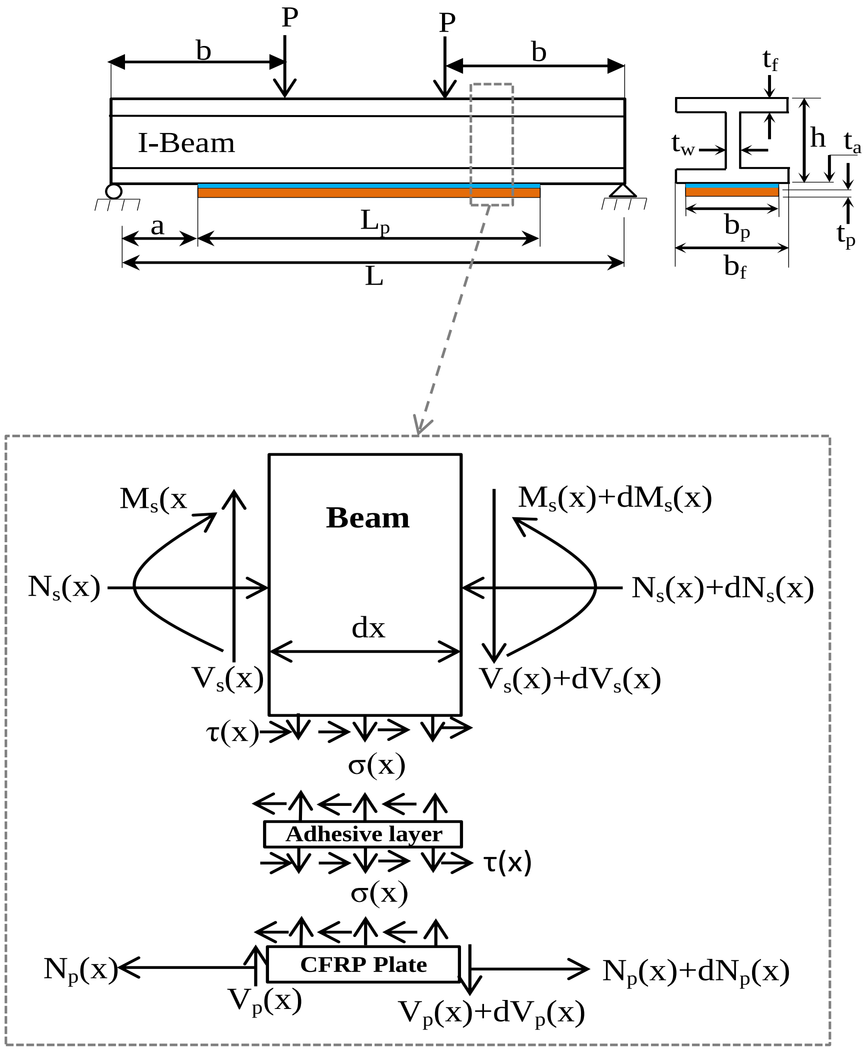


Fatigue Theory

$$\frac{d^2\tau(x)}{dx^2} - \frac{G_a b_p}{t_a}\left(\frac{1}{E_s I_s}+\frac{1}{E_p I_p}+\frac{h^2}{4E_s I_s}\right)\tau(x) = -\frac{G_a}{t_a}\frac{h}{2E_s I_s}V_T(x)$$

$$\tau(x)=\left(\frac{G_a}{t_a\lambda}\left(\frac{N_0}{E_p A_p}+\frac{hPa}{2E_s I_s}\right)+m_1 P\sinh(\lambda\mu)\right)e^{-\lambda x}$$

$$\sigma_{flange}=\frac{hPa}{2I_s}-b_p\left(\frac{h^2}{4I_s}+\frac{1}{A_s}\right)\left(-\frac{\tau(L_p/2)}{\lambda}+m_1 Pa+\frac{G_a N_0}{\lambda^2 t_a E_p A_p}\right)$$



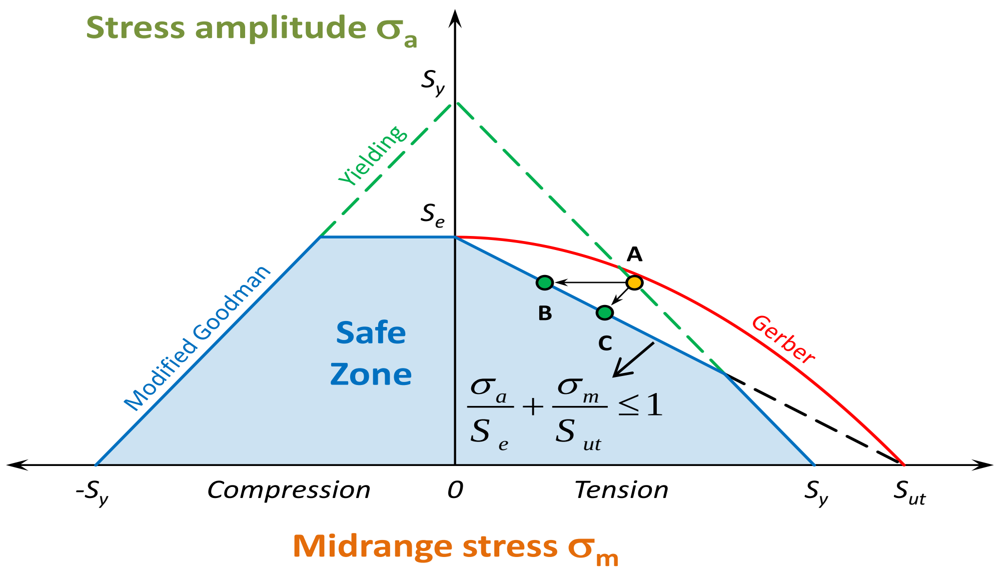
$\tau(x)$	interfacial shear stress along the CFRP plate
σ_{flange}	stress in beam bottom flange
N	force in CFRP plate
N_0	the pre-stress level
G_a	adhesive shear modulus

Note: Subcripts ‘s’ and ‘p’ refers to the steel and the CFRP plate

$$\lambda=\sqrt{\frac{G_a b_p}{t_a}\left(\frac{1}{E_s A_s}+\frac{1}{E_p A_p}+\frac{h^2}{4E_s I_s}\right)}$$

$$m_1=\frac{G_a}{2t_a\lambda^2}\frac{h}{E_s I_s}$$

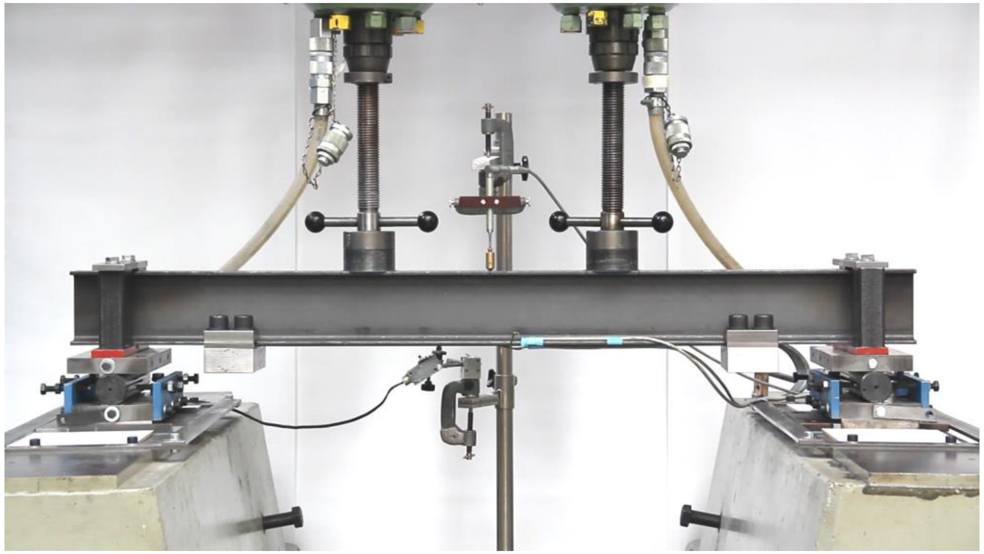
Fatigue Theory



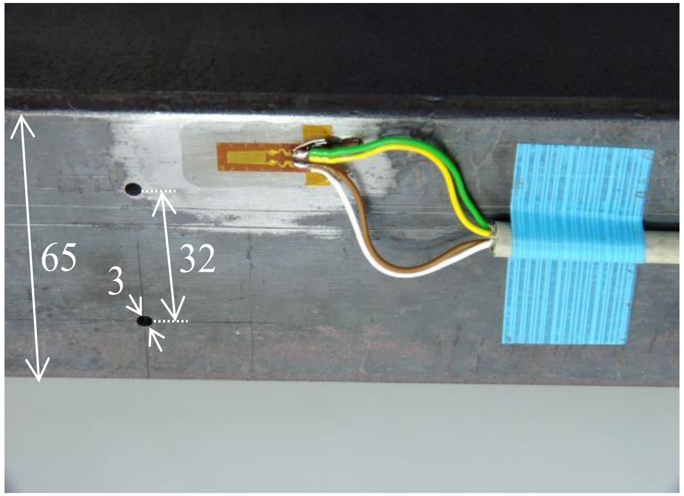
$$\sigma_{flange} = \frac{hPa}{2I_s} - b_p\left(\frac{h^2}{4I_s} + \frac{1}{A_s}\right)\left(-\frac{\tau\left(L_p/2\right)}{\lambda} + m_1 Pa + \frac{G_a N_0}{\lambda^2 t_a E_p A_p}\right)$$

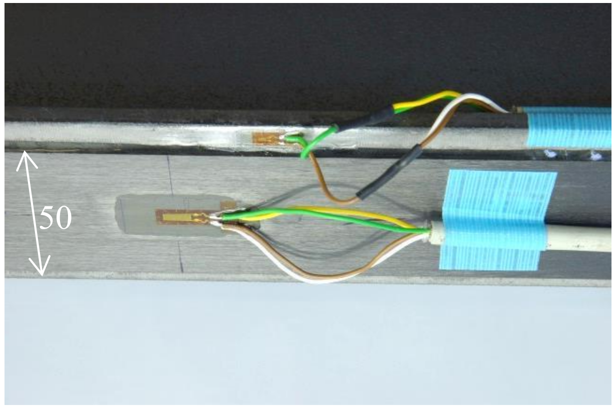
$$\frac{haP_a}{2I_sS_e} - \frac{b_p}{S_e}\left(\frac{h^2}{4I_s} + \frac{1}{A_s}\right)\left(m_1 aP_a + \frac{G_a N_0}{\lambda^2 t_a E_p A_p}\right) + \frac{haP_m}{2I_sS_{ut}} - \frac{b_p}{S_{ut}}\left(\frac{h^2}{4I_s} + \frac{1}{A_s}\right)\left(m_1 aP_m + \frac{G_a N_0}{\lambda^2 t_a E_p A_p} e^{-\lambda L_p/2}\right) \leq \frac{b_p - d}{nb_p k_f}$$

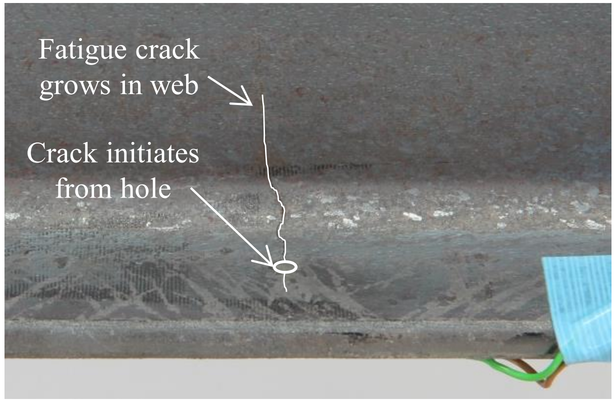
Laboratory Verifications

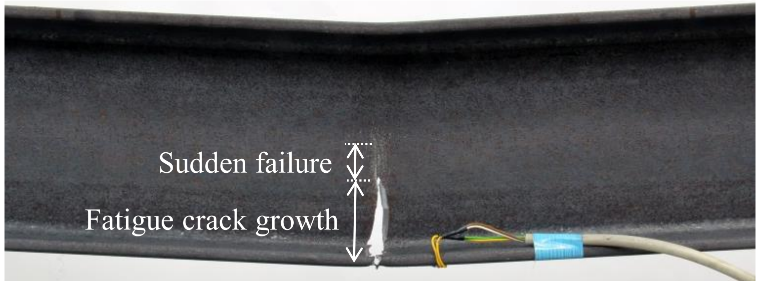


Video

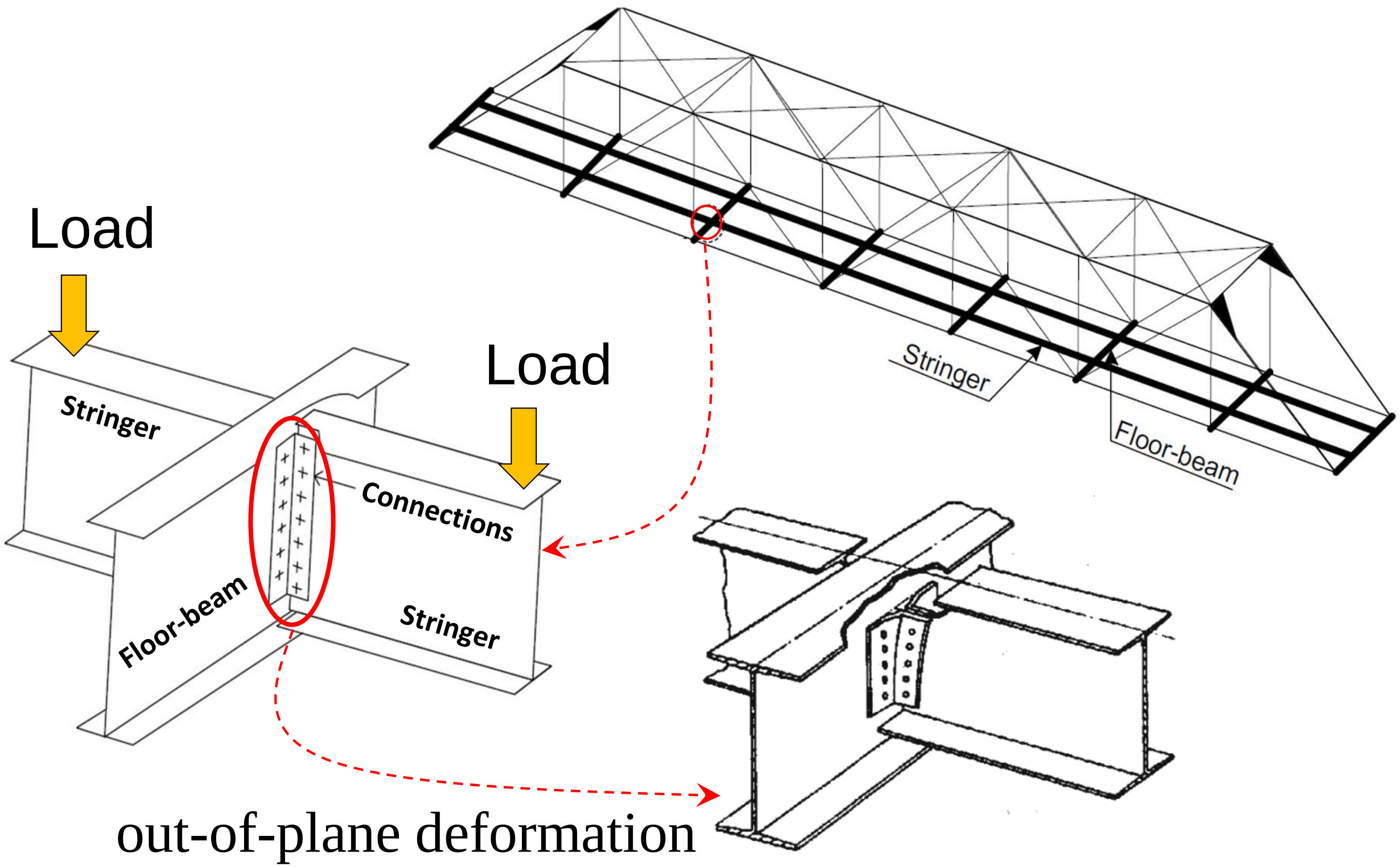




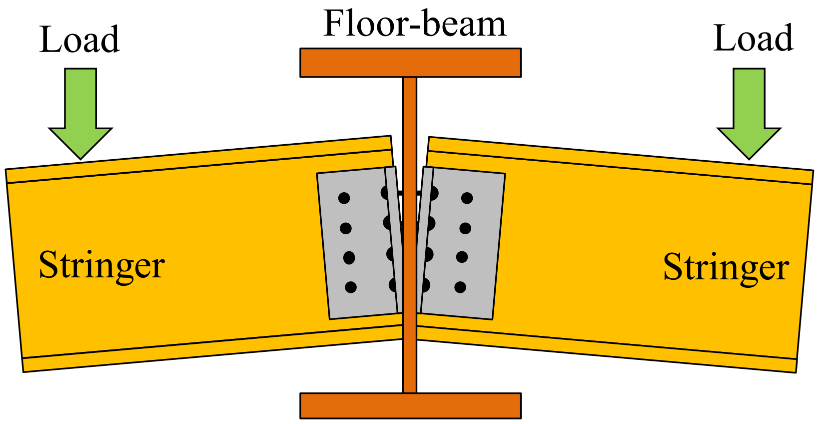




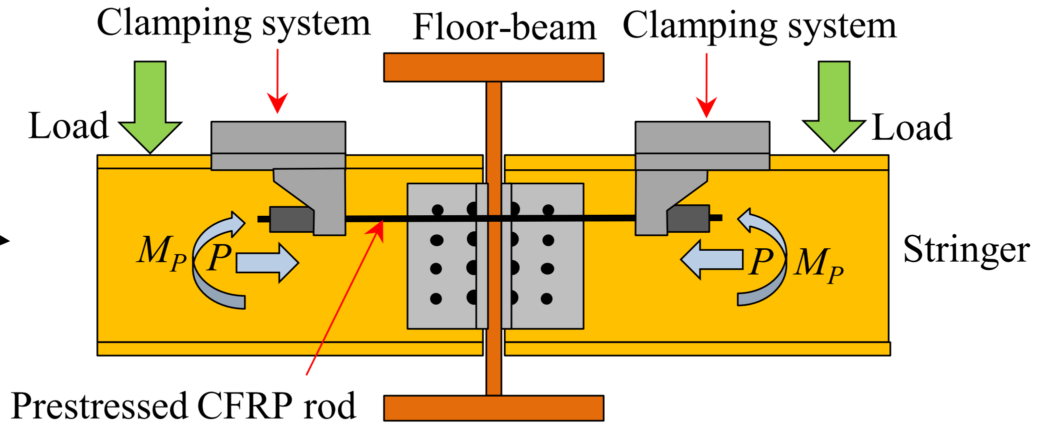
More complicated case: multiaxial fatigue



More complicated case: multiaxial fatigue

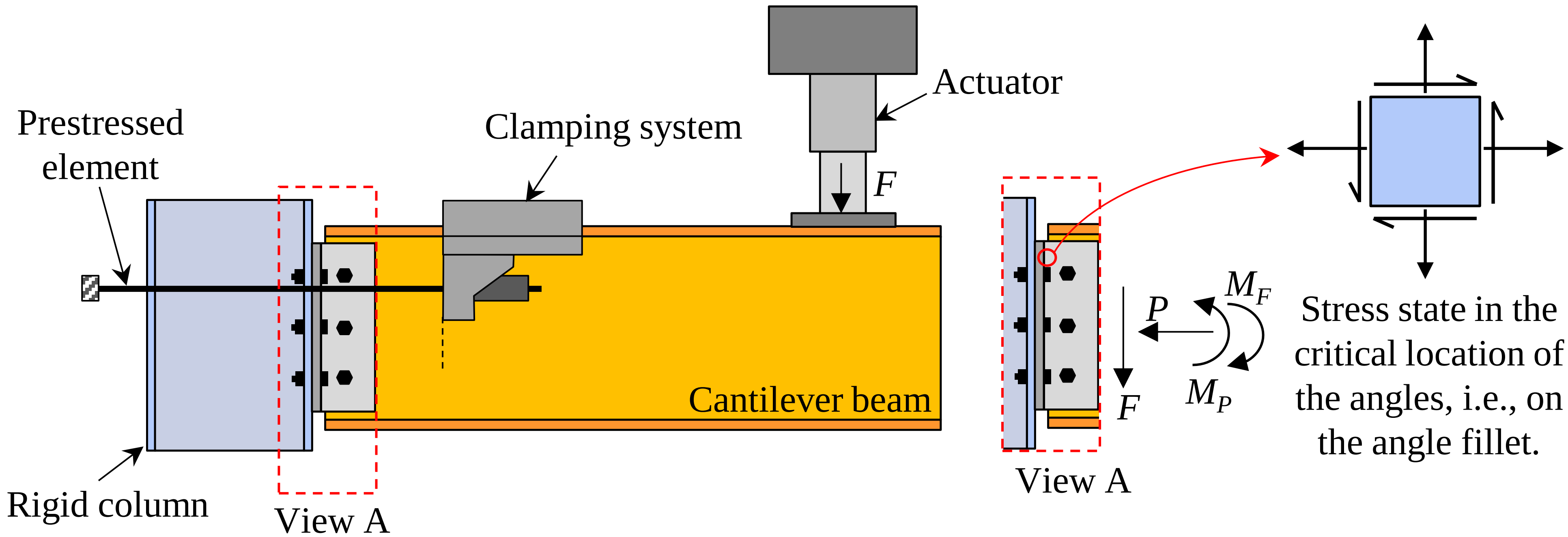


Reducing the out-of-plane deformation by prestressing force



More details in: Heydarinouri, H., Nussbaumer, A., Motavalli, M., & Ghafoori, E. (2021). Multiaxial fatigue criteria for prestressed strengthening of steel connections. International Journal of Fatigue, 153, 106470.

More complicated case: multiaxial fatigue

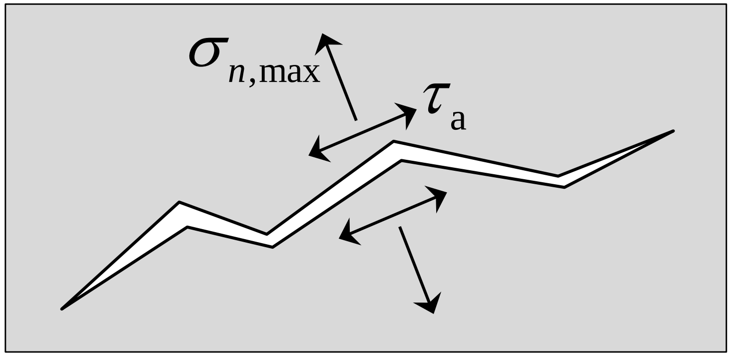


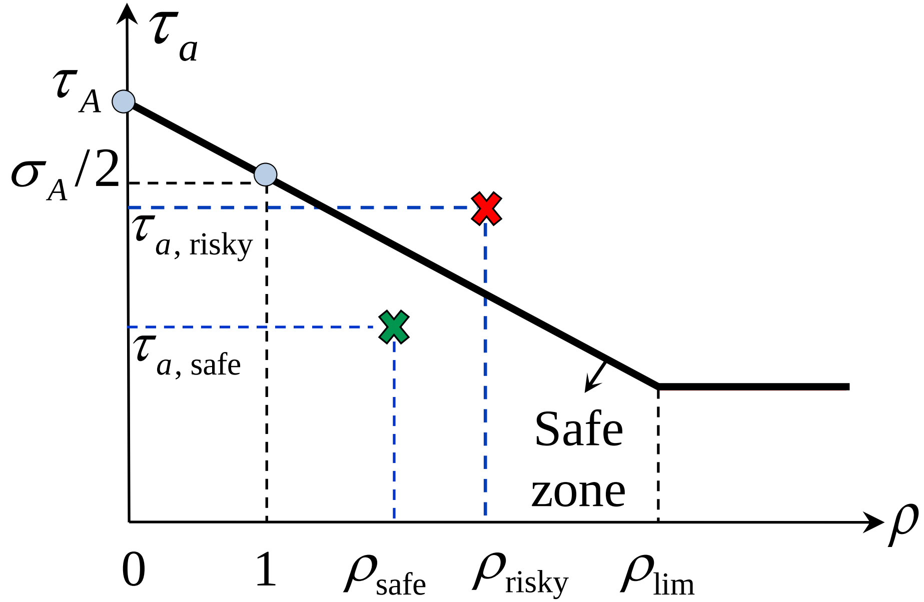
More details in: Heydarinouri, H., Nussbaumer, A., Motavalli, M., & Ghafoori, E. (2021). Multiaxial fatigue criteria for prestressed strengthening of steel connections. International Journal of Fatigue, 153, 106470.

More complicated case: multiaxial fatigue

Critical plane approach

- τ_a : Maximum shear stress amplitude
- $\sigma_{n,max}$:Maximum normal stress on the critical plane





More details in: Heydarinouri, H., Nussbaumer, A., Motavalli, M., & Ghafoori, E. (2021). Multiaxial fatigue criteria for prestressed strengthening of steel connections. International Journal of Fatigue, 153, 106470.

More complicated case: multiaxial fatigue

Critical plane approach

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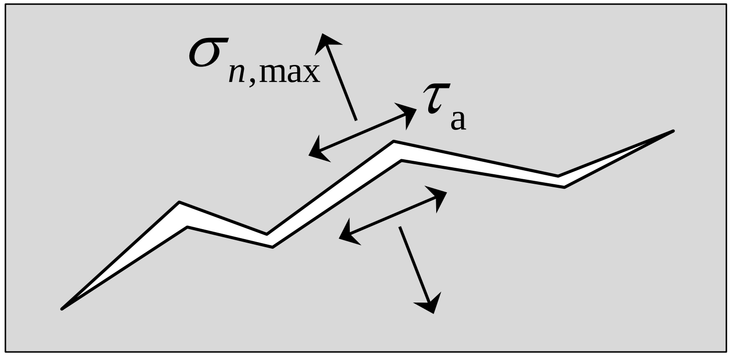
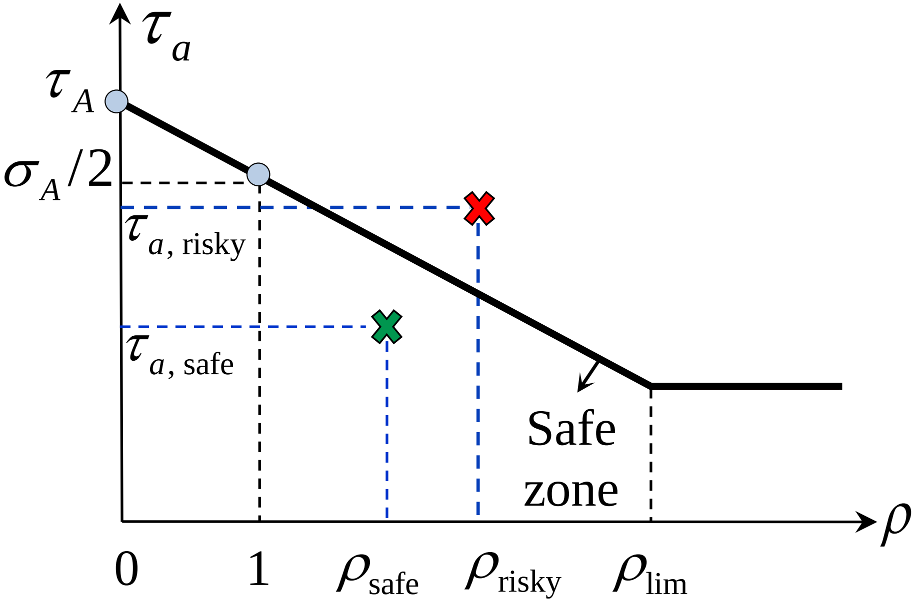




More details in: Heydarinouri, H., Nussbaumer, A., Motavalli, M., & Ghafoori, E. (2021). Multiaxial fatigue criteria for prestressed strengthening of steel connections. International Journal of Fatigue, 153, 106470.

Conclusiones

- **The advantages of the proposed design approach:**
  1. It is a proactive strengthening approach,
  2. It takes into account the combined effects of mean stress and alternating stress levels.
  3. It can be applied in more complicated case of multiaxial fatigue.

- **Two main fatigue retrofit mechanisms for healthy metallic members:**
  1. to decrease the mean stress level by using pre-stressed laminate
  2. to decrease mean and alternating stresses proportionally by using ultra-high modulus laminate

More details in: Ghafoori E., Motavalli M., Zhao X.L., Nussbaumer A., Fontana M. Fatigue design criteria for strengthening metallic beams with bonded CFRP plates. Engineering Structures, 2015. 101: p. 542-557.

Case Study:

Fatigue Strengthening of Münchenstein Railway Bridge

Bridge History

- The Münchenstein rail disaster on 1891 is historically the worst railway accident ever in Switzerland. The bridge had been built in 1875 by Gustave Eiffel, who built the Eiffel Tower later in 1889.
- Prof. Ludwig von Tetmajer, the first director of Empa, was commissioned to investigate the cause of this collapse. His investigation led to modification of Euler’s formula for buckling of slender bars.

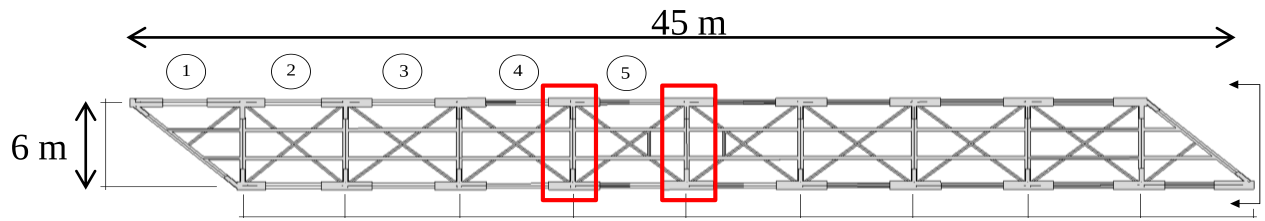
Bridge History

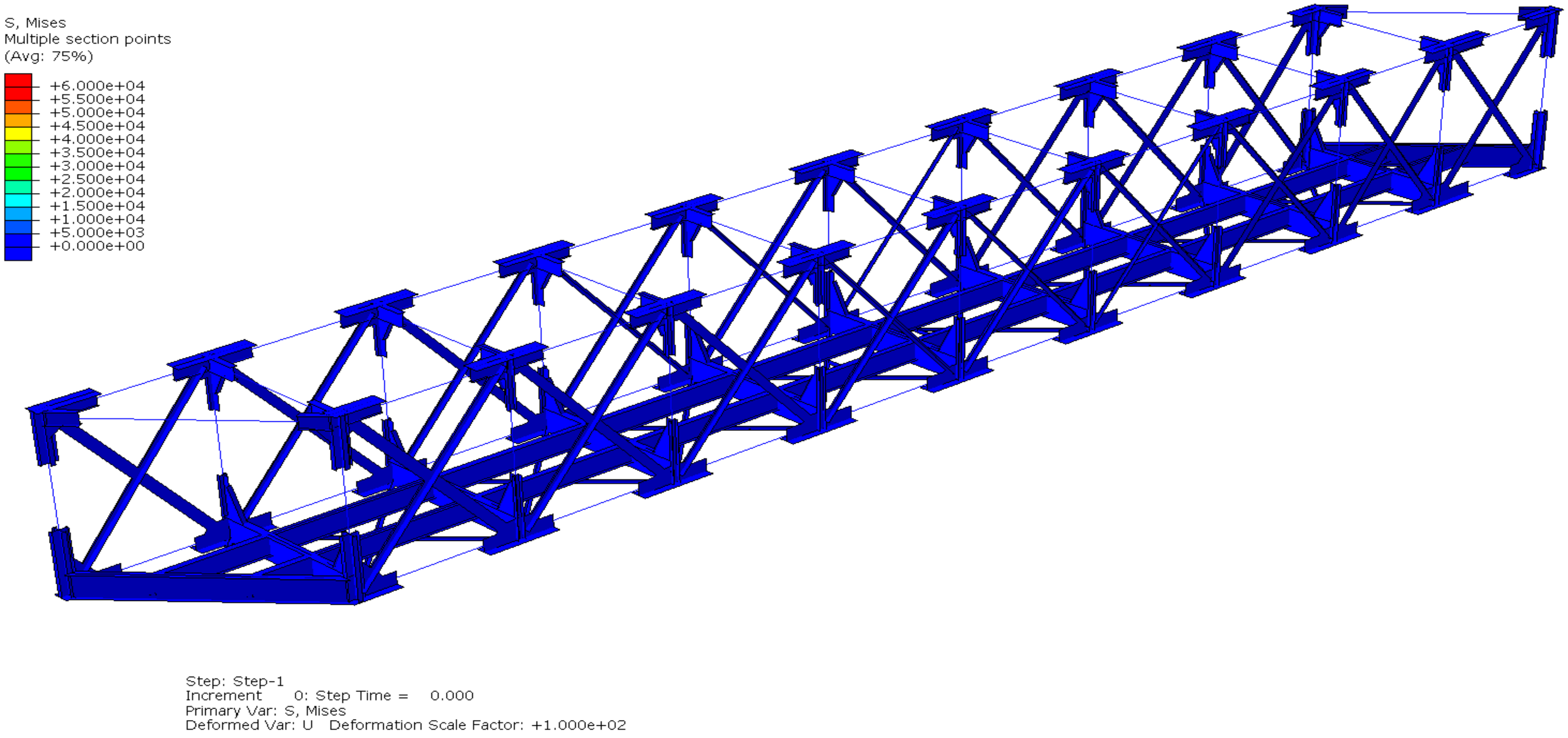
- Based on the verifications done by an engineering office*, the cross-beams of Münchenstein Bridge were the fatigue critical elements if further bridge serviceability after 2030 is intended.

- Therefore, the goal of a pilot project was to demonstrate the capability and the effectiveness of a pre-stressed un-bonded strengthening system to reinforce this bridge.

*Private report submitted to SBB: Ingenieurbüro SIA HUBER+GEMPERLE, Schlussbericht Tragwerksbeurteilung Brücke I, Münchenstein, Page 6, 2010.

FE Modeling

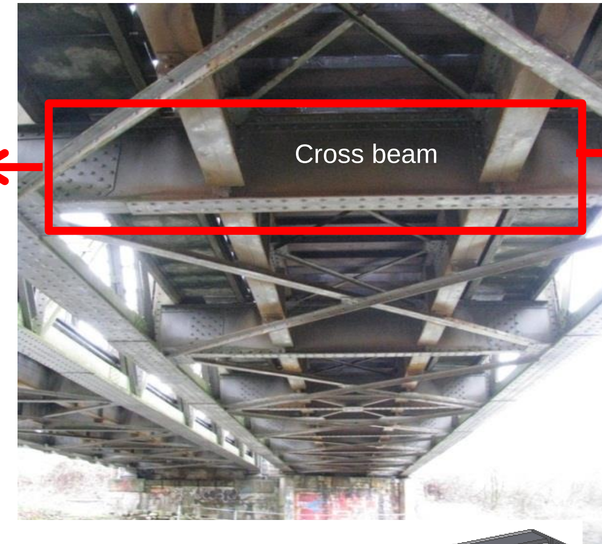

45 m
1
2
3
4
5
6 m


S, Mises
Multiple section points
(Avg: 75%)
+6.000e+04
+5.500e+04
+5.000e+04
+4.500e+04
+4.000e+04
+3.500e+04
+3.000e+04
+2.500e+04
+2.000e+04
+1.500e+04
+1.000e+04
+5.000e+03
+0.000e+00
Step: Step-1
Increment 0: Step Time = 0.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+02

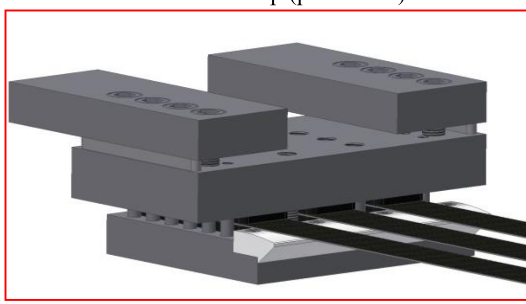
PUR System

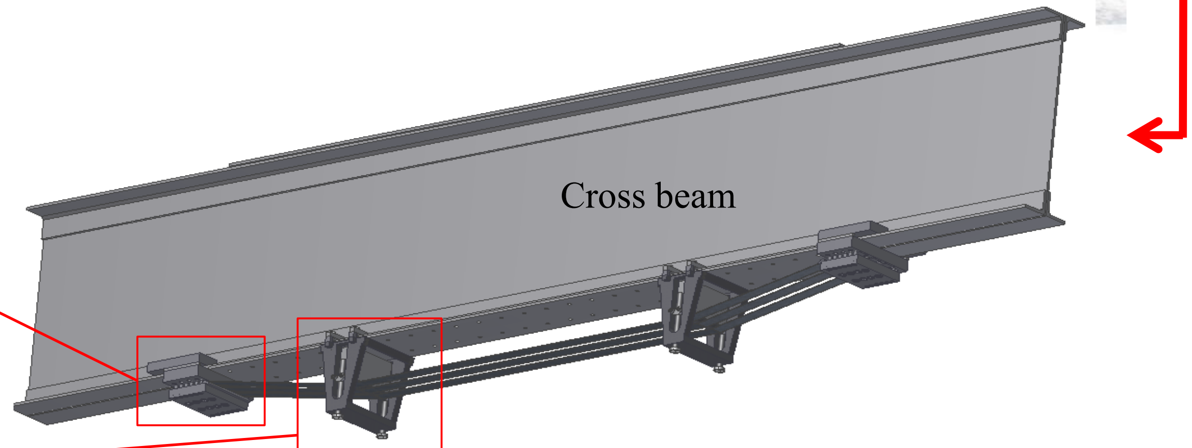
Prestressed un-bonded retrofit (PUR)

1. Applicable to unsmooth surfaces (i.g., riveted beams).
2. Fast installation (no gluing & no surface preparation).
3. Easy to prestress (no hydraulic jacks).
4. No traffic interruptions for bond curing.
5. Minimum damage (no hole, glue & grinding).
6. Adjustable prestressing level (to compensate relaxation).
7. Easy to remove.

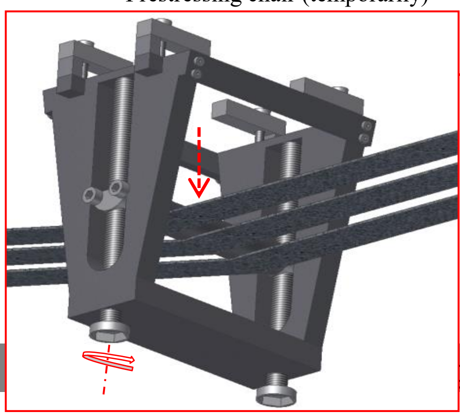


Clamp (permanent)

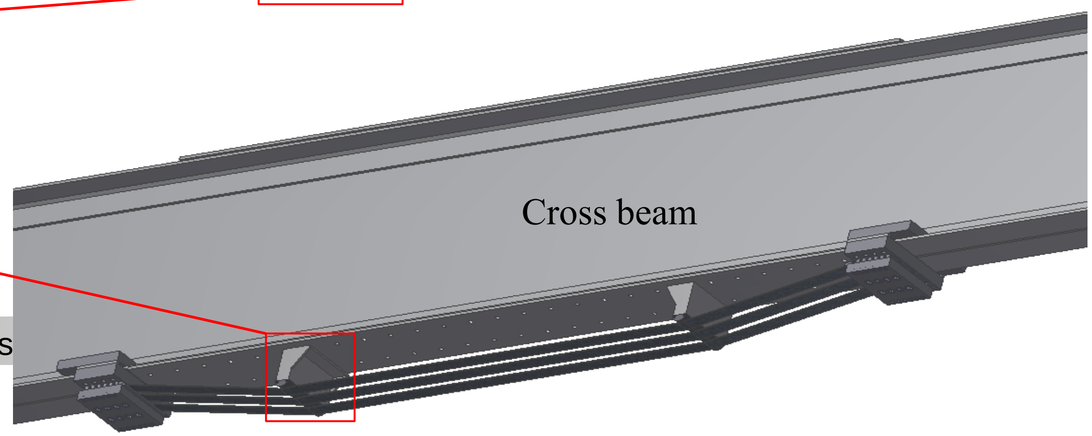




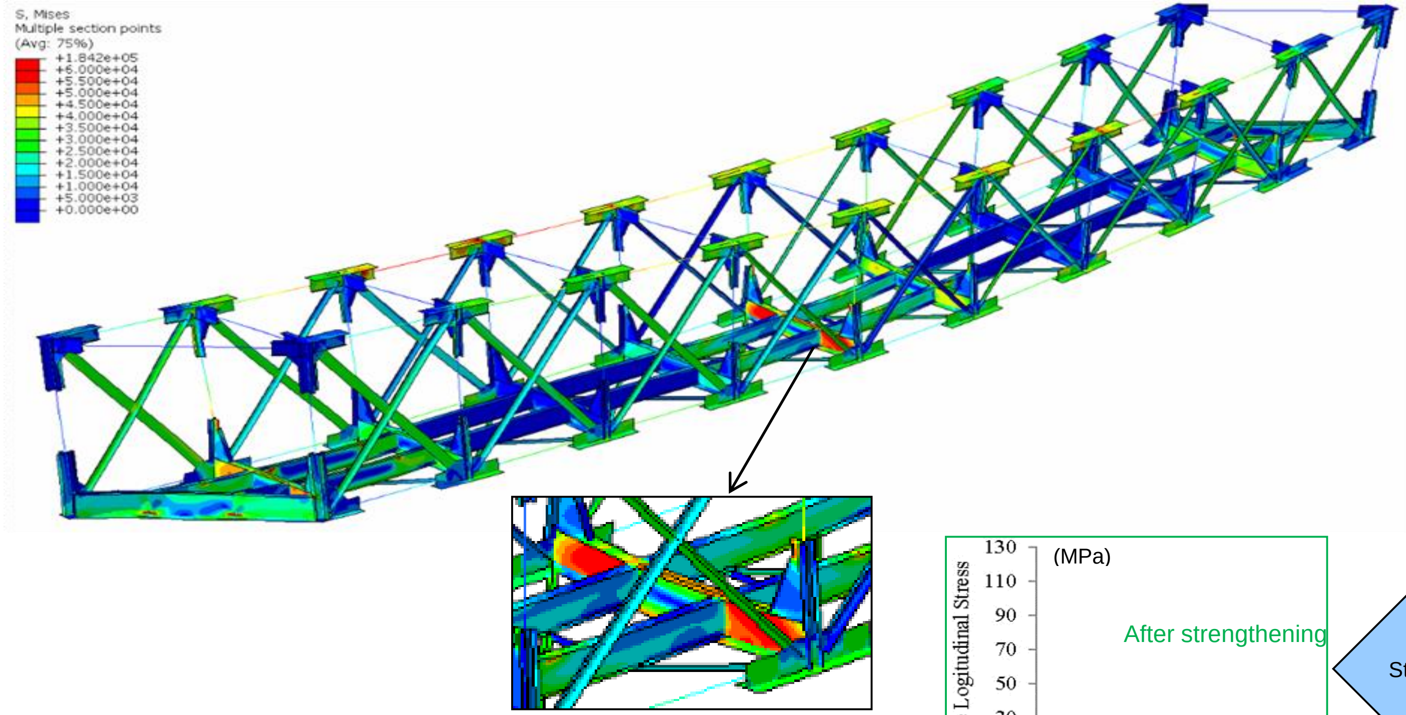
Prestressing chair (temporarily)

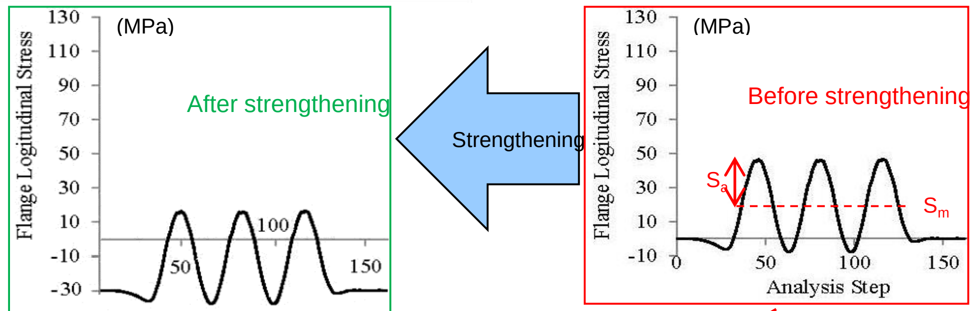


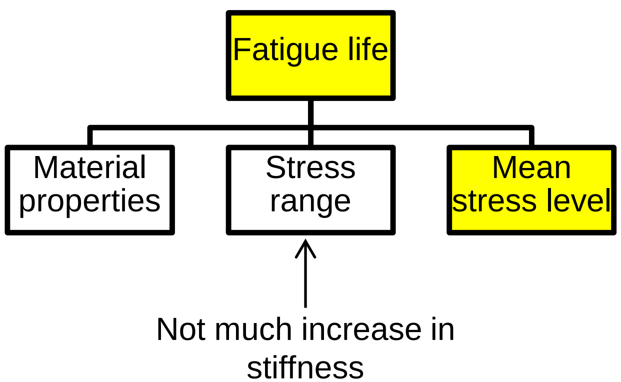
Column (permanent)



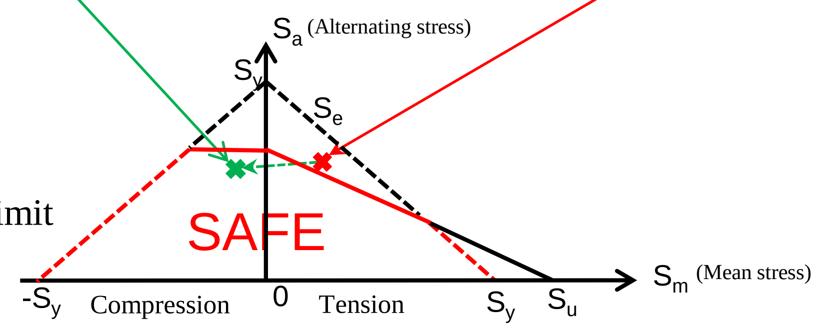
Fatigue Theory







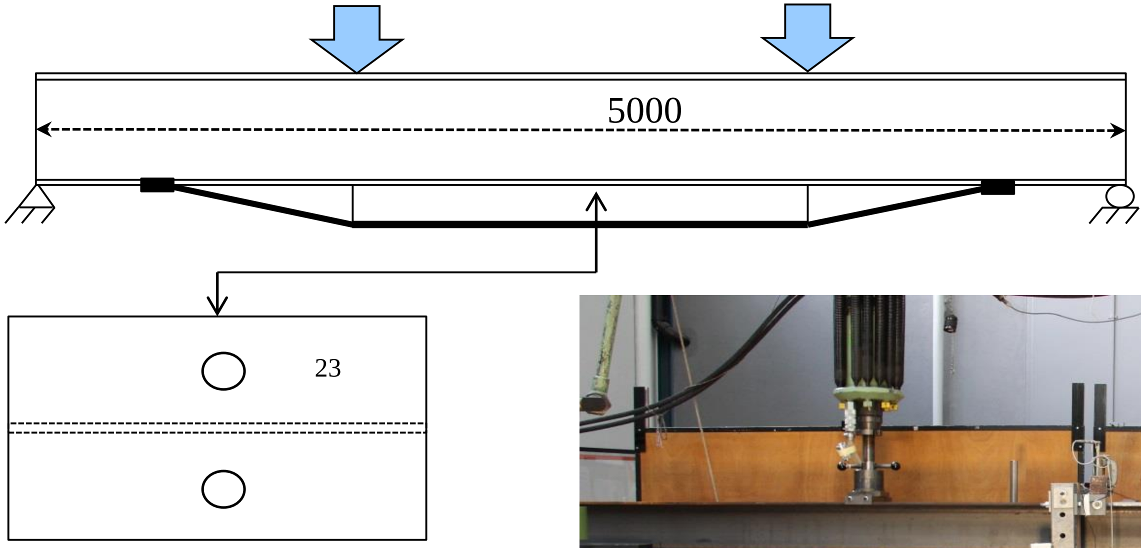
$S_m=(\sigma_{max}+\sigma_{min})/2$
$S_a=(\sigma_{max}-\sigma_{min})/2$
S_y=yield limit
S_u=ultimate strength
S_e= fatigue endurance limit



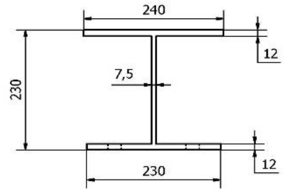
Modified Goodman Constant Life Diagram (CLD)

Laboratory Experiments

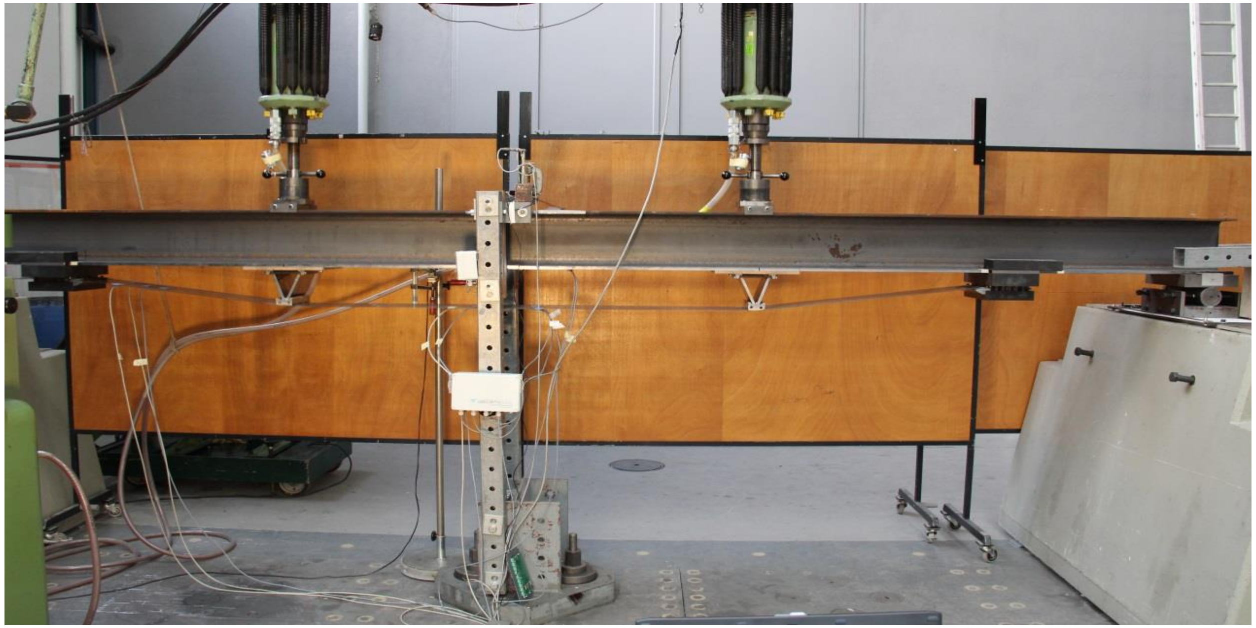
Cyclic loading



Detail of rivet holes in bottom flange of beam

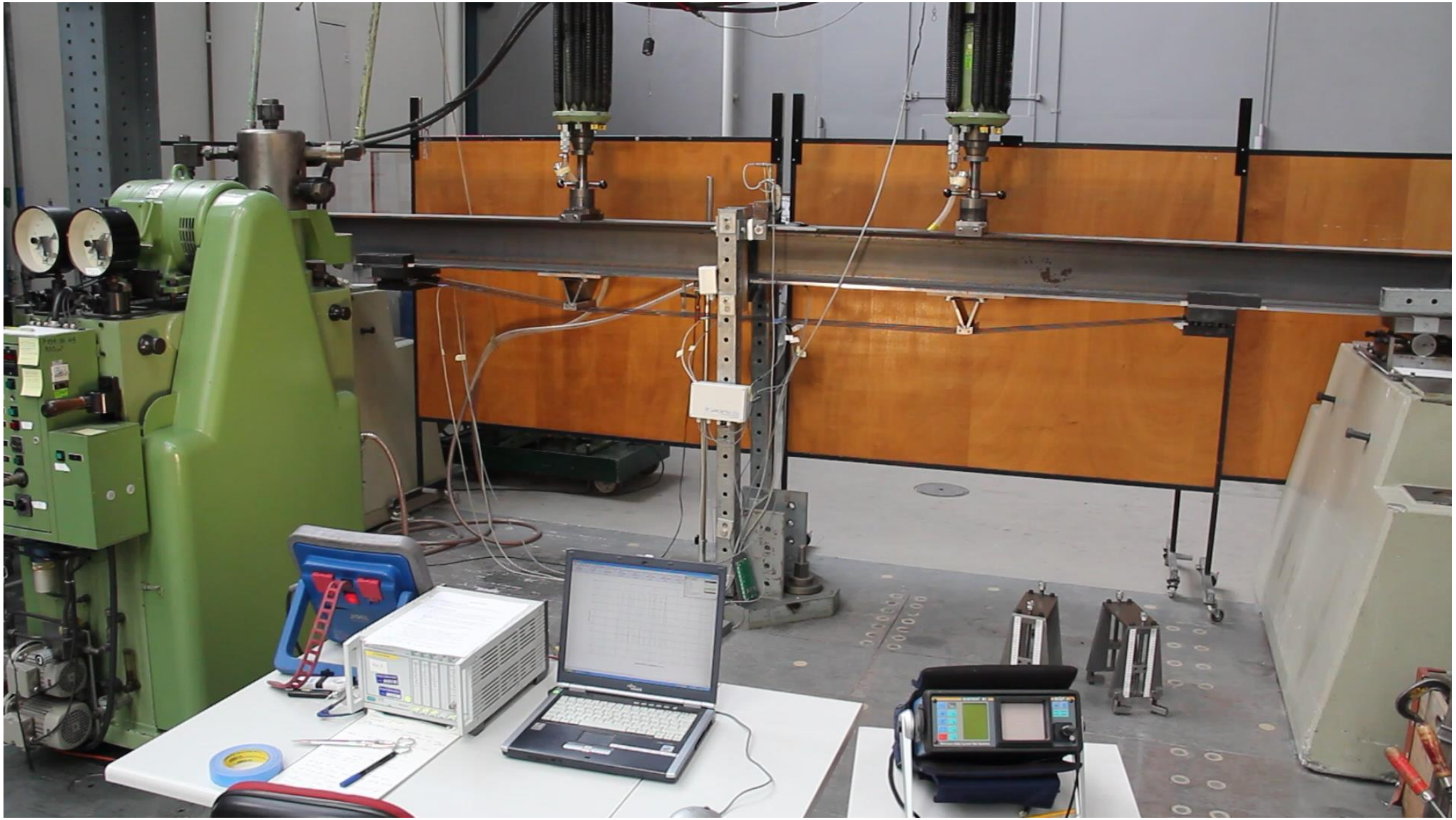


Dimensions in mm

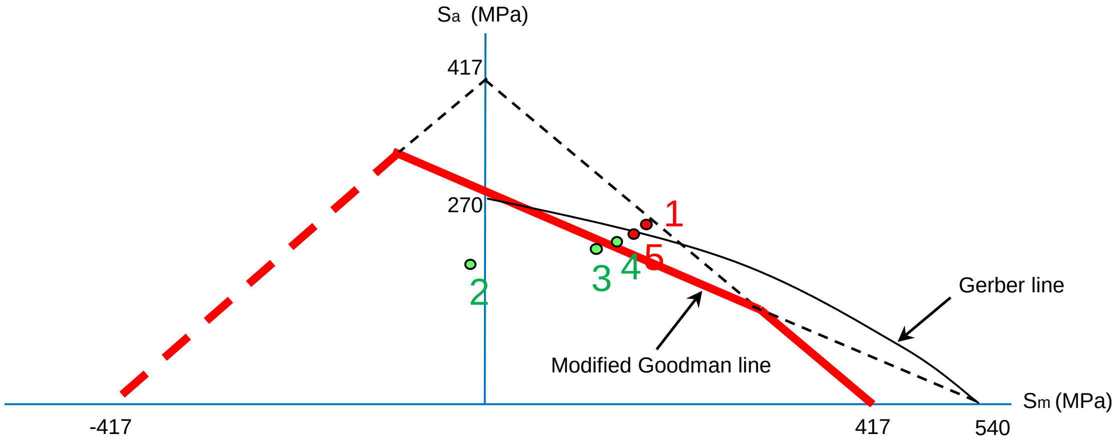


Laboratory Experiments

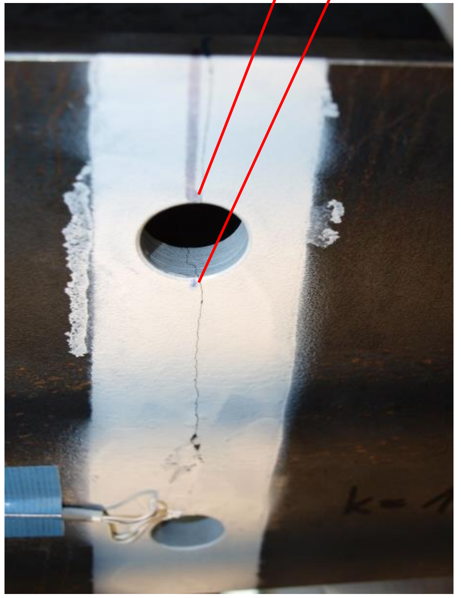
Video



Laboratory Experiments



Mode-I Fatigue Crack



Fatigue test 1 (beam 1), not strengthened: F=[2.5-68] kN -> N= 500’000 cycles -> cracked

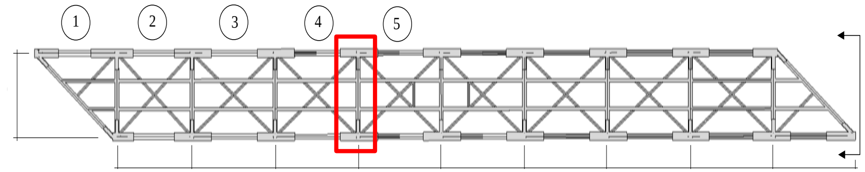
Fatigue test 2 (beam 2), 30% prestressing: F=[2.5-68] kN -> ΔN=2’000’000 cycles -> No crack

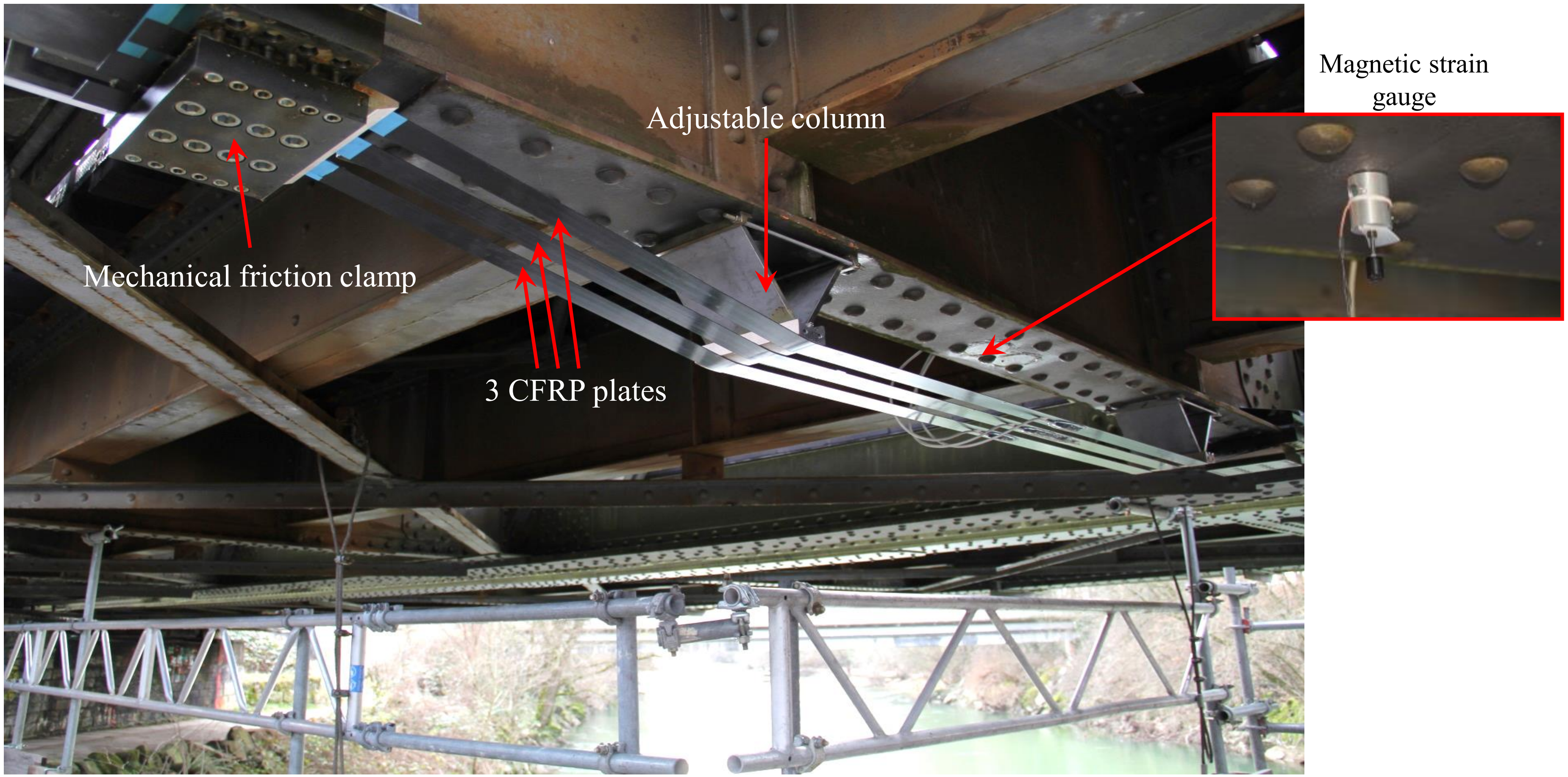
Fatigue test 3 (beam 2), 22% prestressing: F=[2.5-68] kN -> ΔN=3’000’000 cycles -> No crack

Fatigue test 4 (beam 2), 14% prestressing: F=[2.5-68] kN -> ΔN=3’000’000 cycles -> No crack

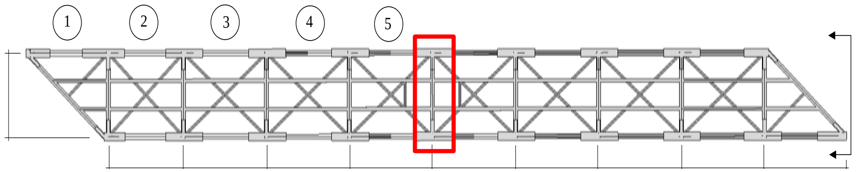
Fatigue test 5 (beam 2), 4% prestressing: F=[2.5-68] kN -> ΔN=1’500’000 cycles -> cracked

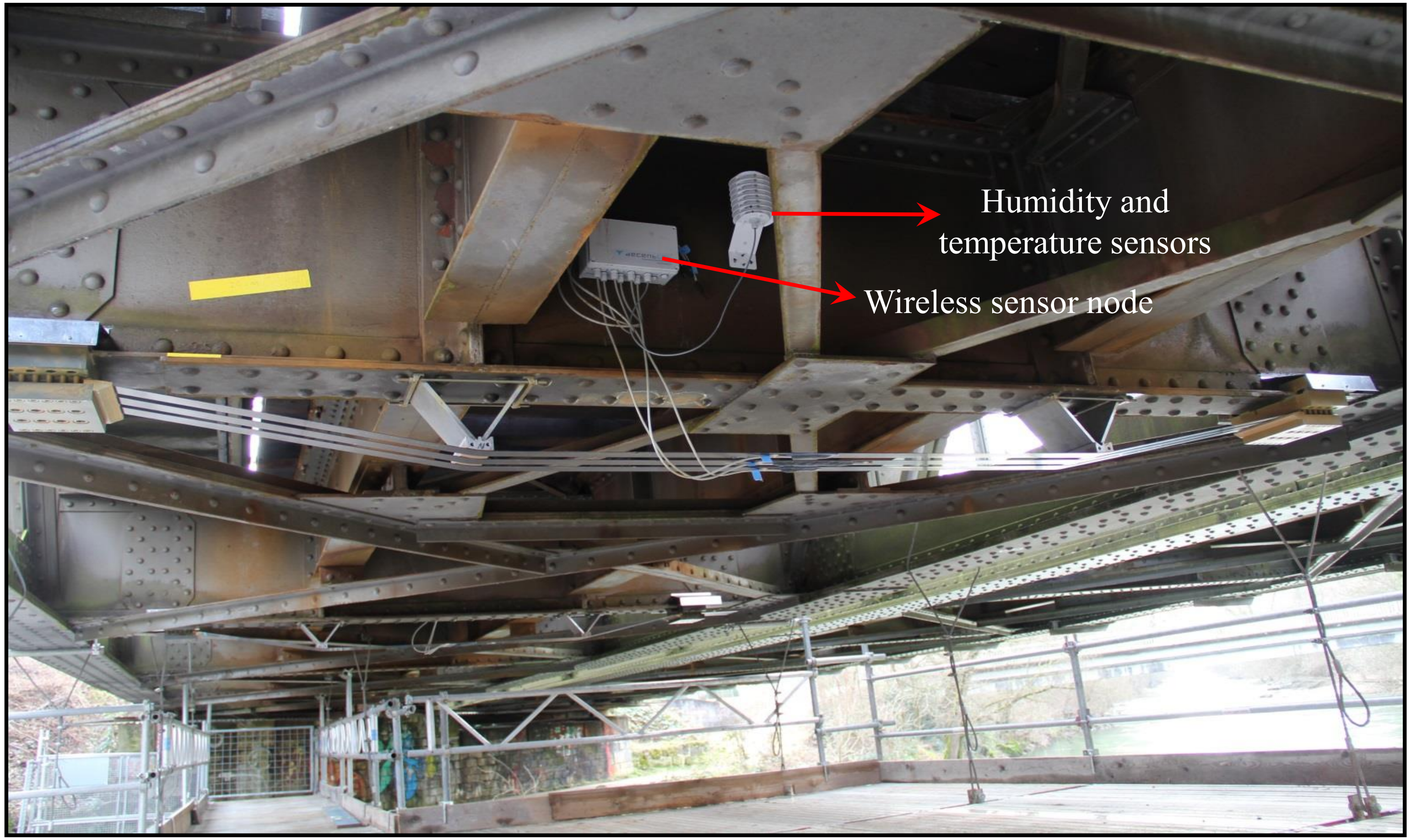
Laboratory Experiments



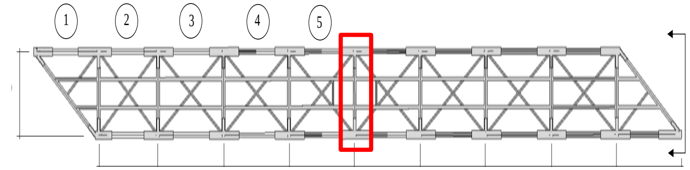


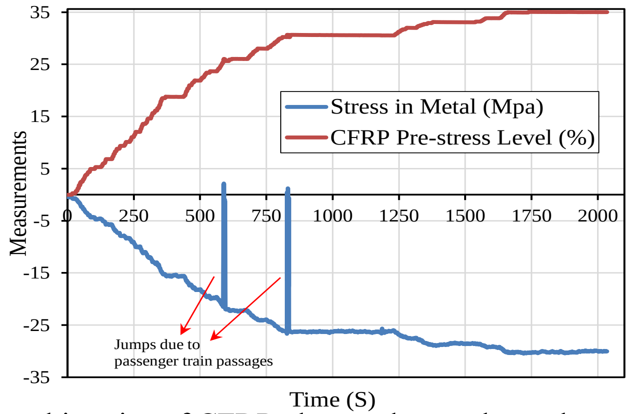
Bridge Strengthening



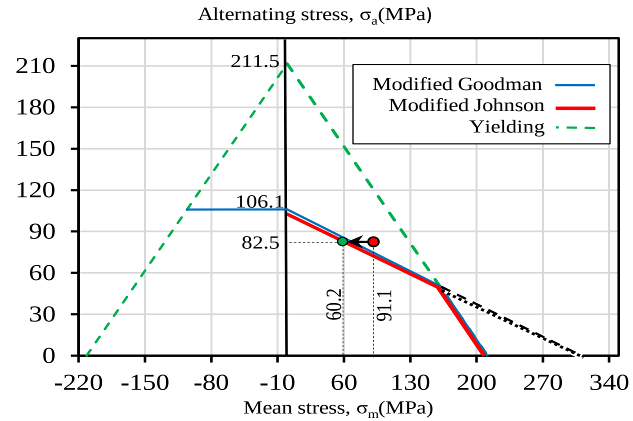


Bridge Strengthening

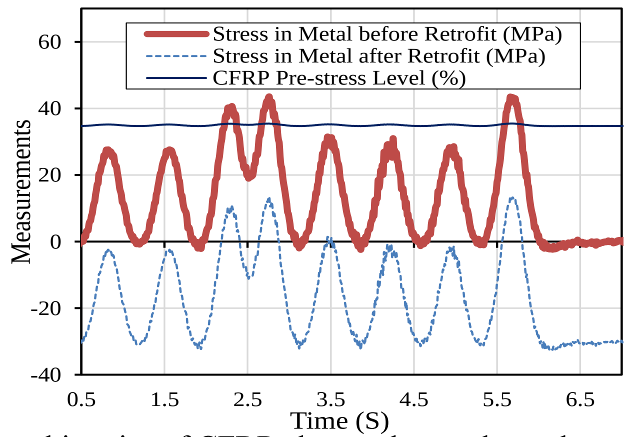




Stress-histories of CFRP plate and cross-beam bottom flange while pre-stressing



CLD presentation of shifting stresses from finite life zone to infinite life region using pre-stressed CFRP material (D4 load model)



Stress-histories of CFRP plate and cross-beam bottom flange before & after strengthening due to S3 train

A S3 passenger train crossing Münchenstein Bridge

Case Study:

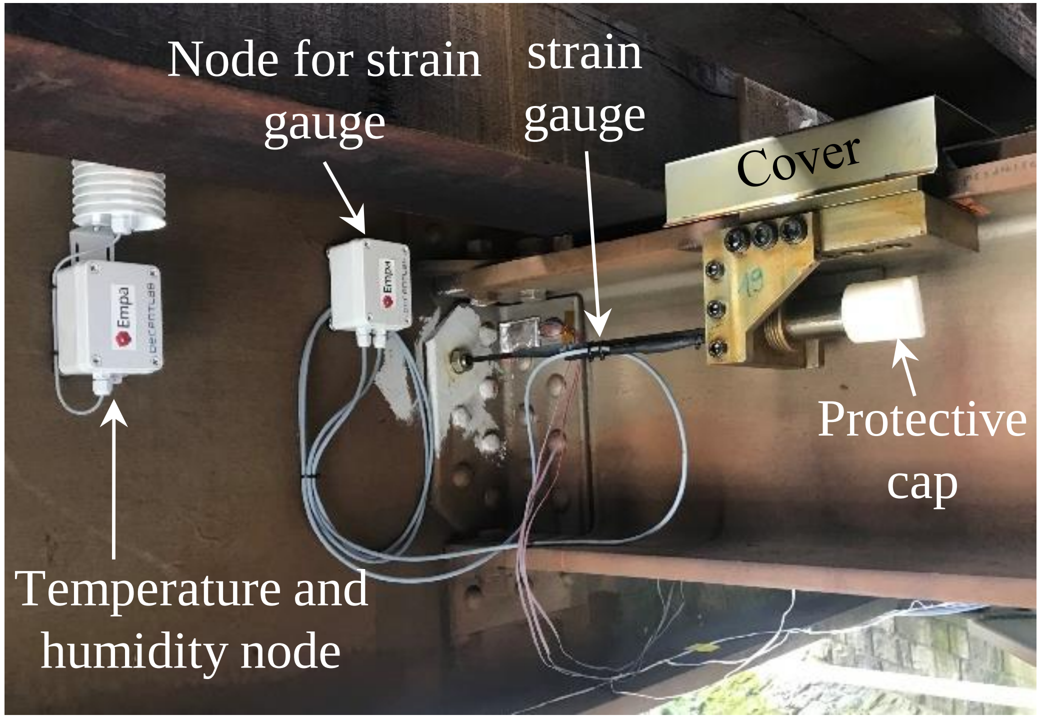
Fatigue Strengthening of Aabach Railway Bridge Connections

Aabach Bridge in Lachen, Switzerland

- Riveted railway bridge
- Built in 1928
- Total Length: 38.7 m
- Subjected to passenger and freight trains

Aabach Bridge in Lachen, Switzerland

Strengthening of the connections



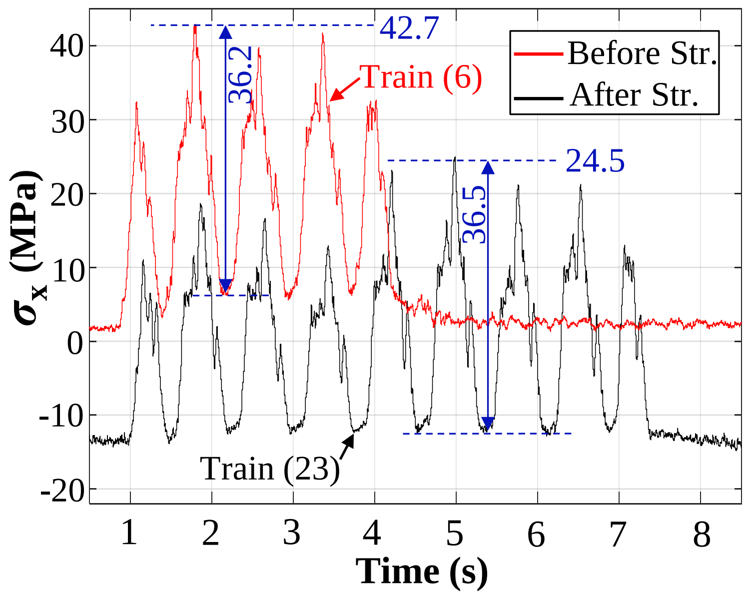
Rosette strain gauge for the short-term measurements

More details in: Heydarinouri, H., Nussbaumer, A., Motavalli, M., & Ghafoori, E. (2021). Strengthening of steel connections in a 92-year-old railway bridge using prestressed CFRP rods: Multiaxial fatigue design criterion. J Bridge Eng, 26(6), 04021023.

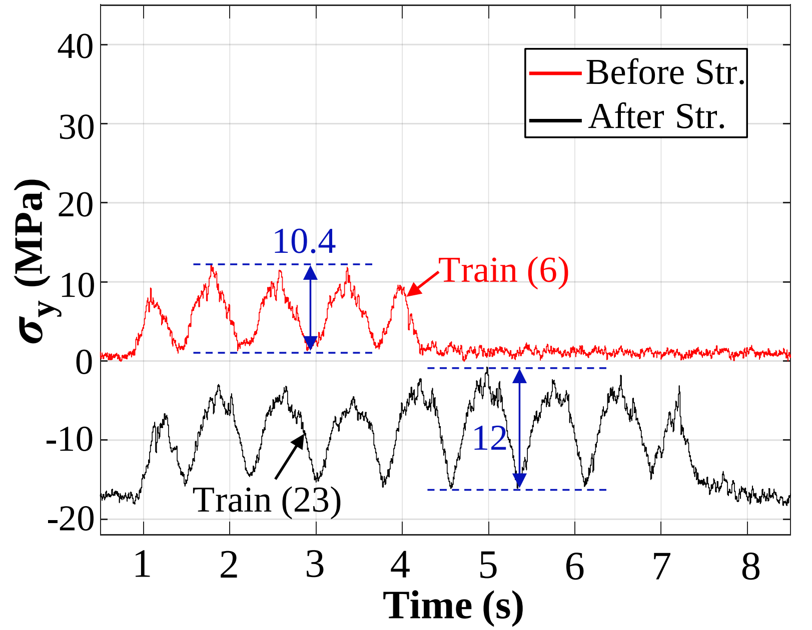
Aabach Bridge in Lachen, Switzerland

Strengthening of the connections

Strengthening effect on the stresses due to passage of **passenger trains**.



x-direction



y-direction

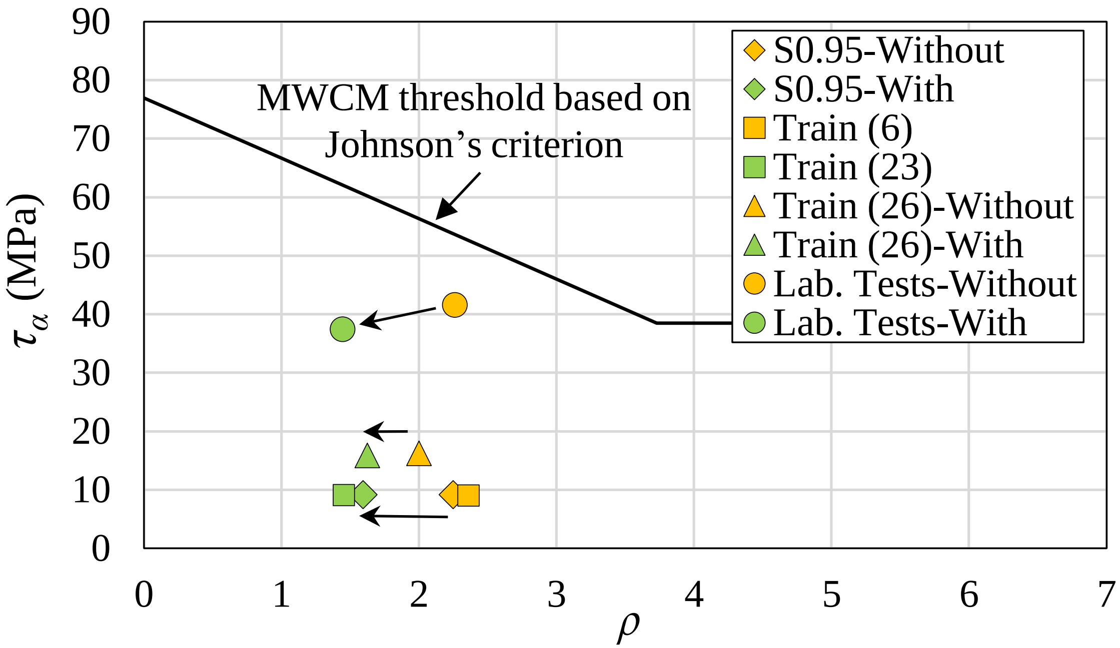
Strengthening system reduced on only the mean stress, and not the stress range.

More details in: Heydarinouri, H., Nussbaumer, A., Motavalli, M., & Ghafoori, E. (2021). Strengthening of steel connections in a 92-year-old railway bridge using prestressed CFRP rods: Multiaxial fatigue design criterion. J Bridge Eng, 26(6), 04021023.

Aabach Bridge in Lachen, Switzerland

Strengthening of the connections

- MWCM diagram to evaluate the fatigue state before and after strengthening.



The effectiveness of the strengthening system in reducing the stresses depends on the type of the train.

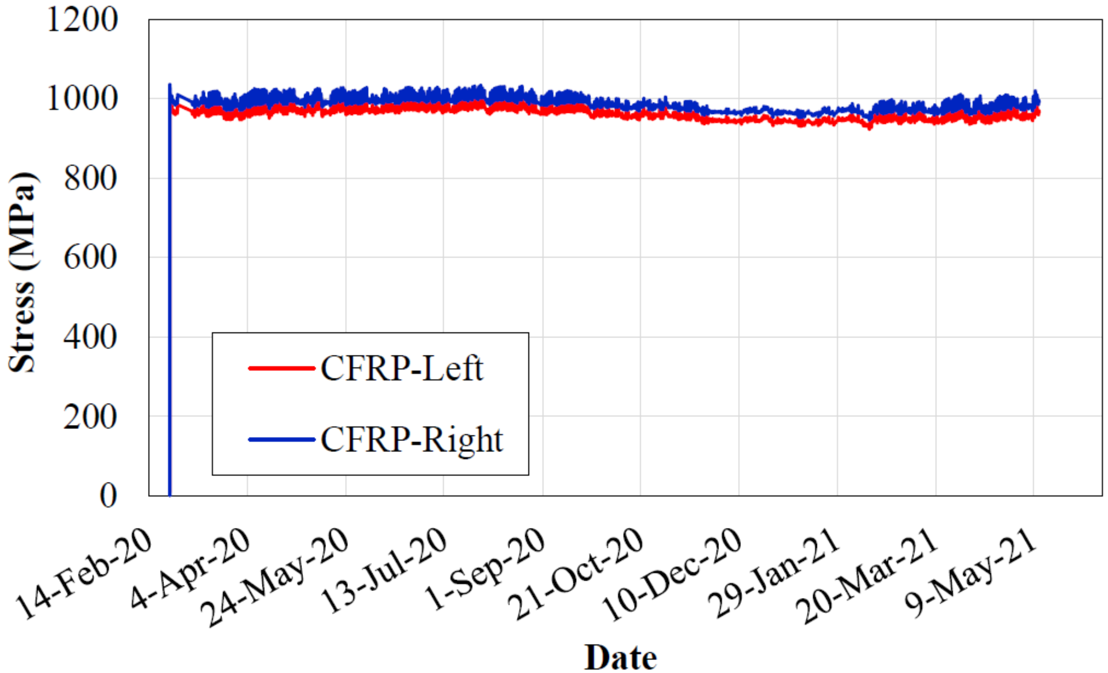
More details in: Heydarinouri, H., Nussbaumer, A., Motavalli, M., & Ghafoori, E. (2021). Strengthening of steel connections in a 92-year-old railway bridge using prestressed CFRP rods: Multiaxial fatigue design criterion. J Bridge Eng, 26(6), 04021023.

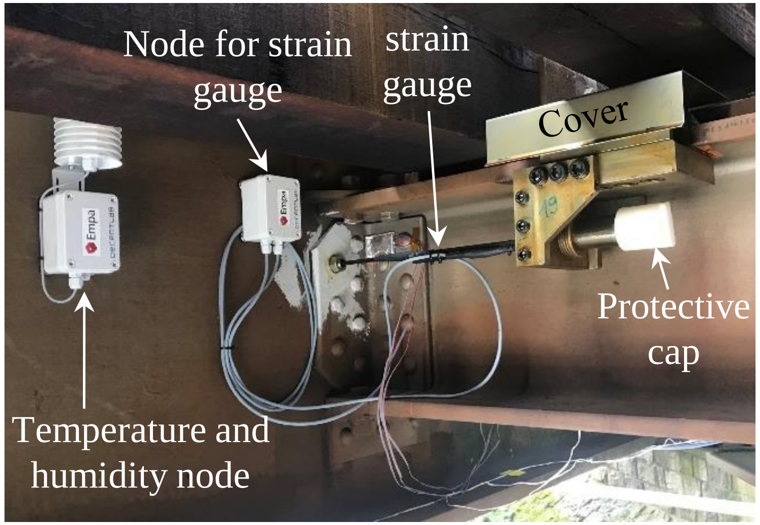
Aabach Bridge in Lachen, Switzerland

Strengthening of the connections

- Long-term monitoring

Stress history of the CFRP rods





No prestressing loss occurred in the CFRP rods since the installation.

More details in: Heydarinouri, H., Nussbaumer, A., Motavalli, M., & Ghafoori, E. (2021). Strengthening of steel connections in a 92-year-old railway bridge using prestressed CFRP rods: Multiaxial fatigue design criterion. J Bridge Eng, 26(6), 04021023.

Conclusions: Prestressed vs. Non-prestressed CFRP Plates

Advantages:

- Utilization of high tensile strength of CFRP materials
- Prestressed FRPs can carry both a portion of the dead load and the additional live load carried by the structure
- Increasing yielding load
- Increasing ultimate load capacity
- Substantial increase in fatigue life
- Possible arrest of existing fatigue cracks

Conclusions: Prestressed vs. Non-prestressed CFRP Plates

Disadvantages:

- Large amount of labor work for prestressing (you can almost forget about CFRP cost).
- High interfacial shear stresses at plate ends => earlier debonding => use of mechanical anchorage system

Conclusions: Bonded vs. Un-bonded CFRP-steel Composite Systems

- **Weak point:**

The main difference between FRP–steel and FRP–concrete bonded joints is that in the former, failure will likely occur in the adhesive layer and in the latter failure is expected to occur in the concrete. Thus the weakest point an FRP-steel composite systems is the adhesive.

- **Surface preparation:**

Prior to bond application, surface of steel beam should be cleaned and all paint and anti-corrosion coating have to be removed.

- **High temperature:**

Compared to concrete, steel has a high thermal conductivity (about 50 W/mK) and has significant ability to transfer heat rapidly to the adhesive. Moreover, the rate of sunlight absorption by steel is much greater than the rate of steel electromagnetic radiation (black body radiation); therefore, steel members exposed to direct sunlight on a hot day will easily become much hotter than the ambient temperature. This effect makes the adhesive adjacent to a hot steel surface soften excessively when the service temperature of the steel substrate approaches the glass transition temperature of the adhesive.

- **Metallic riveted bridges:**

Due to the flat configuration of FRP plates, they cannot be bonded to the surface of structures that are not sufficiently smooth. Because the cover plate is riveted to the steel girders in steel-riveted bridges, for example, there is a high rivet density and the bonded FRP reinforcement system cannot be used.

- **Heritage structures:**

The components of strengthening systems for heritage structures need to be designed for easy removal when there is a need to restore the structure to its original unstrengthened construction design. In a bonded reinforcement system, FRP strengthening materials cannot be easily separated from the beam due to the applied glue.

More details in: Ghafoori E, et al., Fatigue strengthening of damaged steel beams using unbonded and bonded prestressed CFRP plates, International Journal of Fatigue, 2012, 44 , pp. 303-315.

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Thank You for Your Attention!

Any Questions?