Selected topics on advanced composites in engineering structures

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Manual for Repair and Retrofit of Fatigue Cracks in Steel Bridges

March 2013

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Fatigue-related structural problems

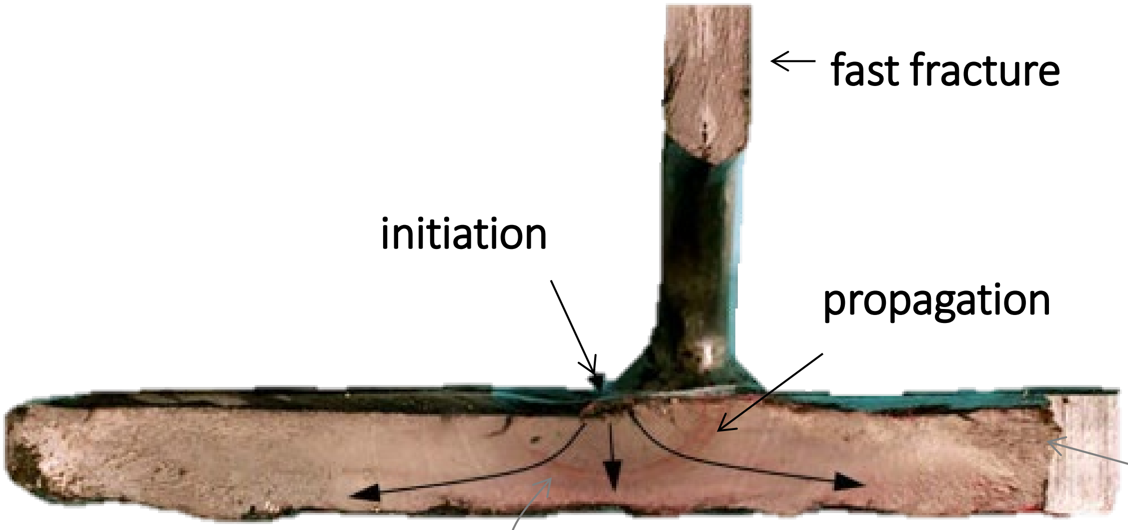
Maintenance Actions to Address Fatigue Cracking in Steel Bridge Structures

PROPOSED GUIDELINES AND COMMENTARY

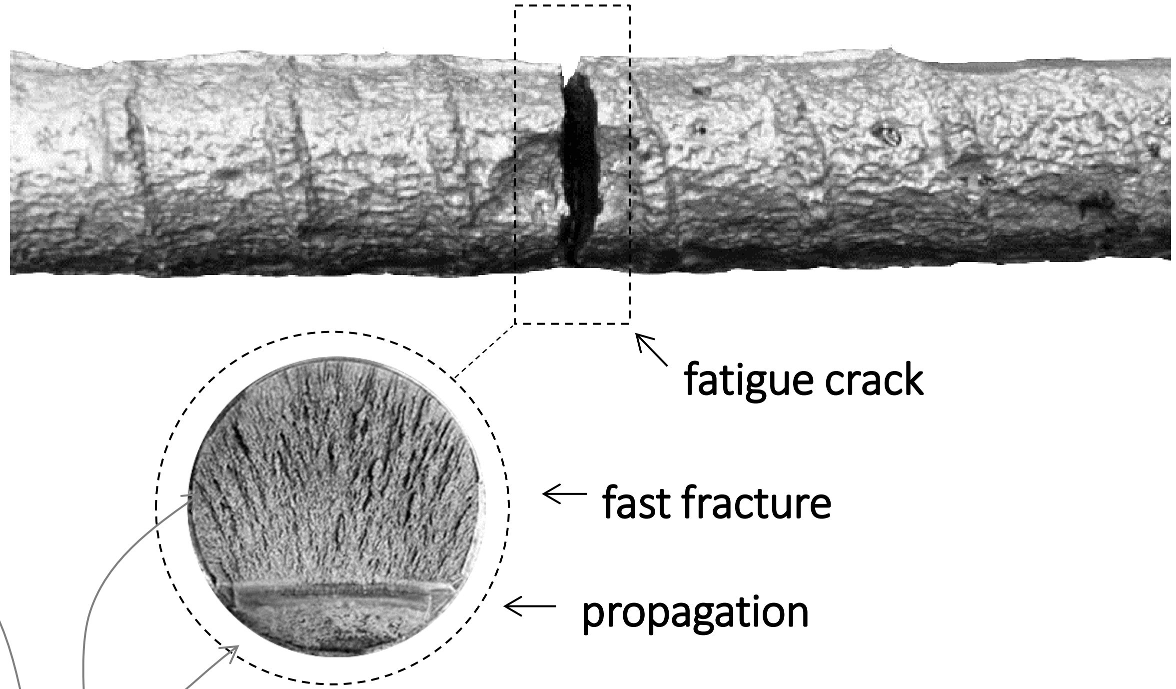
Prepared for:
NCHRP Transportation Research Board of
The National Academies

Fatigue-related structural problems:
Crack initiation and fracture

Steel girder



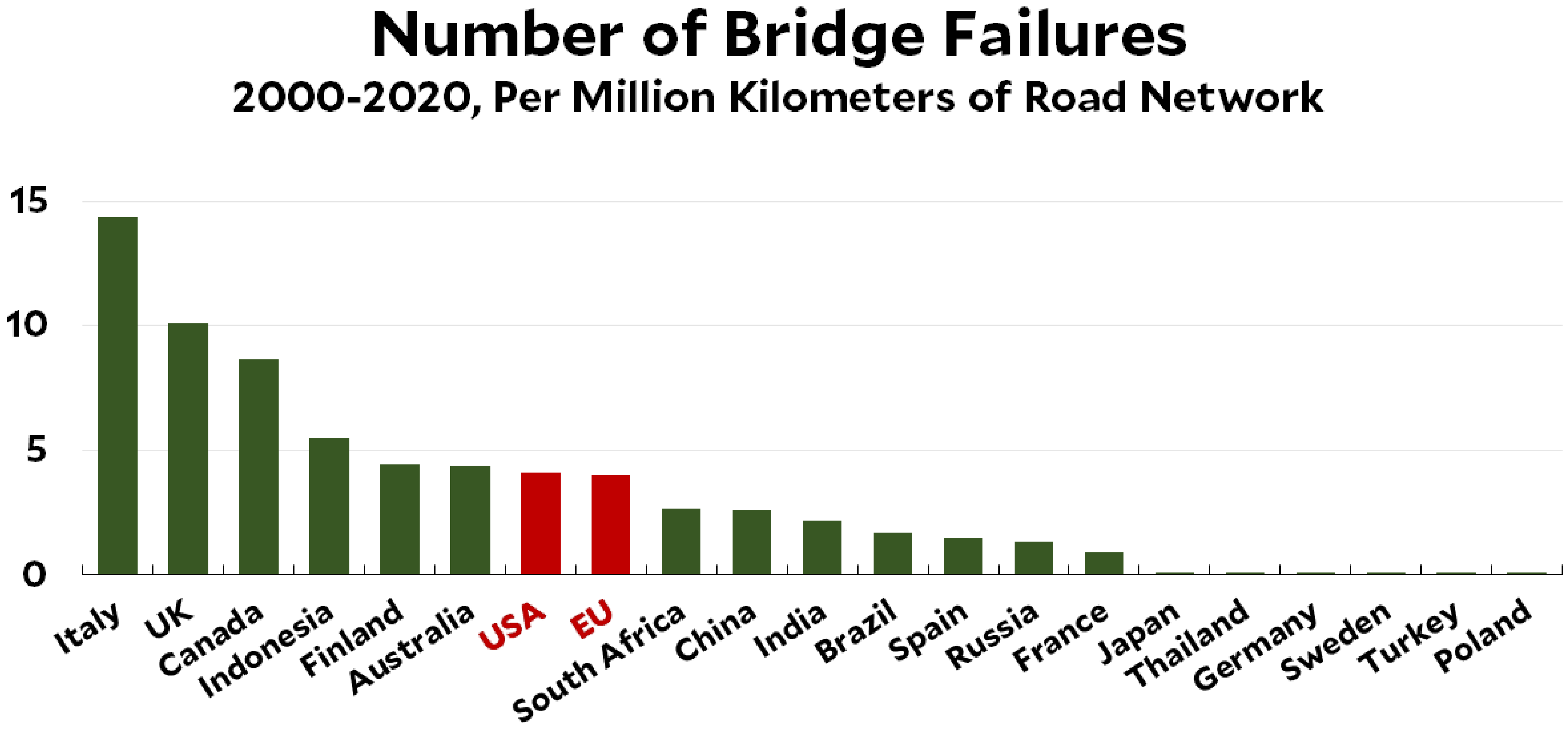
Steel rebar



Striations outlining the shape of the crack as it grew

Chevron marks pointing back to fracture initiation

Fatigue-related structural problems:
Crack initiation and fracture



https://en.wikipedia.org/wiki/List_of_bridge_failures

Fatigue-related structural problems:
Structural Health Monitoring

Exhibit 6-19: Bridges by Age, 2015

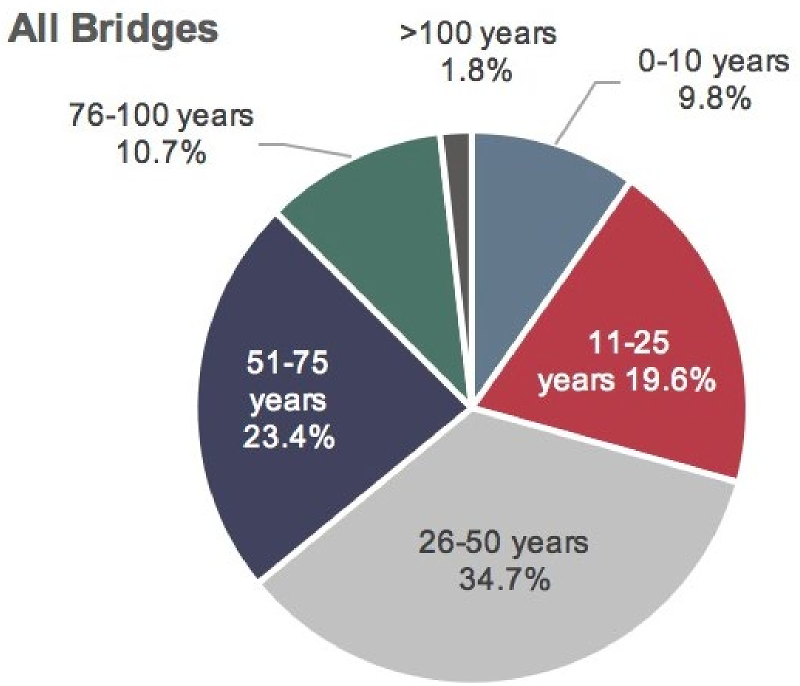
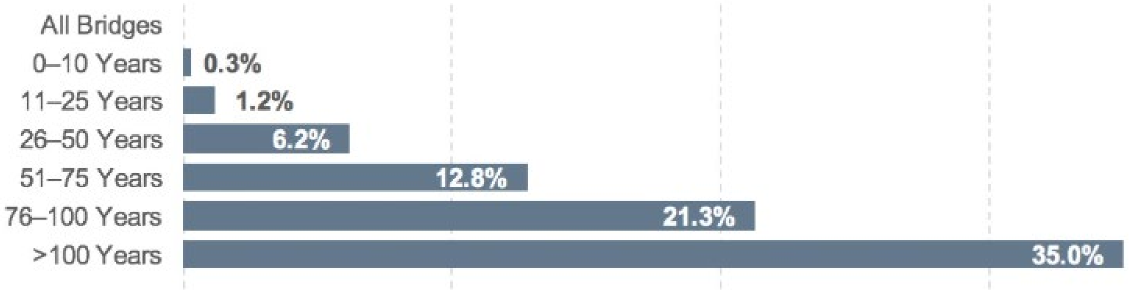


Exhibit 6-20: Bridges Rated Poor, by Age, 2015



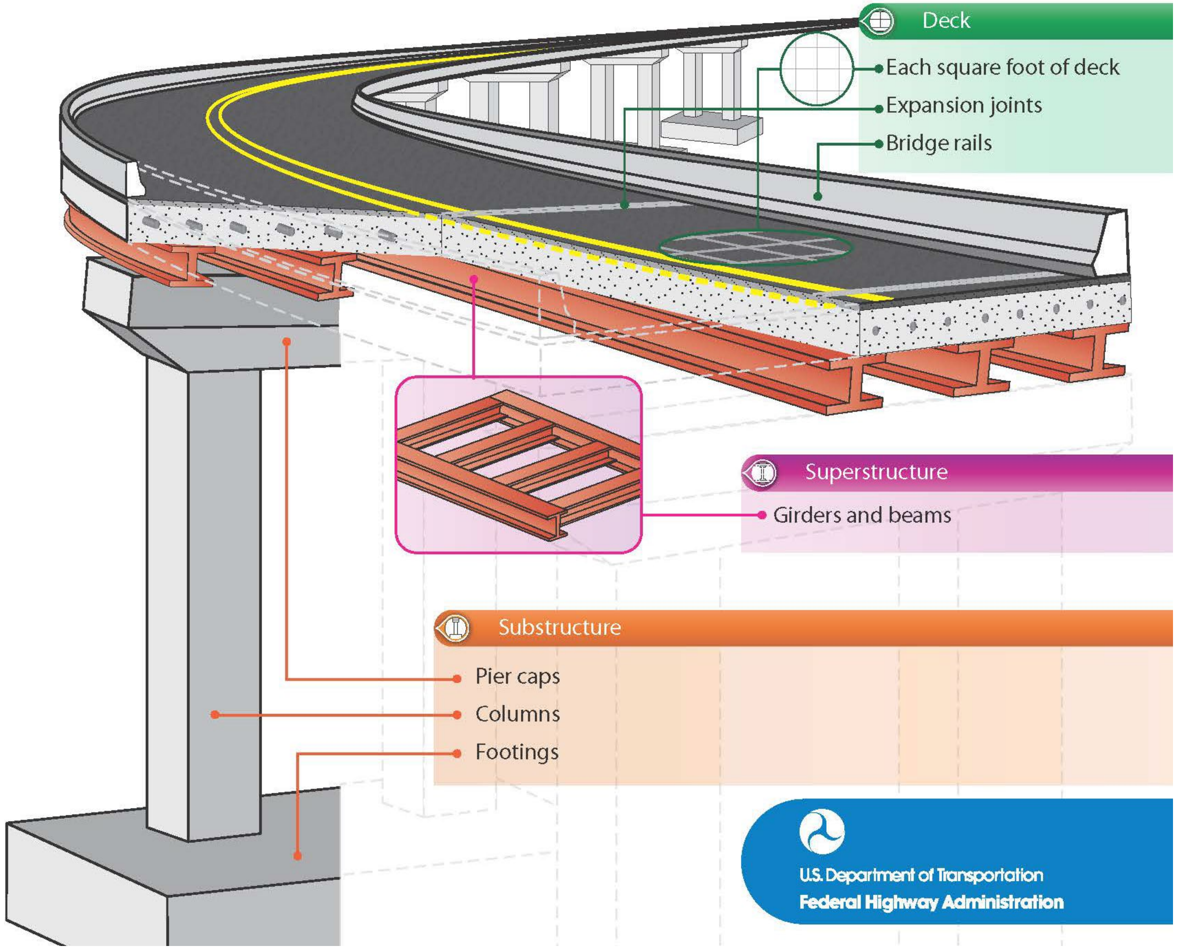
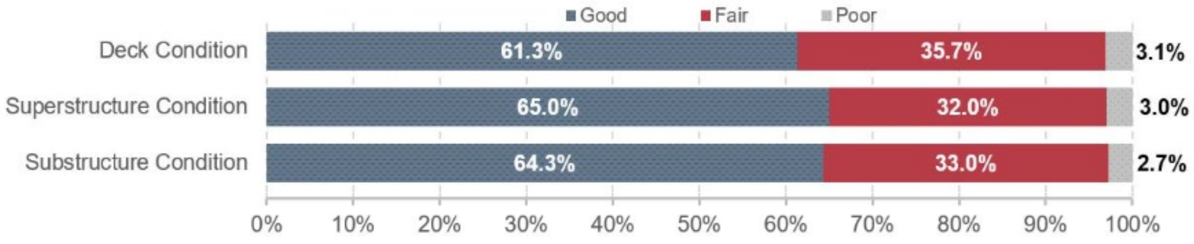


Exhibit 6-7: Systemwide Bridge Conditions, Weighted by Deck Area, 2015



Source: National Bridge Inventory.

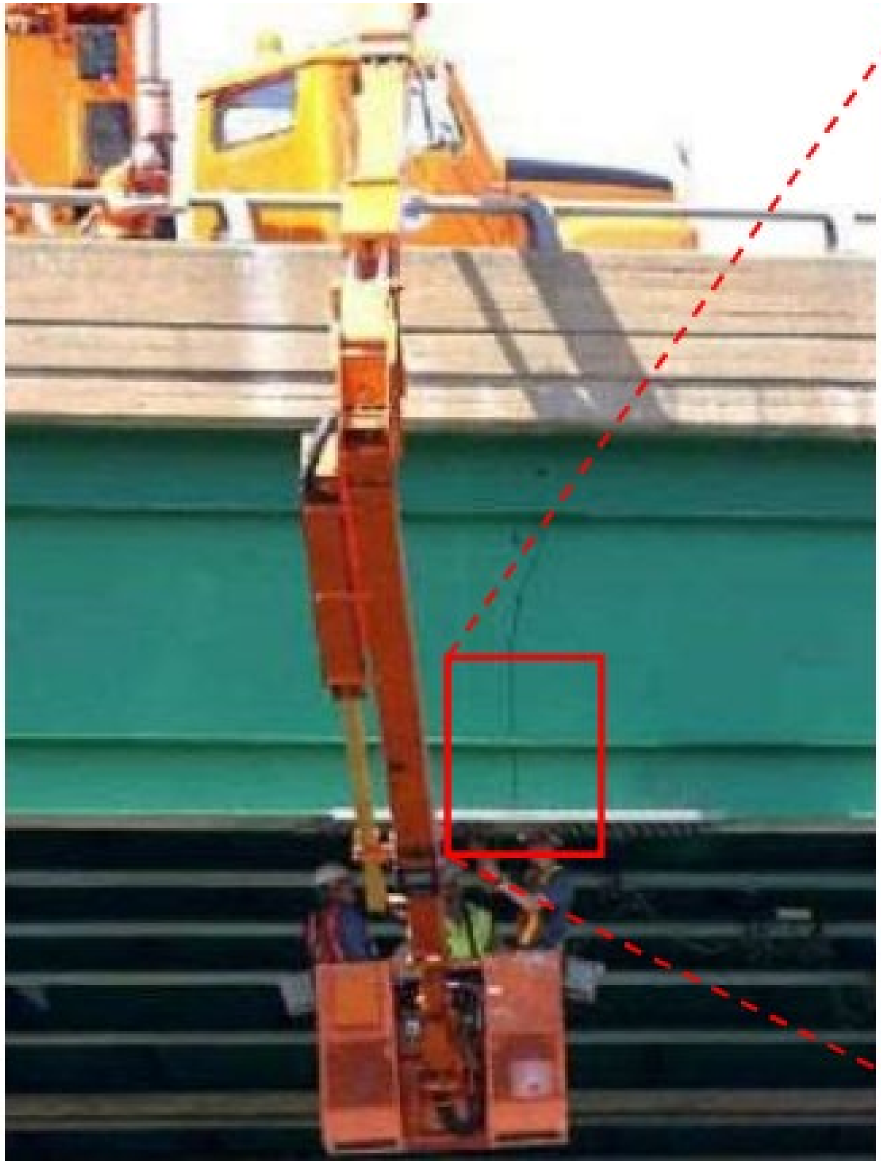
Fatigue-related structural problems:
Local collapse

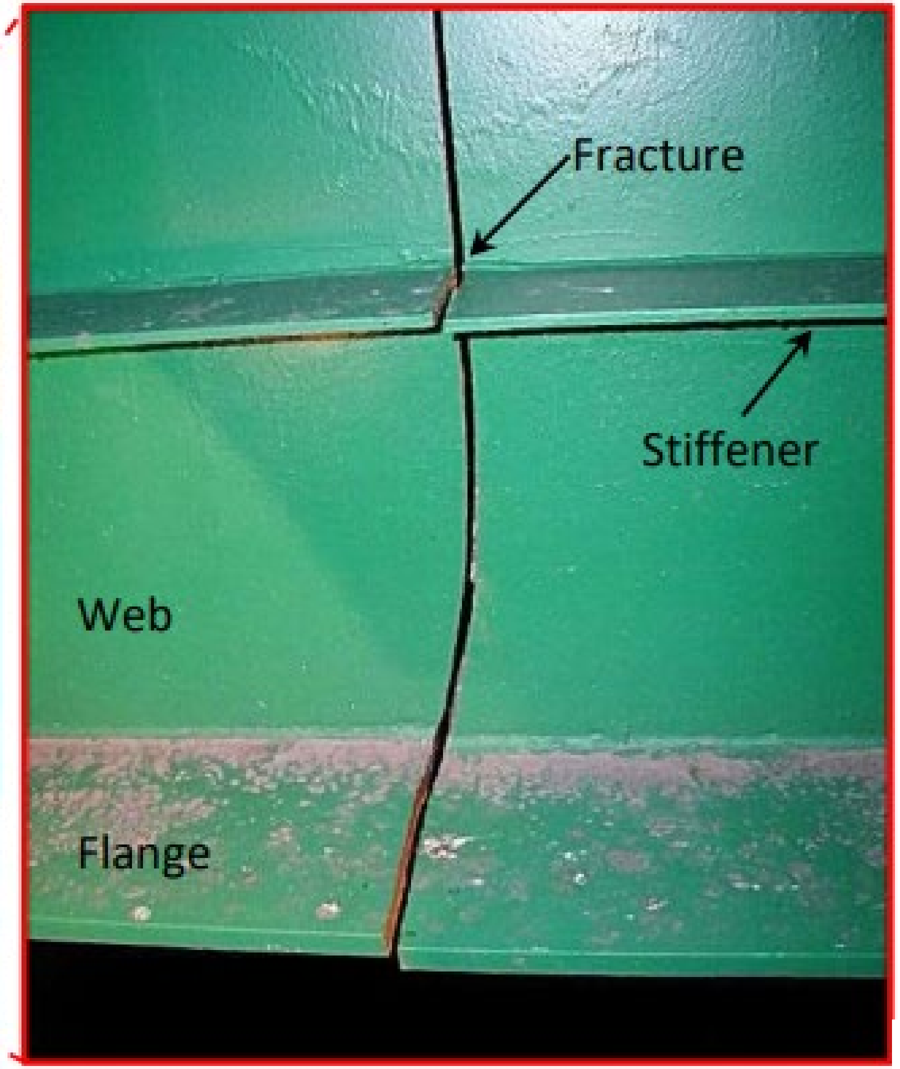
Northbound Lake Shore Drive bridge – Chicago (US) - 2022

Fatigue-related structural problems:
Local collapse

The Diefenbaker Bridge –
Saskatchewan (Canada) - 2011

Fatigue-related structural problems:
Local collapse



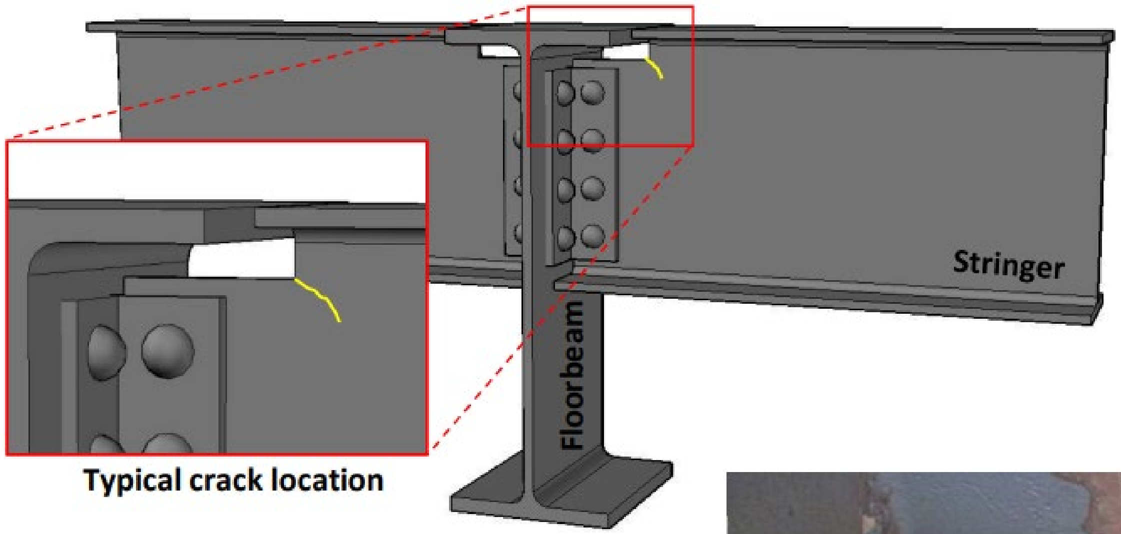


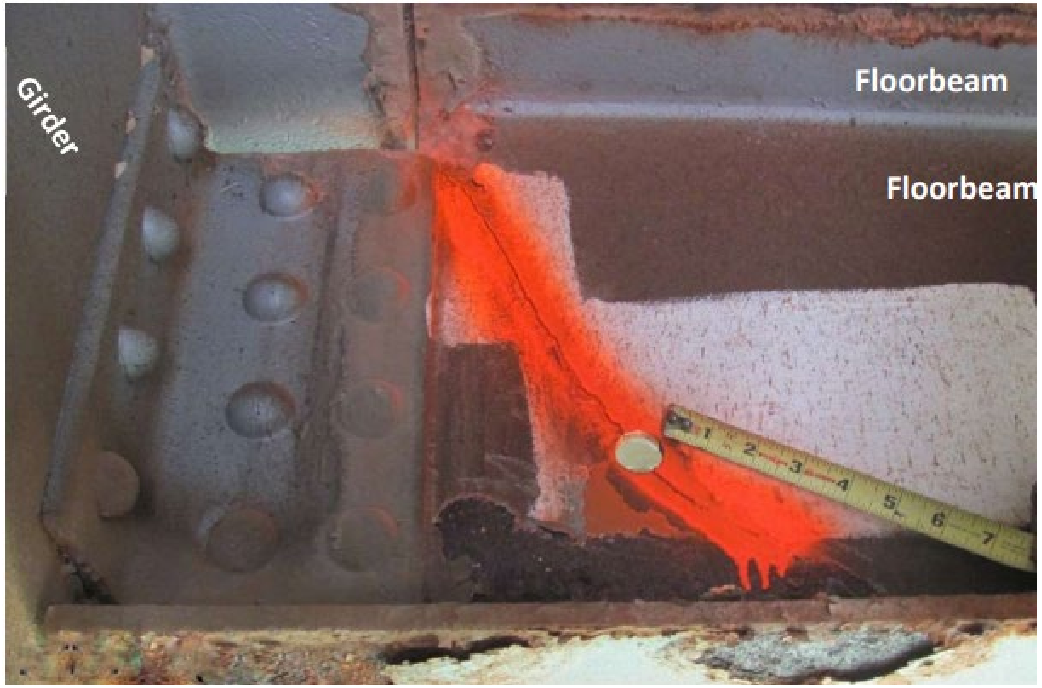
Bridge over Brandywine River–
Delaware (US) - 2005

Fatigue-related structural problems:
Local collapse

I-40 bridge – Memphis (US) - 2021

Fatigue-related structural problems:
Crack initiation

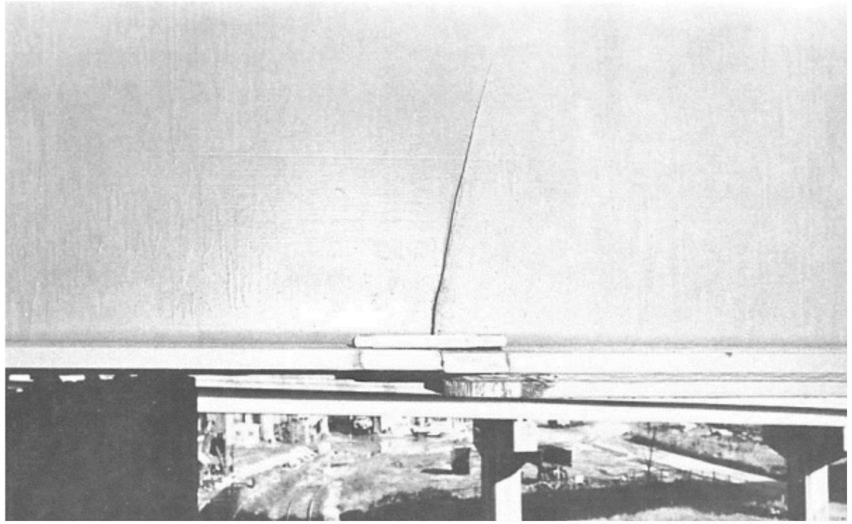


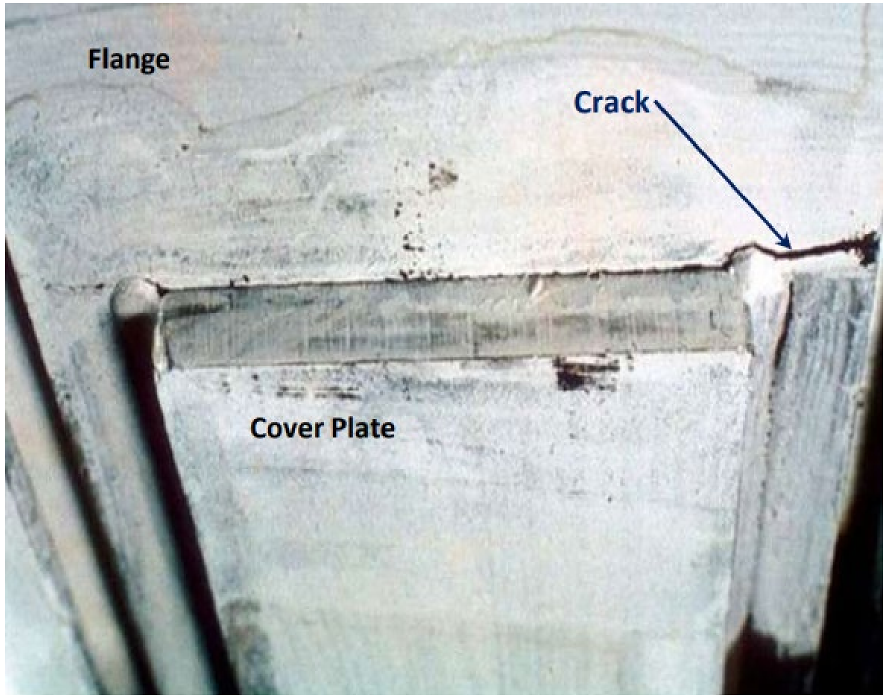


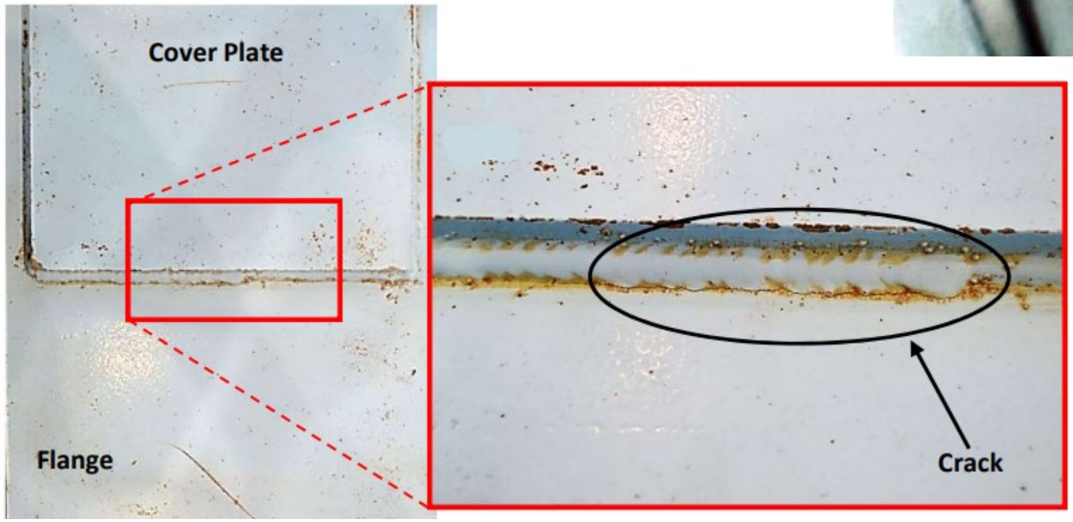
Initiation spot?

Re-entrant corners
Cover-plate welds
Stiffener-plate root
Tack welds
Connection angles

Fatigue-related structural problems:
Crack initiation







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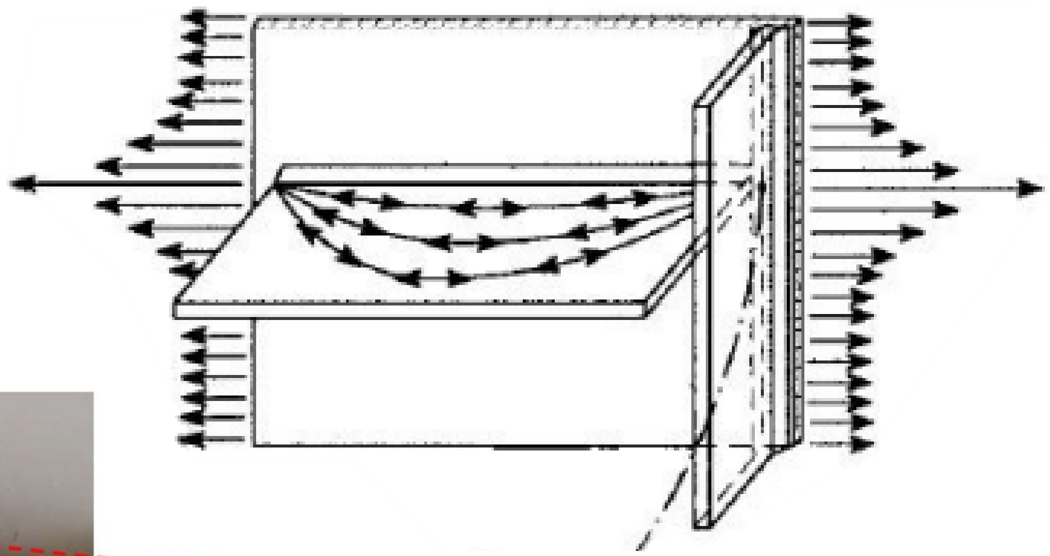

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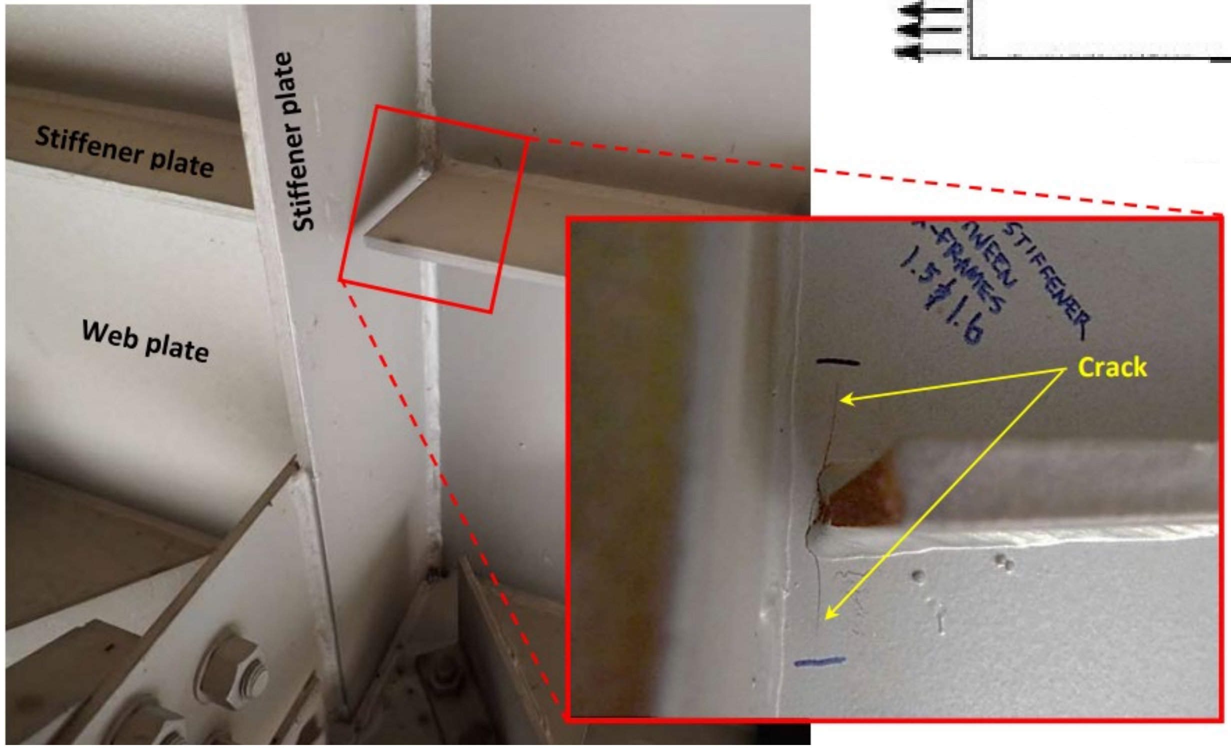
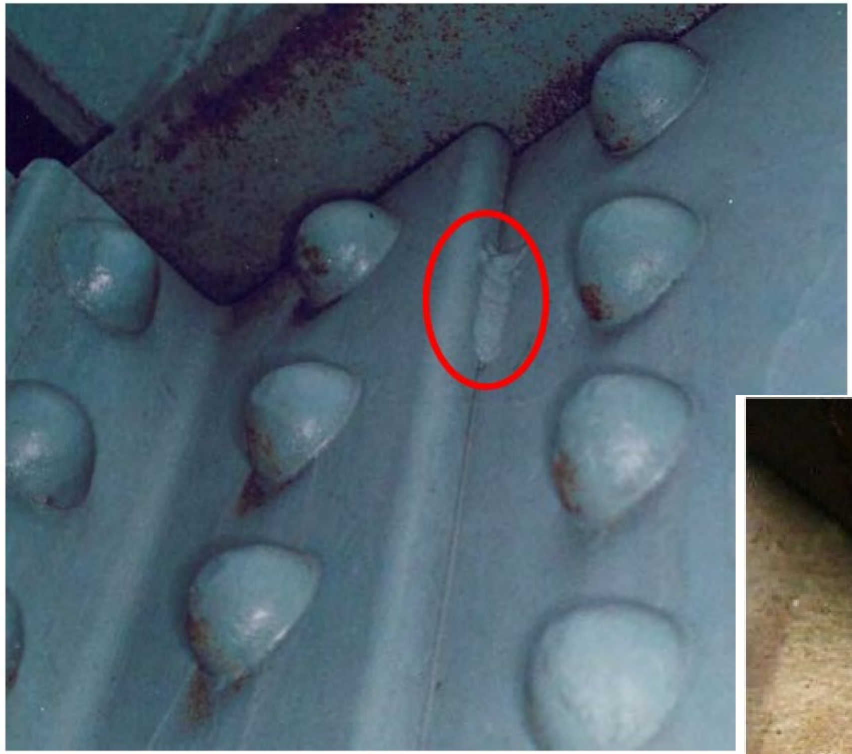
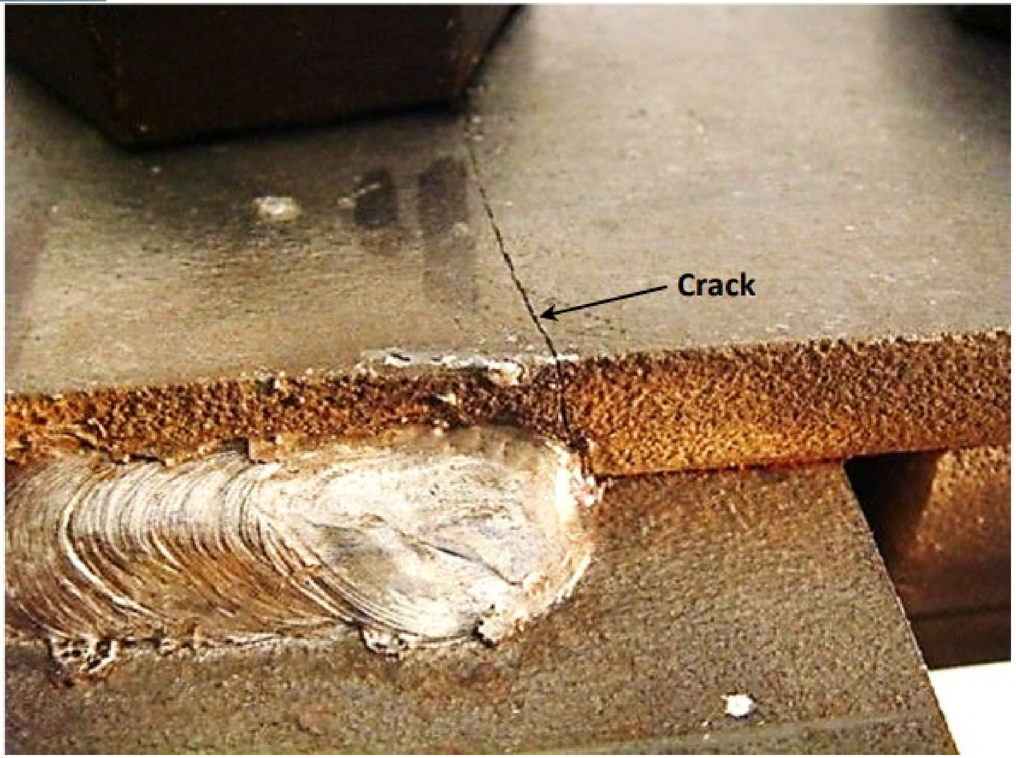


Fatigue-related structural problems:

Crack initiation





Initiation spot?

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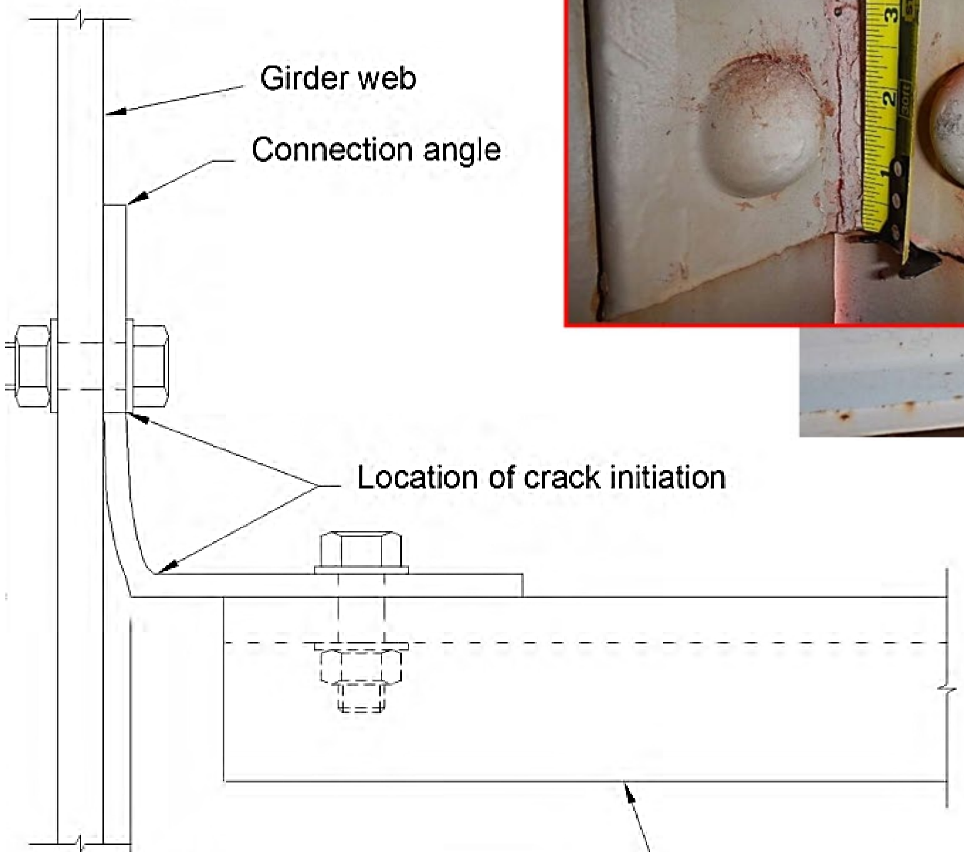
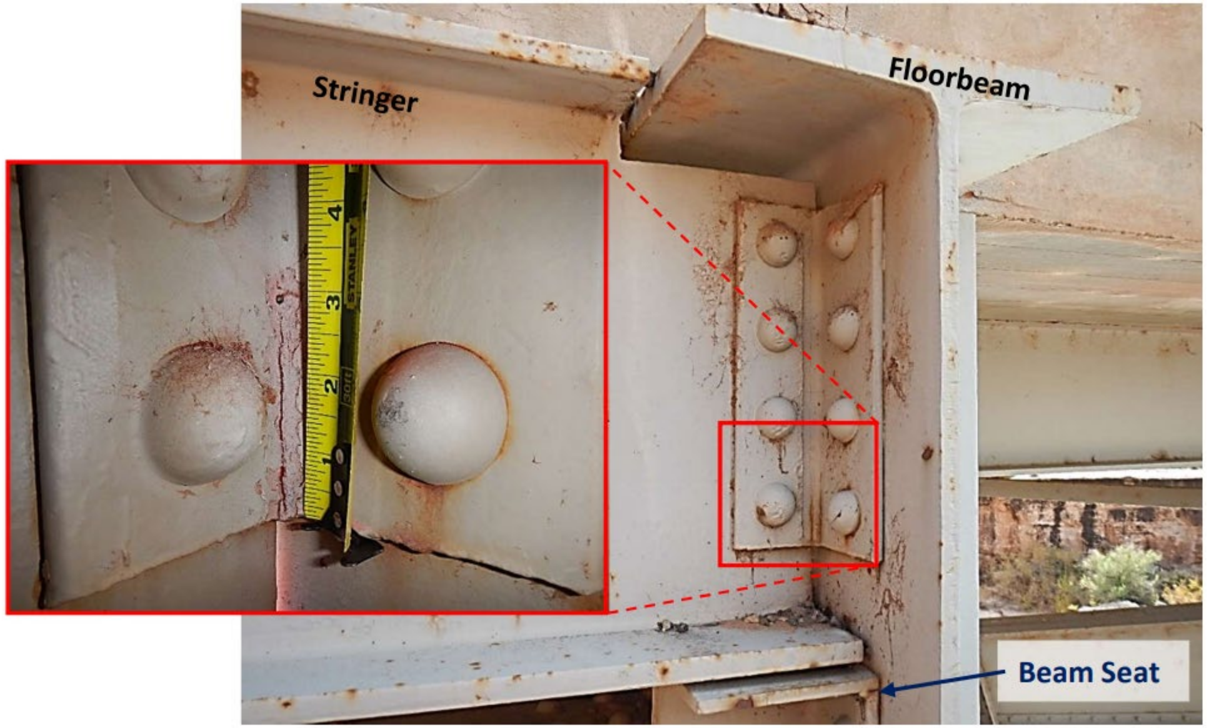
Fatigue-related structural problems:
Crack initiation

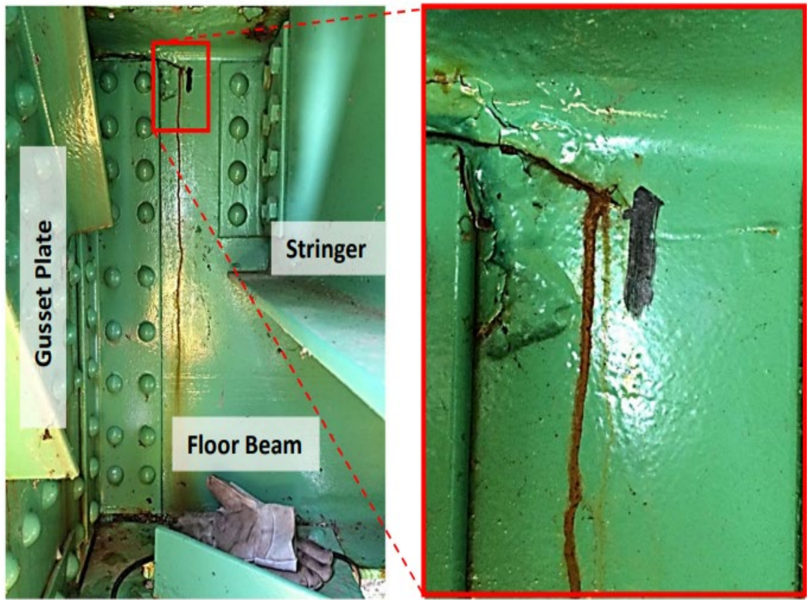




Initiation spot?

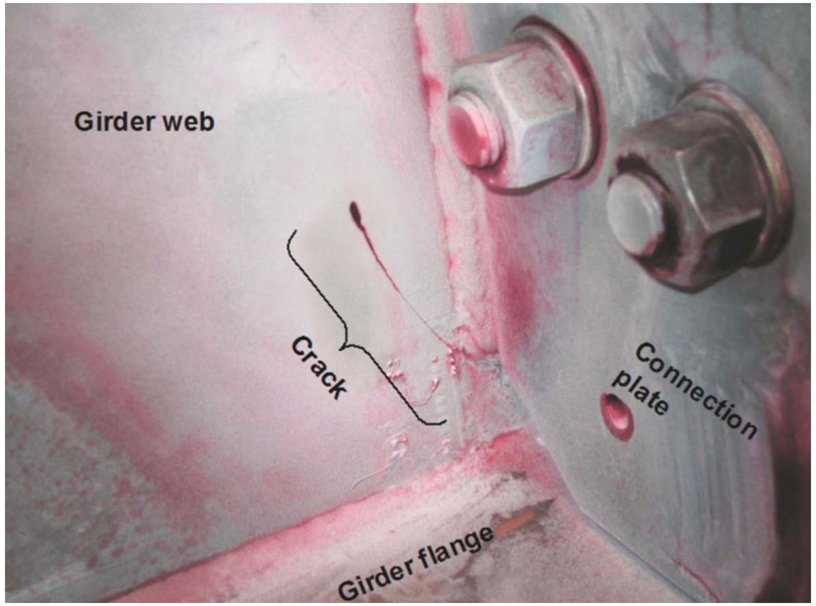
Re-entrant corners
Cover-plate welds
Stiffener-plate root
Tack welds
Connection angles

Fatigue-related structural problems:
Crack front detection



Rust staining

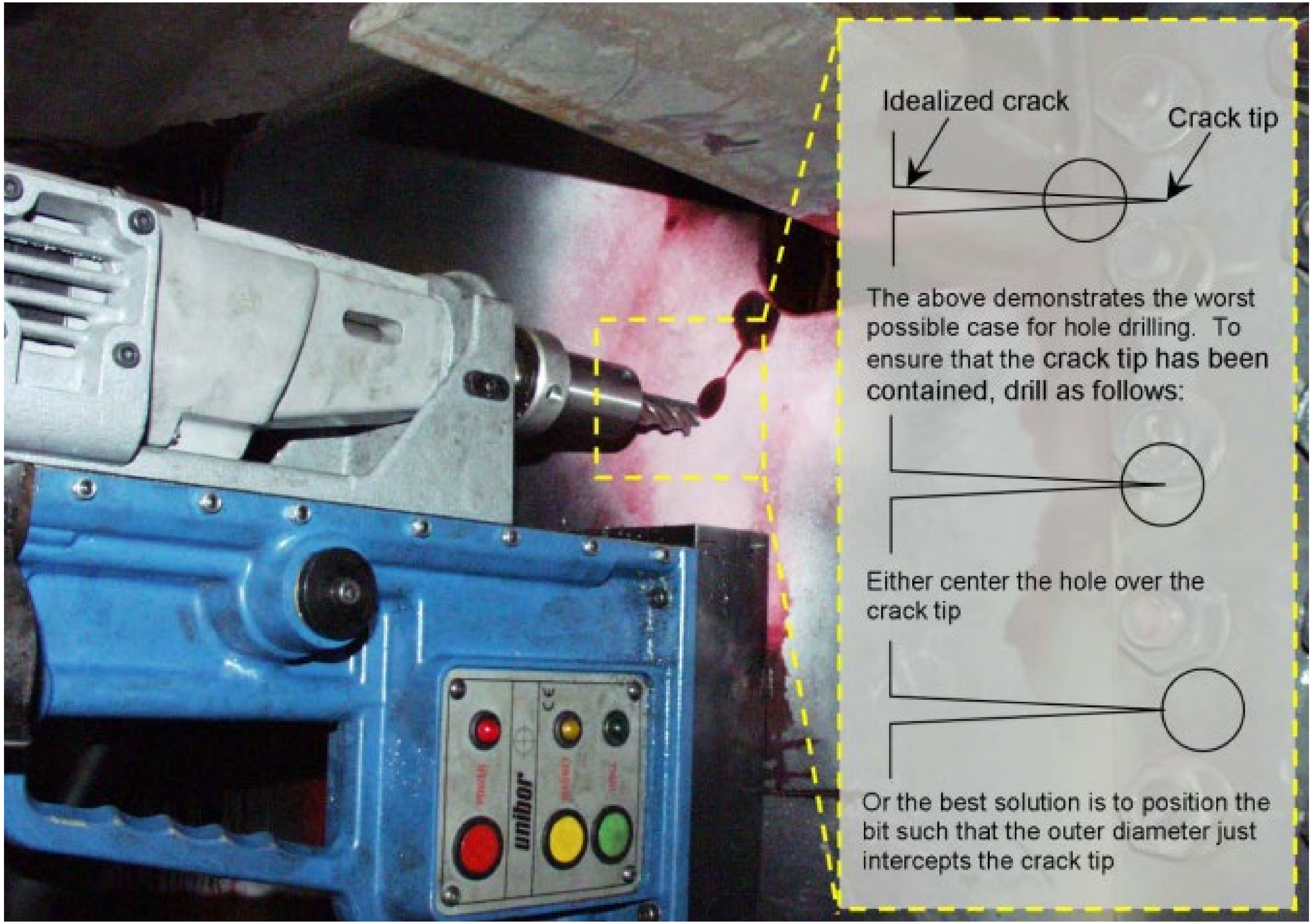
Magnetic Particle Test



Red dye penetrant

Fatigue-related structural problems:

Crack retardation techniques



Crack retardation

Hole drilling

Smoothing transitions

Weld grinding

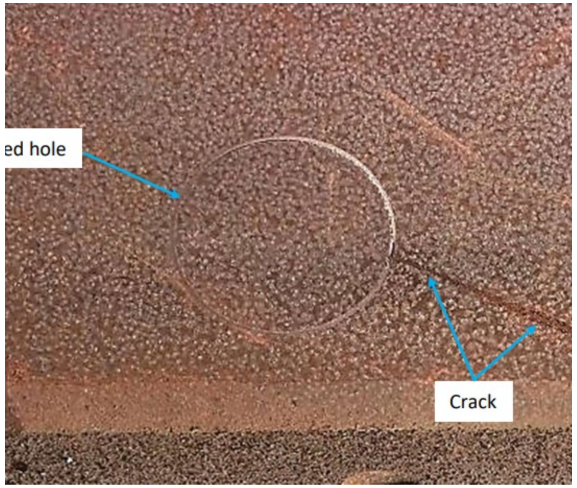
Doubler palte

Fatigue-related structural problems:
Crack retardation techniques

Crack retardation

Hole drilling
Smoothing transitions
Weld grinding
Doubler palte

Annular cut	Drilled hole	Finished

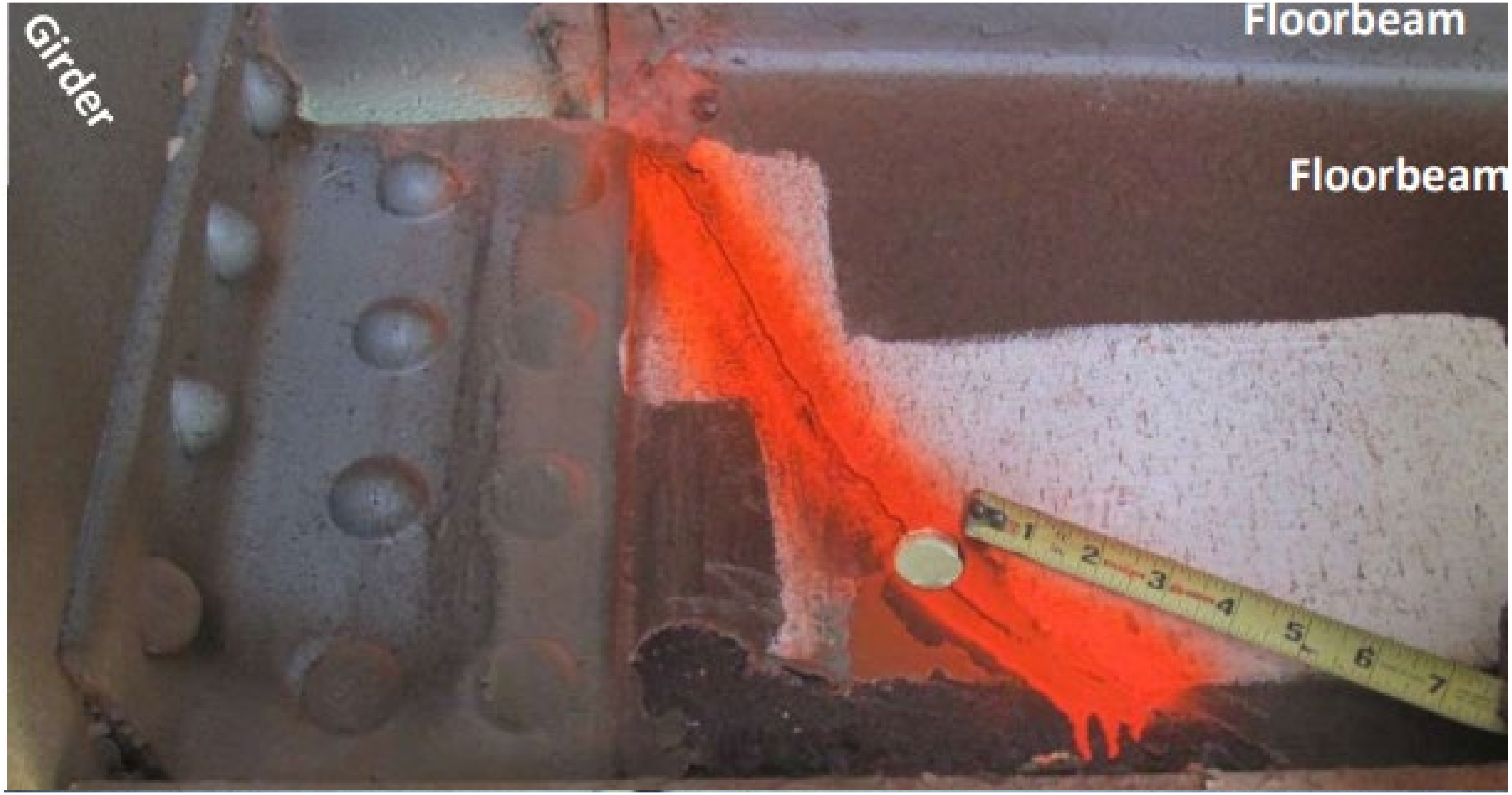


Rough edges and burrs

To be completed with protective paint

Fatigue-related structural problems:
Crack retardation techniques

⚠ Crack reinitiation ⚠



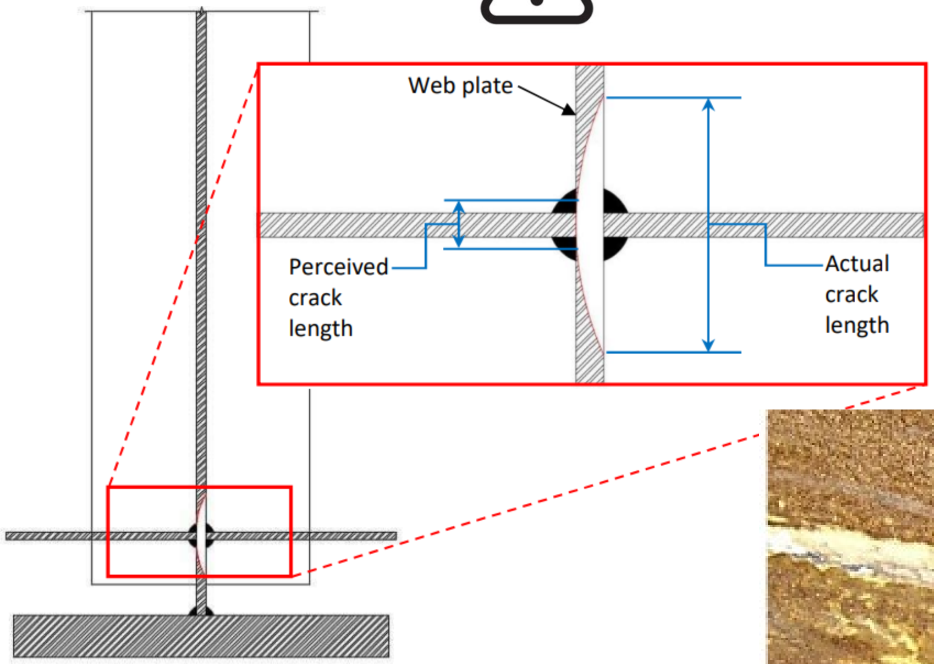
Crack retardation

Hole drilling
Smoothing transitions
Weld grinding
Doubler palte

Fatigue-related structural problems:

Crack retardation techniques

Crack Tunneling



Crack retardation

Hole drilling

Smoothing transitions

Weld grinding

Doubler palte

Fatigue-related structural problems:

Crack retardation techniques

Bad coped beam detail
(sharp corner)

Better coped beam detail
(smooth ground transition radius)

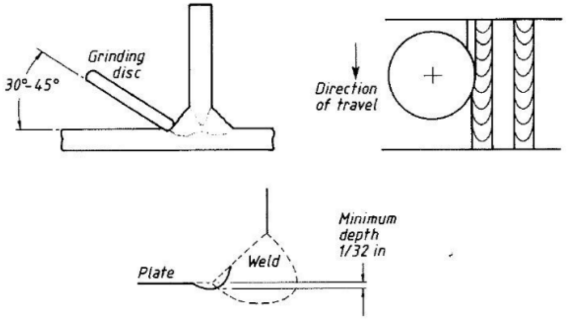
Crack retardation

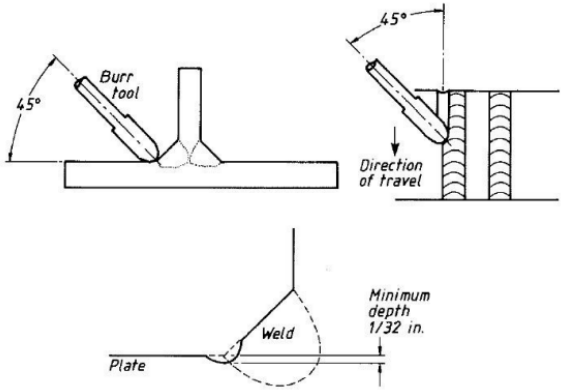
Hole drilling
Smoothing transitions
Weld grinding
Doubler palte

Fatigue-related structural problems:
Crack retardation techniques

Crack retardation

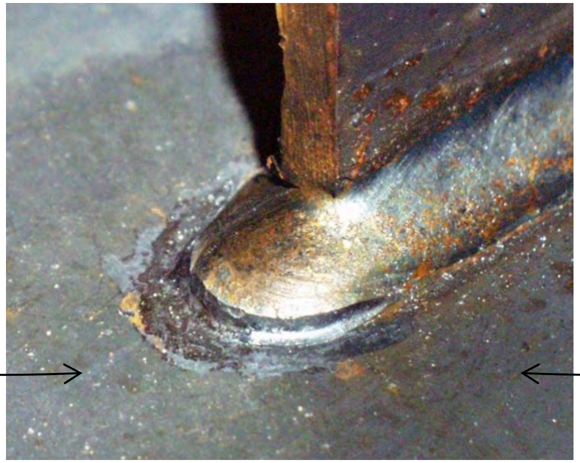
- Hole drilling
- Smoothing transitions
- Weld grinding
- Doubler palte





Disc Grinding

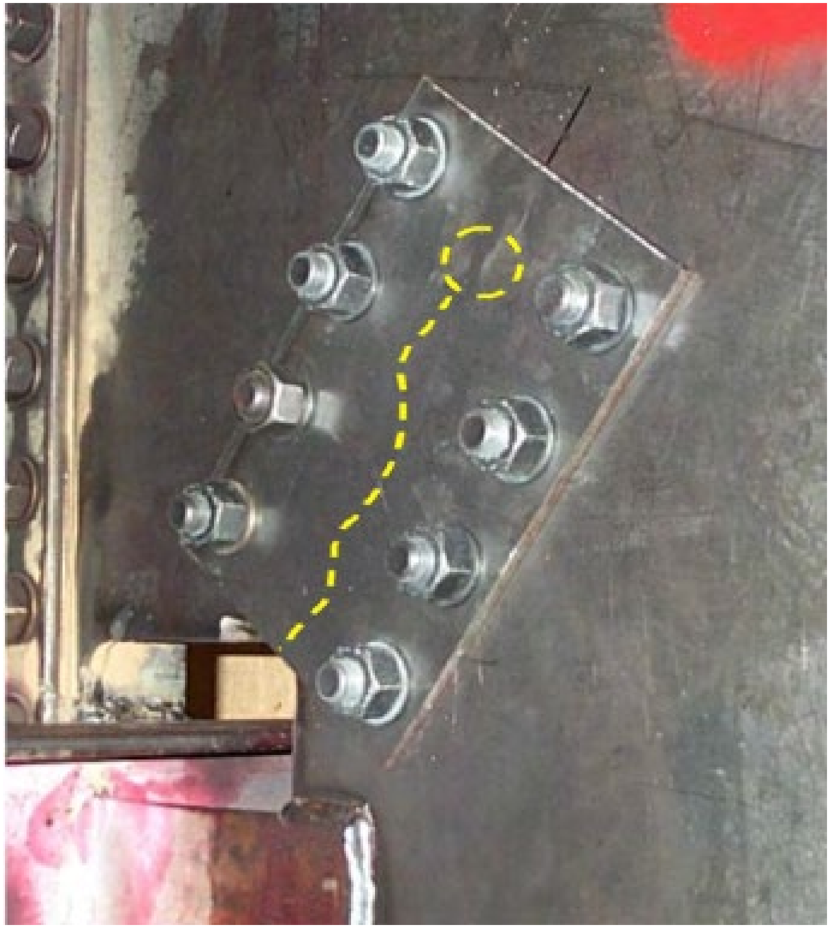
Grinded weld toe

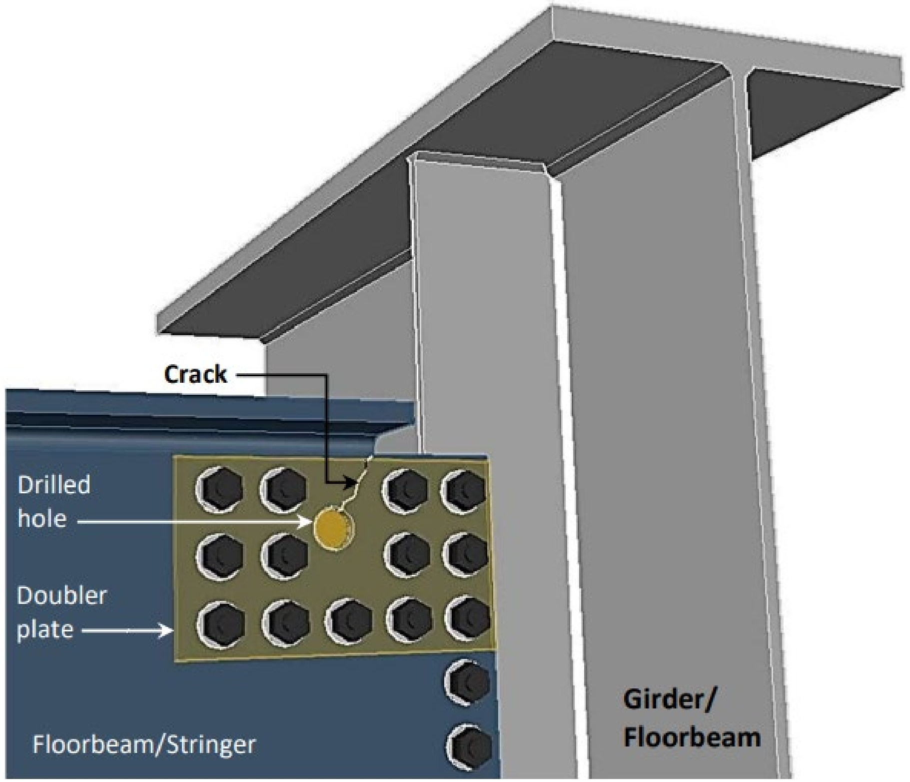


Burr Grinding

Fatigue-related structural problems:

Crack retardation techniques



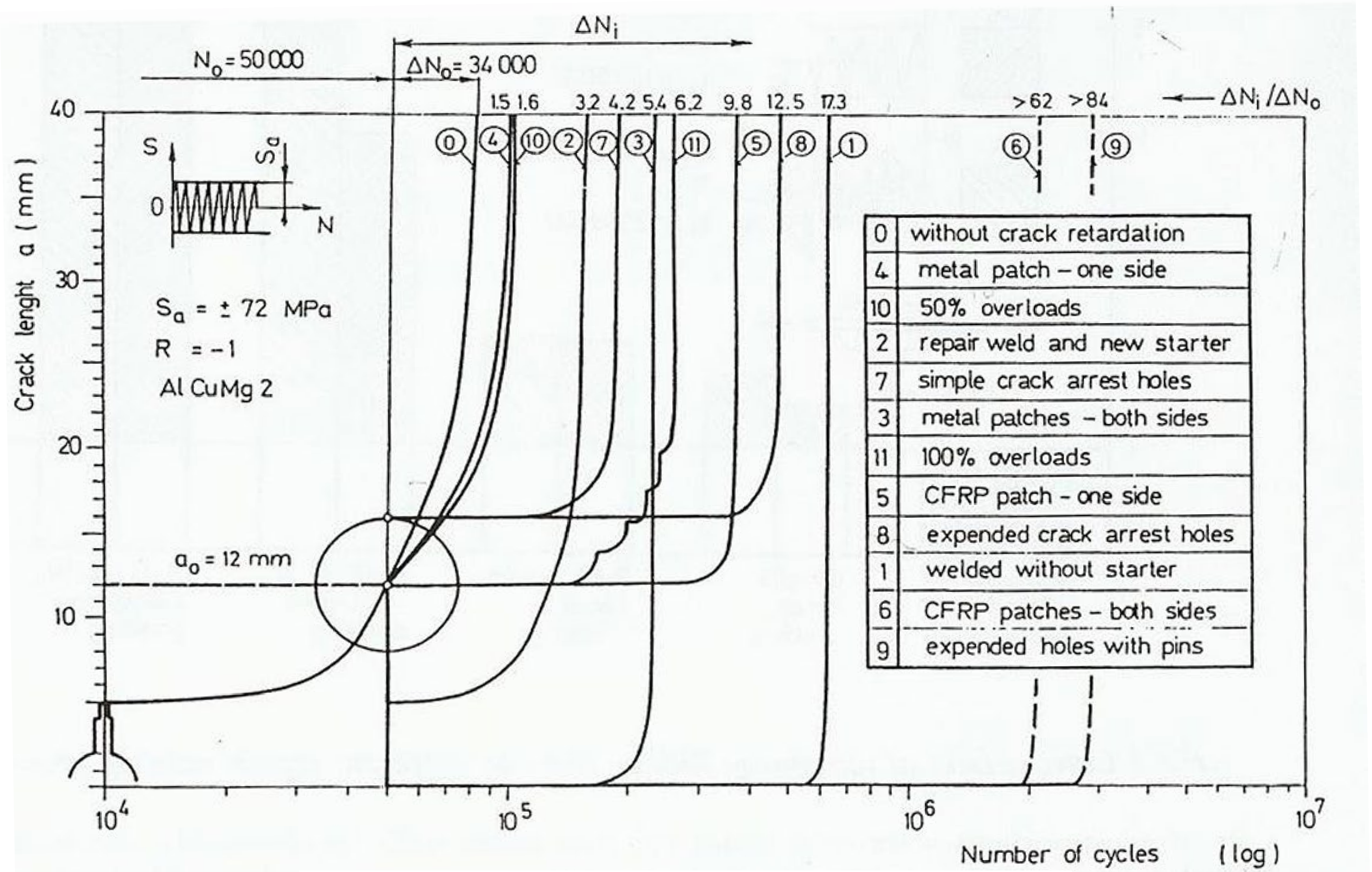


Crack retardation

Hole drilling
Smoothing transitions
Weld grinding
Doubler palte

Fatigue-related structural problems:

Crack retardation techniques



[15] Z. Domazet, "COMPARISON OF FATIGUE CRACK RETARDATION METHODS," 1996.

Crack retardation

Hole drilling
Smoothing transitions
Weld grinding
Doubler palte

Fatigue-related structural problems:
Crack retardation techniques

Crack retardation

Hole drilling
Smoothing transitions
Weld grinding
Doubler palte

FRP EBR patch

State Highway 92 bridge, Iowa (US): CFRP Plates

KY 32 Bridge, Kentucky: UHM CFRP Plates

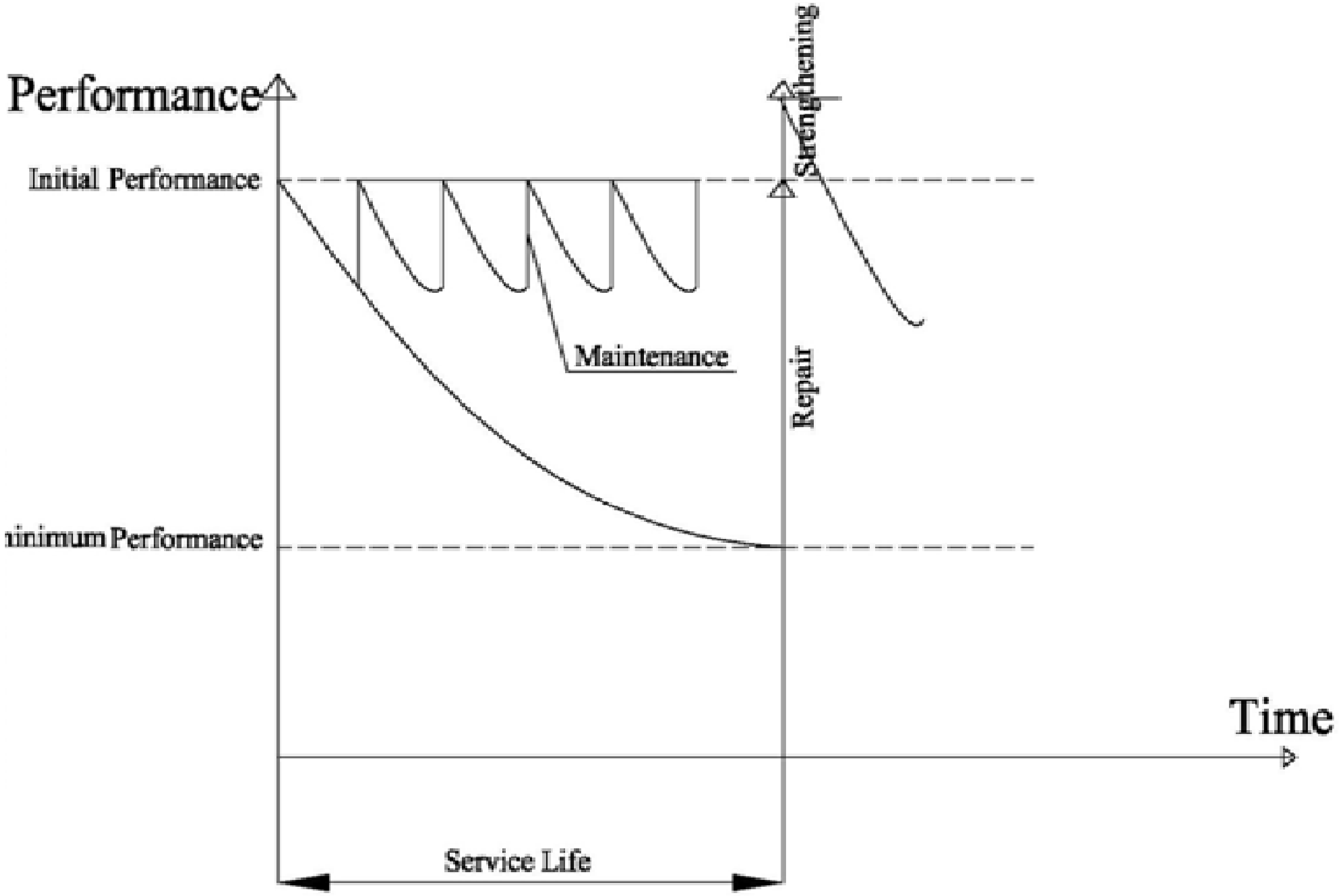
Steel Girder Bridge located in Guthrie County, Iowa: CFRP (P-T) Rods

- ADVANTAGES
  - High strength-to-weight ratio
  - Fast and easy application
  - Non-corrosive
  - Good long-term behaviour

- DISADVANTAGES
  - Limited resistance to high temperatures
  - Low fire resistance
  - Non-ductile debonding failure

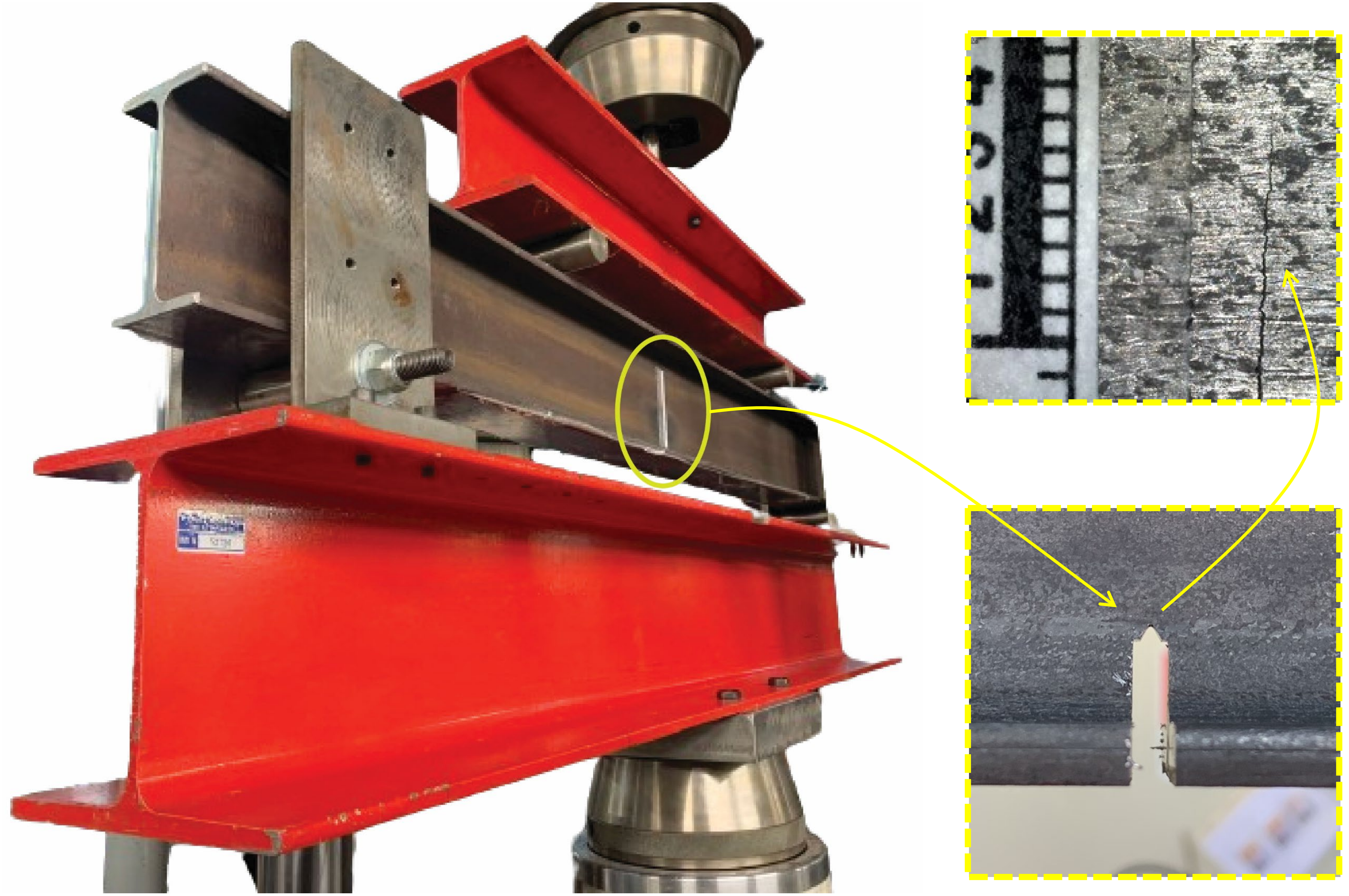
Fatigue-related structural problems:
Crack retardation techniques

Structural Health Monitoring

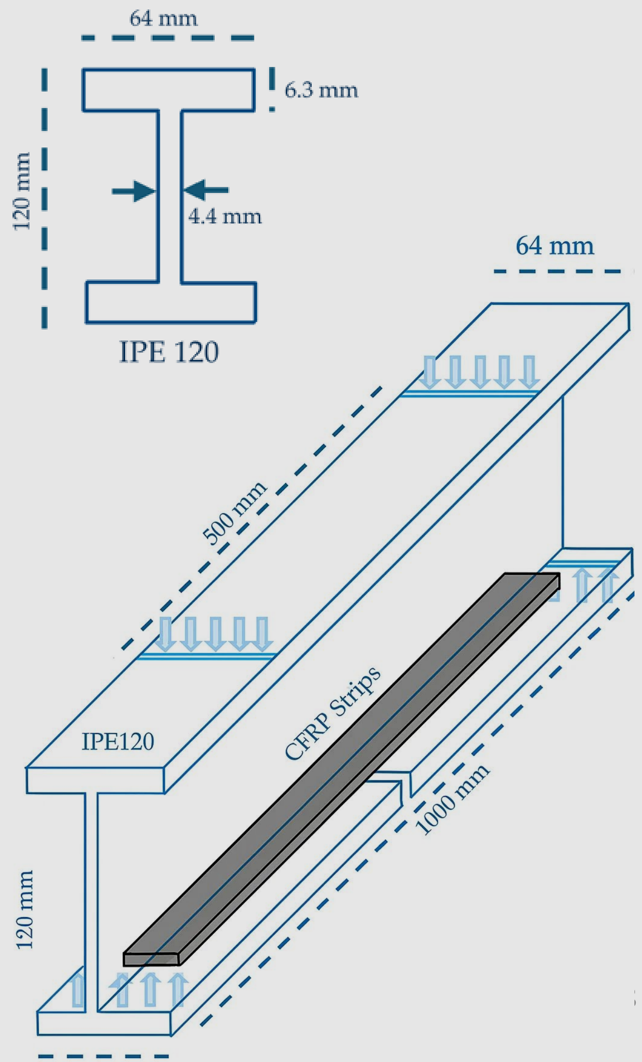


FRP-repaired steel beam: an experimental study

FRP-repaired steel beam:
An experimental study



Specimen geometry



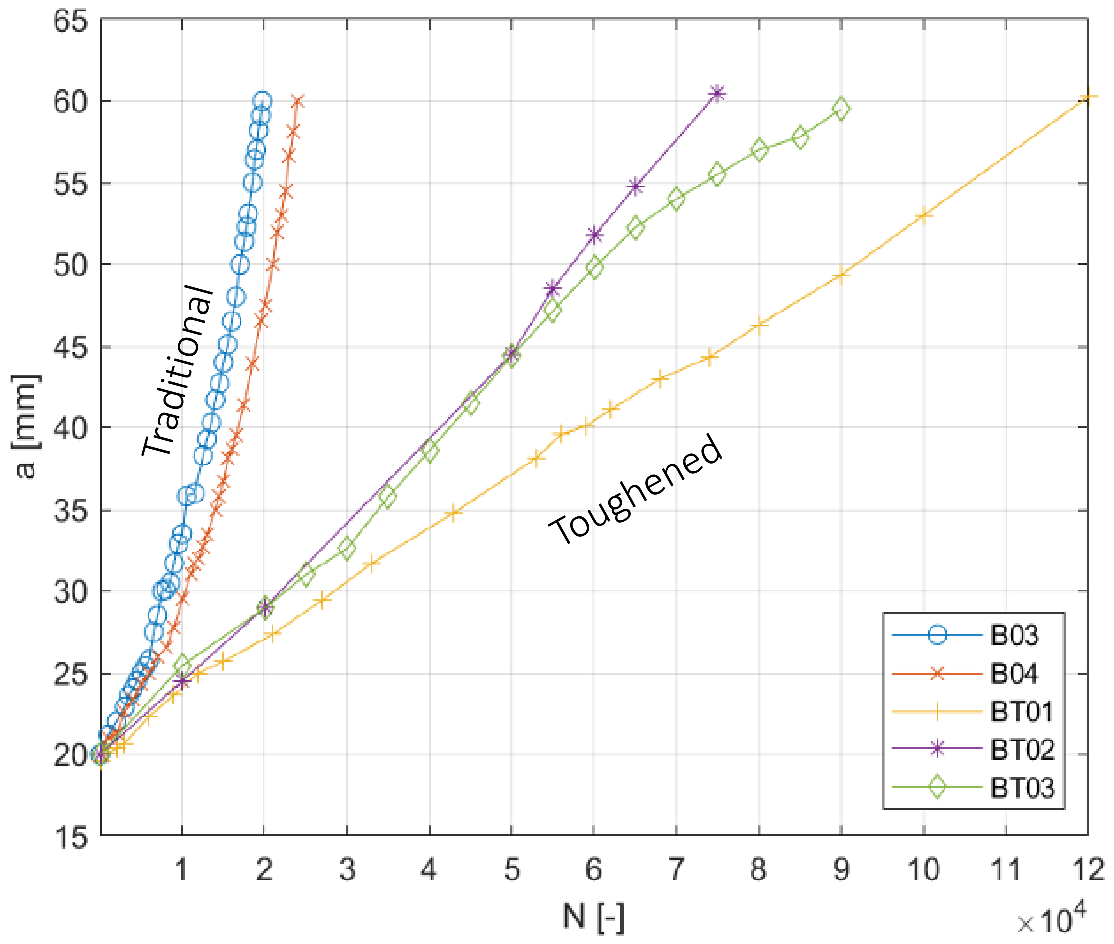
FRP-repaired steel beam:
An experimental study

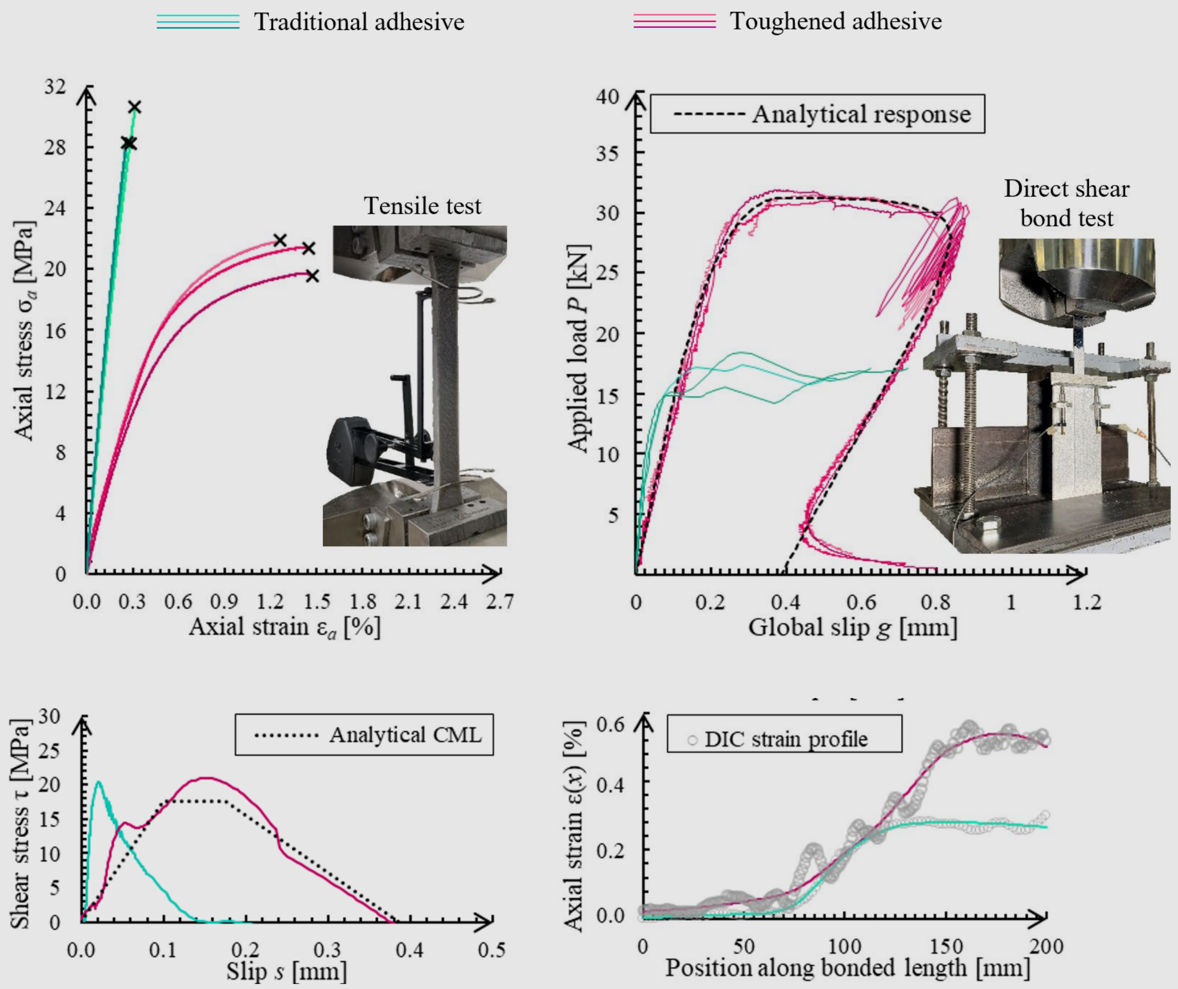
Two-component adhesive

Application of a 2 mm adhesive layer

CFRP bonding and curing

FRP-repaired steel beam:
An experimental study





FRP-repaired steel beam:
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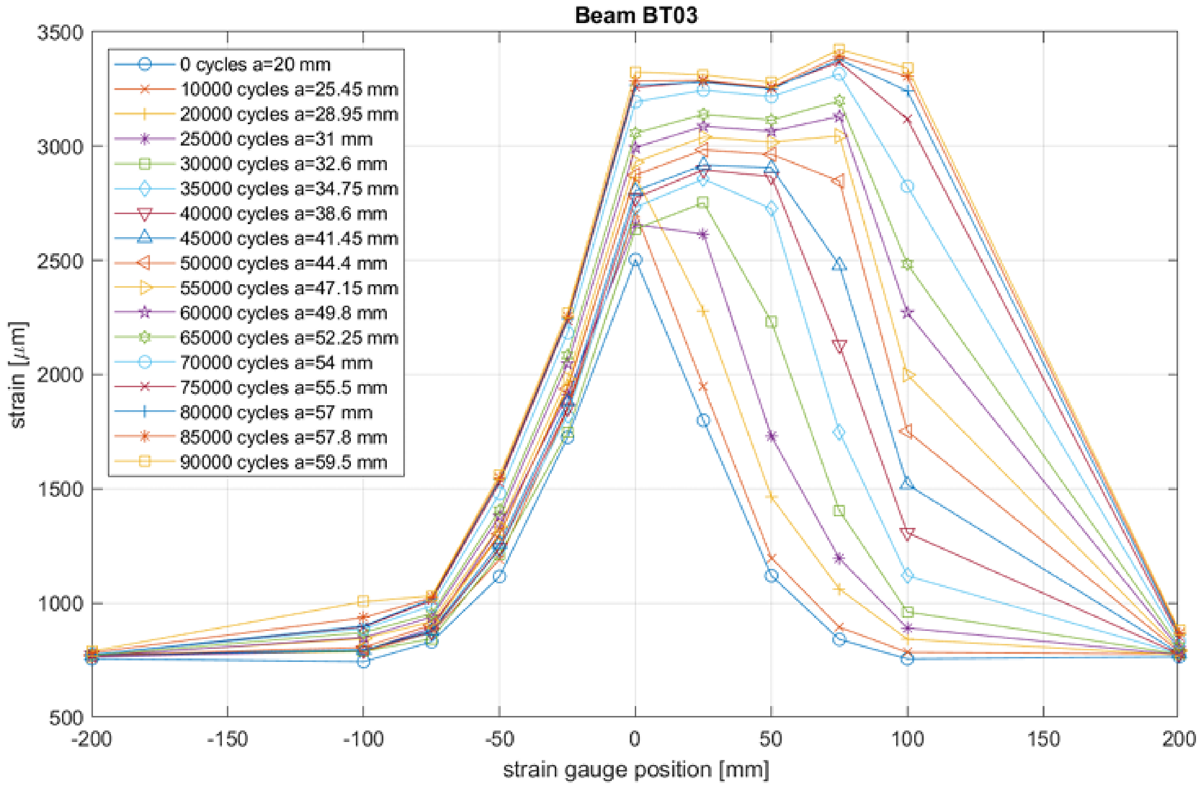
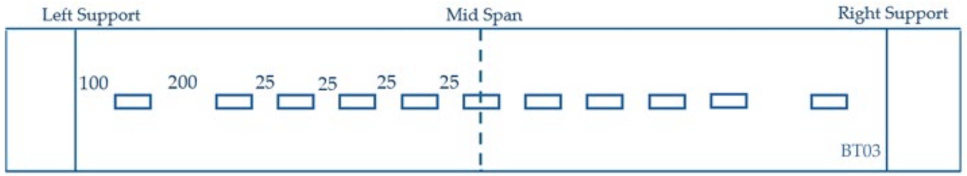


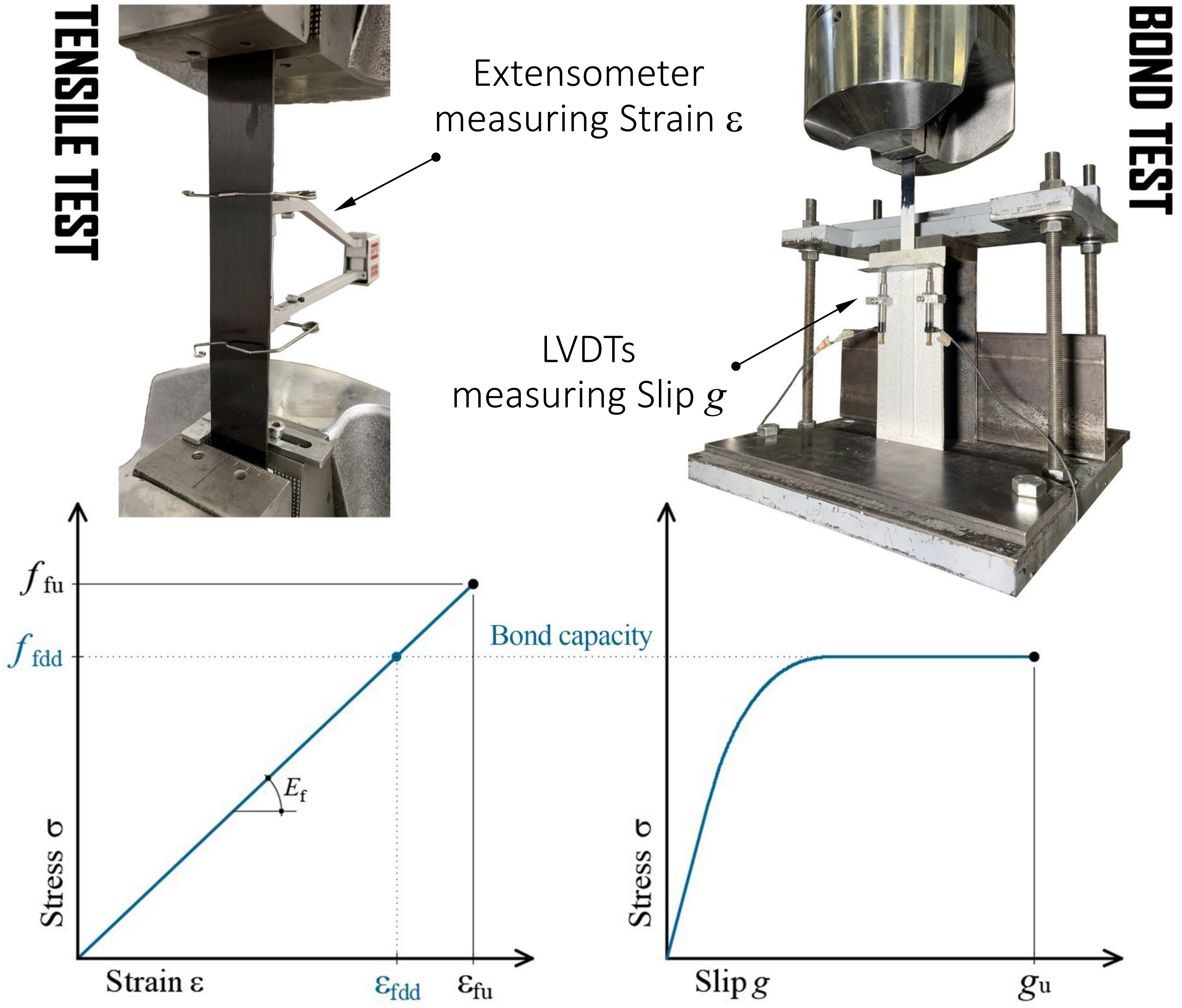


Fatigue behavior of FRP-steel joints

- EFFECT OF FATIGUE ON FRP-STEEM JOINTS
- Fatica sul composito l'abbiamo gia affrontato --> fatica sul giunto
- Fatica sperimentale sul giunto: setup e modalità di crisi
- Fatica sperimentale sul giunto: riduzione di rigidezza, accumulo di deformazione palstica e scorrimento, energia dissipata
- POST-Fatica sperimentale sul giunto: LOAD RESPONSE E capacità residua
- POST-Fatica sperimentale sul giunto: valutazione di profile dic strain e legame con la capacità residua

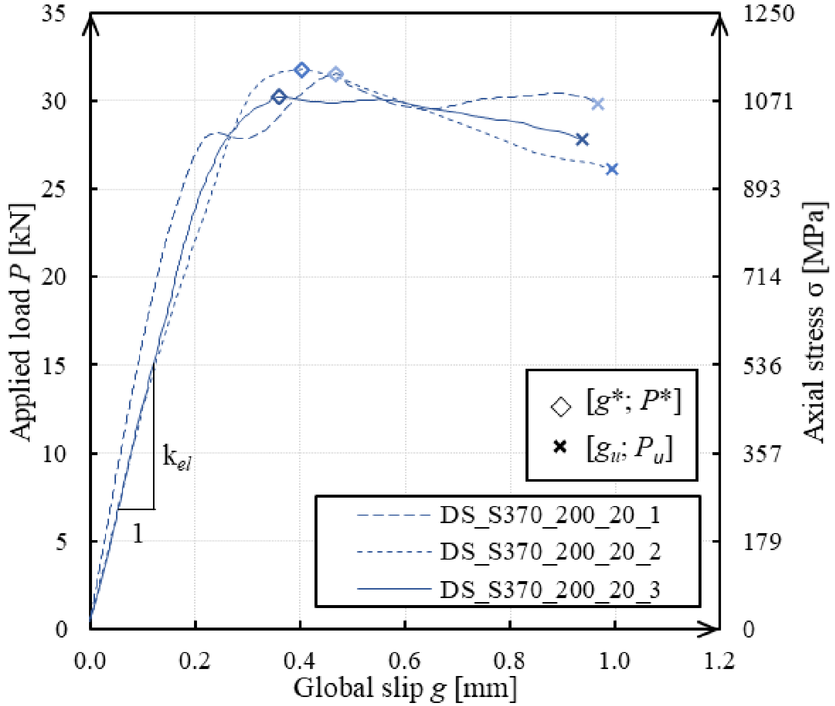
Fatigue behavior of FRP-steel joints:

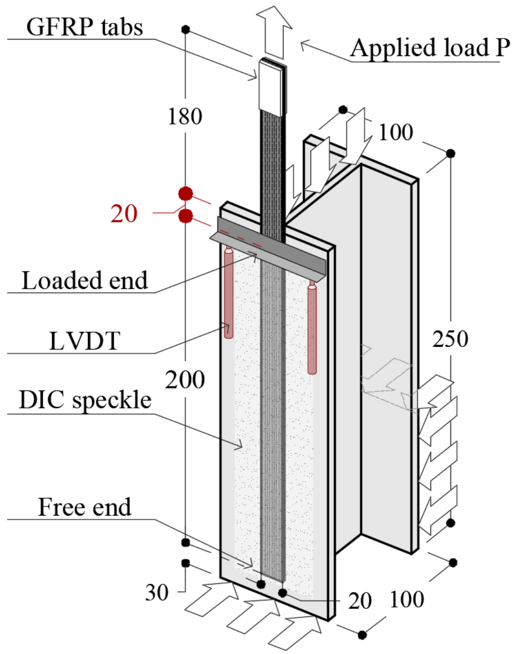
FRP strengthening of RC structures (standards-based overview)



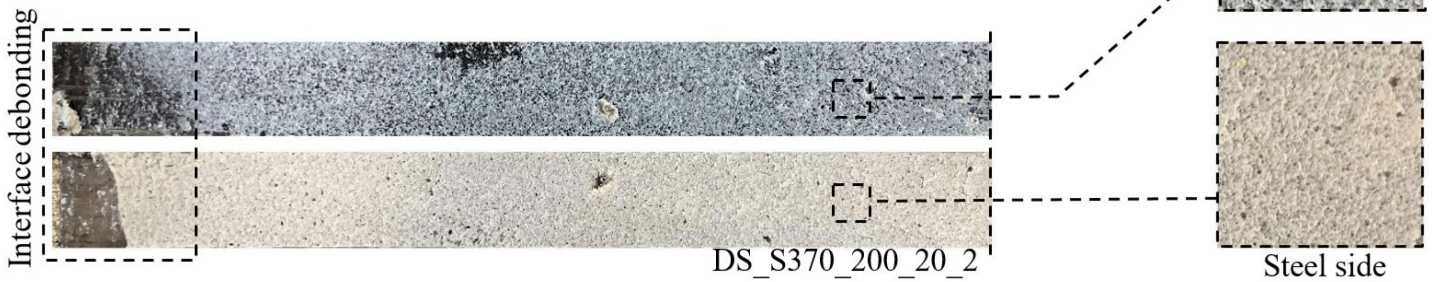
Experimental assessment of bond capacity: **typical setup & static load response**

Results of static tests

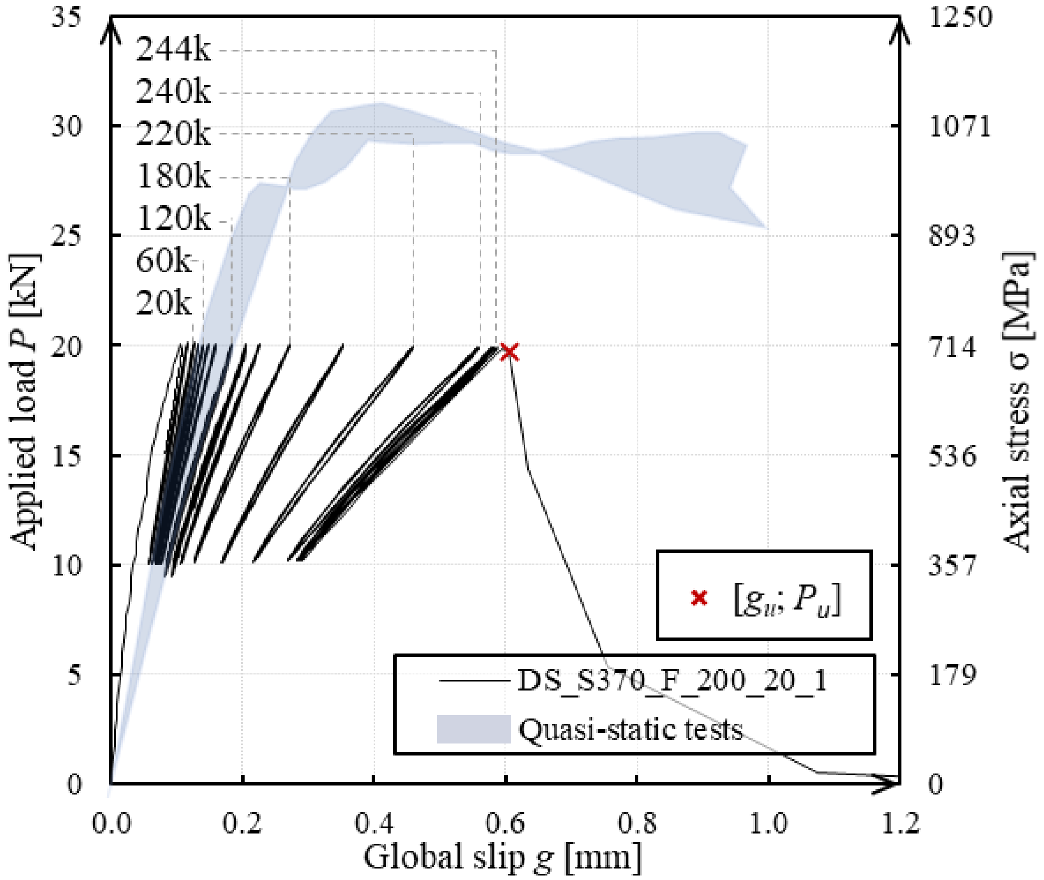


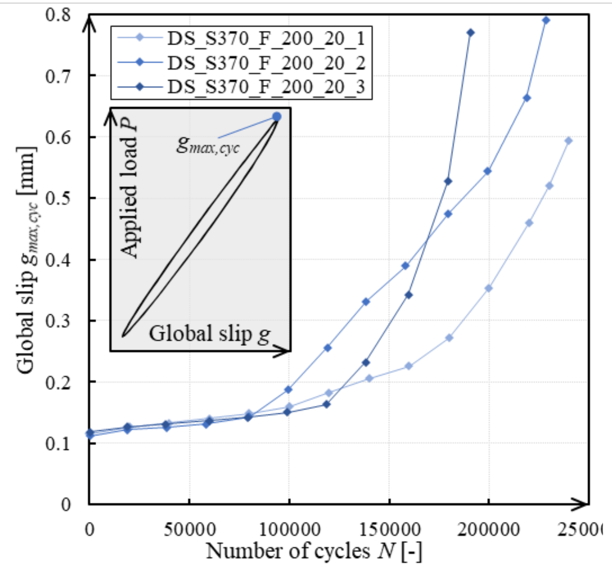


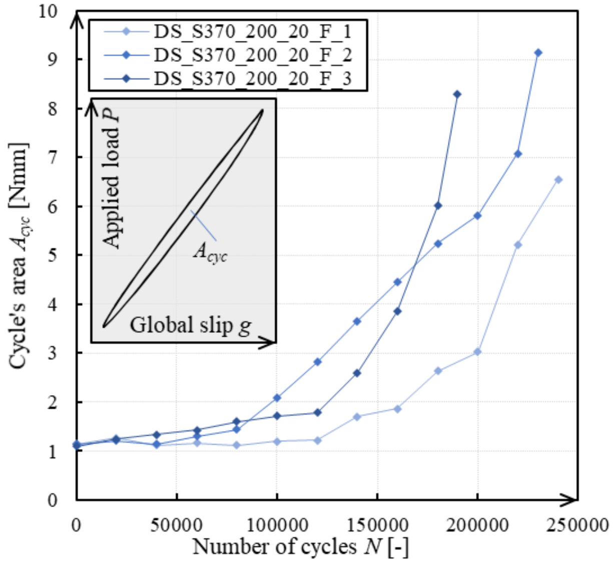
Debonding type: cohesive

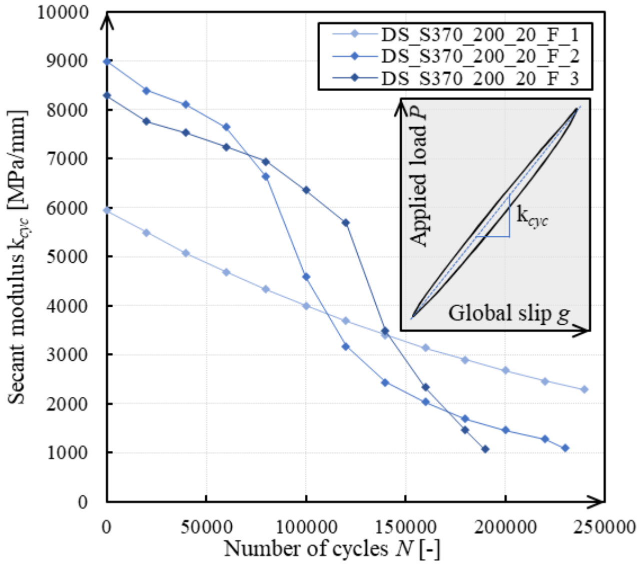


Fatigue behavior of FRP-steel joints:
Cyclic load response and behavior

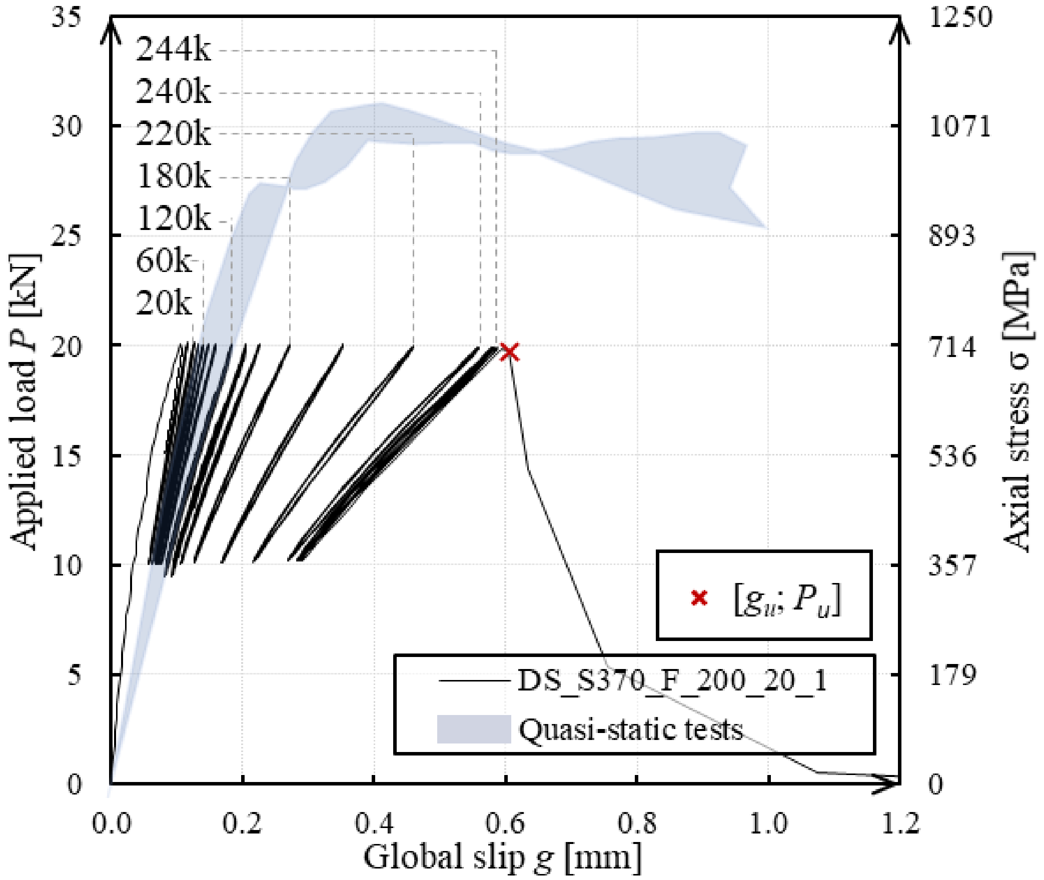


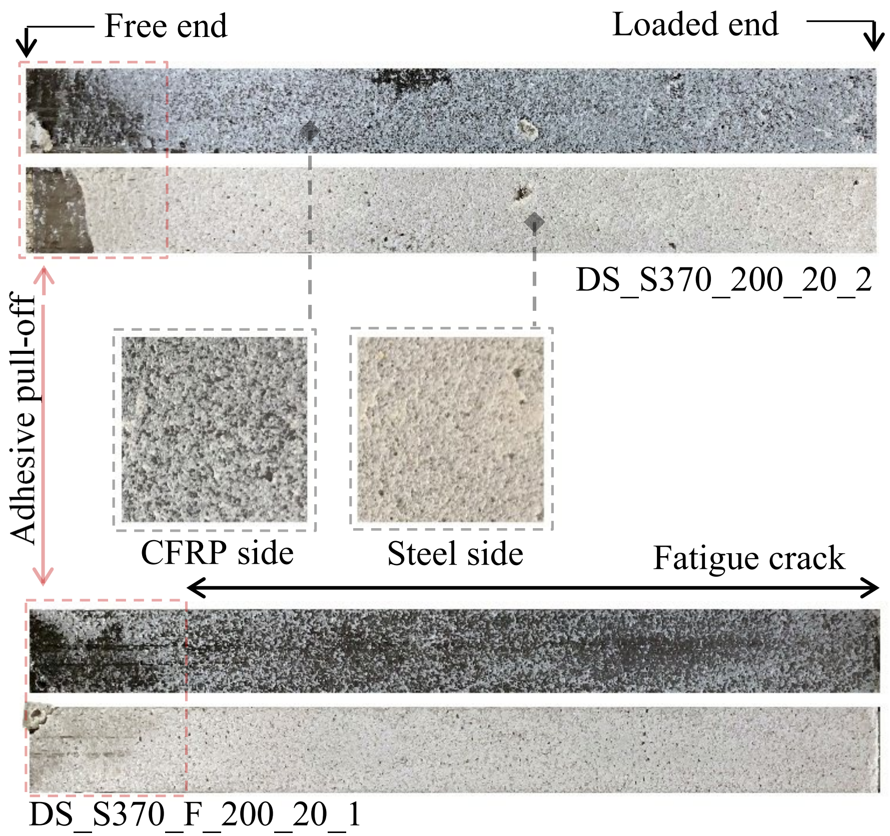




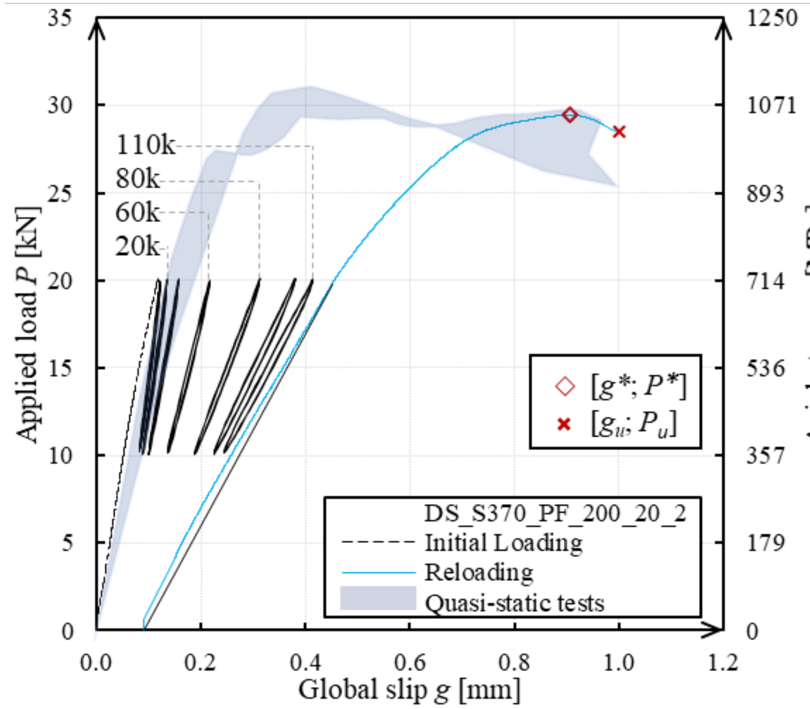


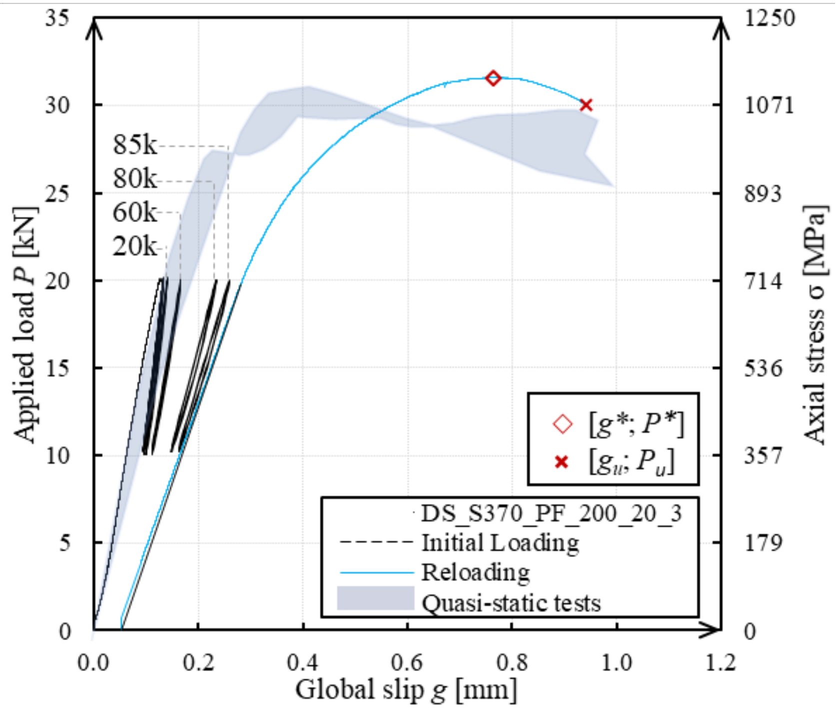
Fatigue behavior of FRP-steel joints:
Cyclic load response and behavior

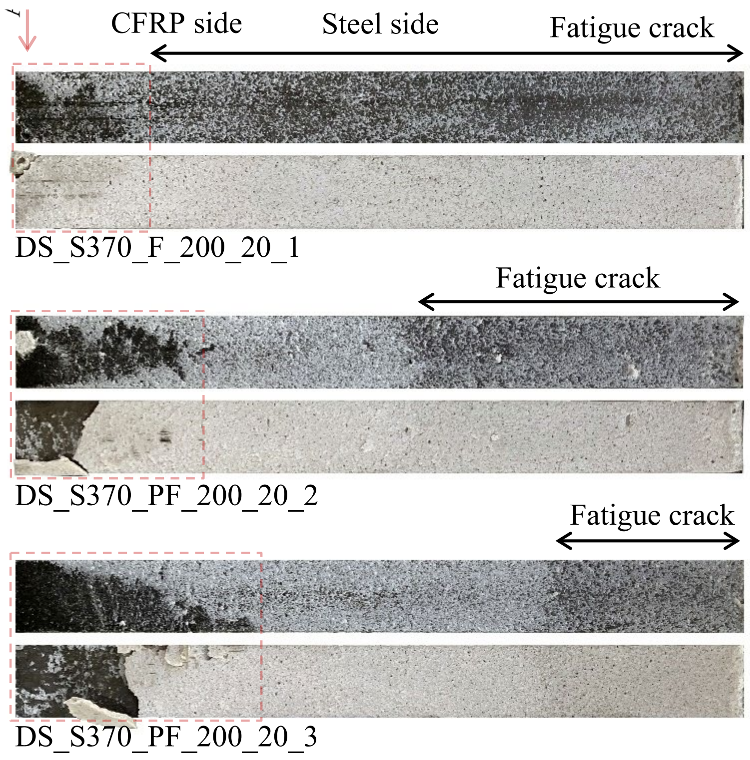




Fatigue behavior of FRP-steel joints:
Post-cyclic load response and behavior







Fatigue behavior of FRP-steel joints:
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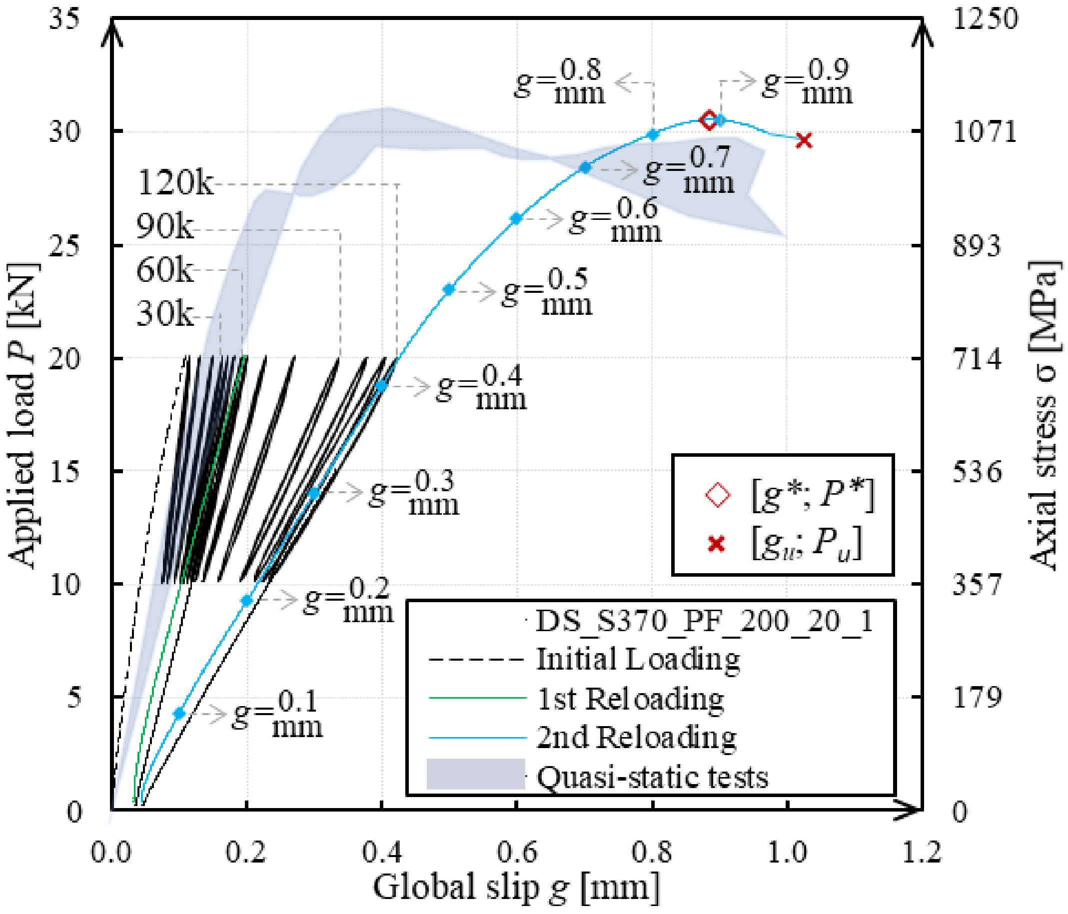
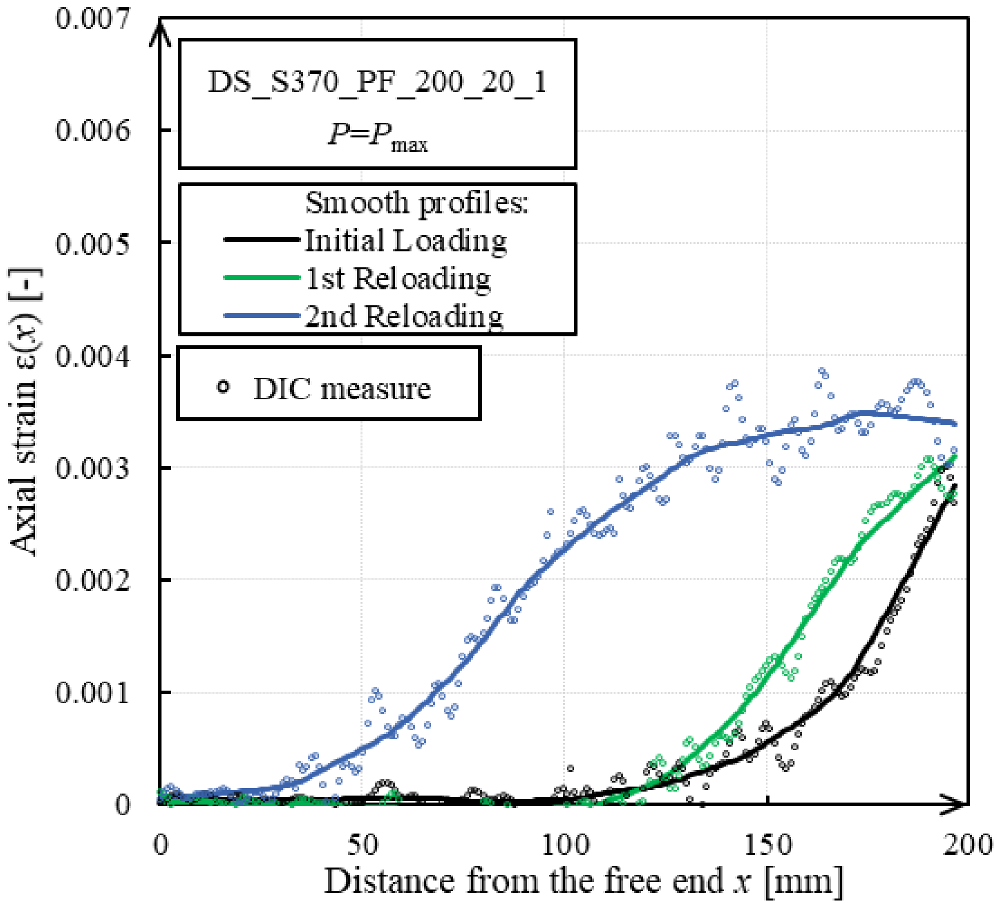
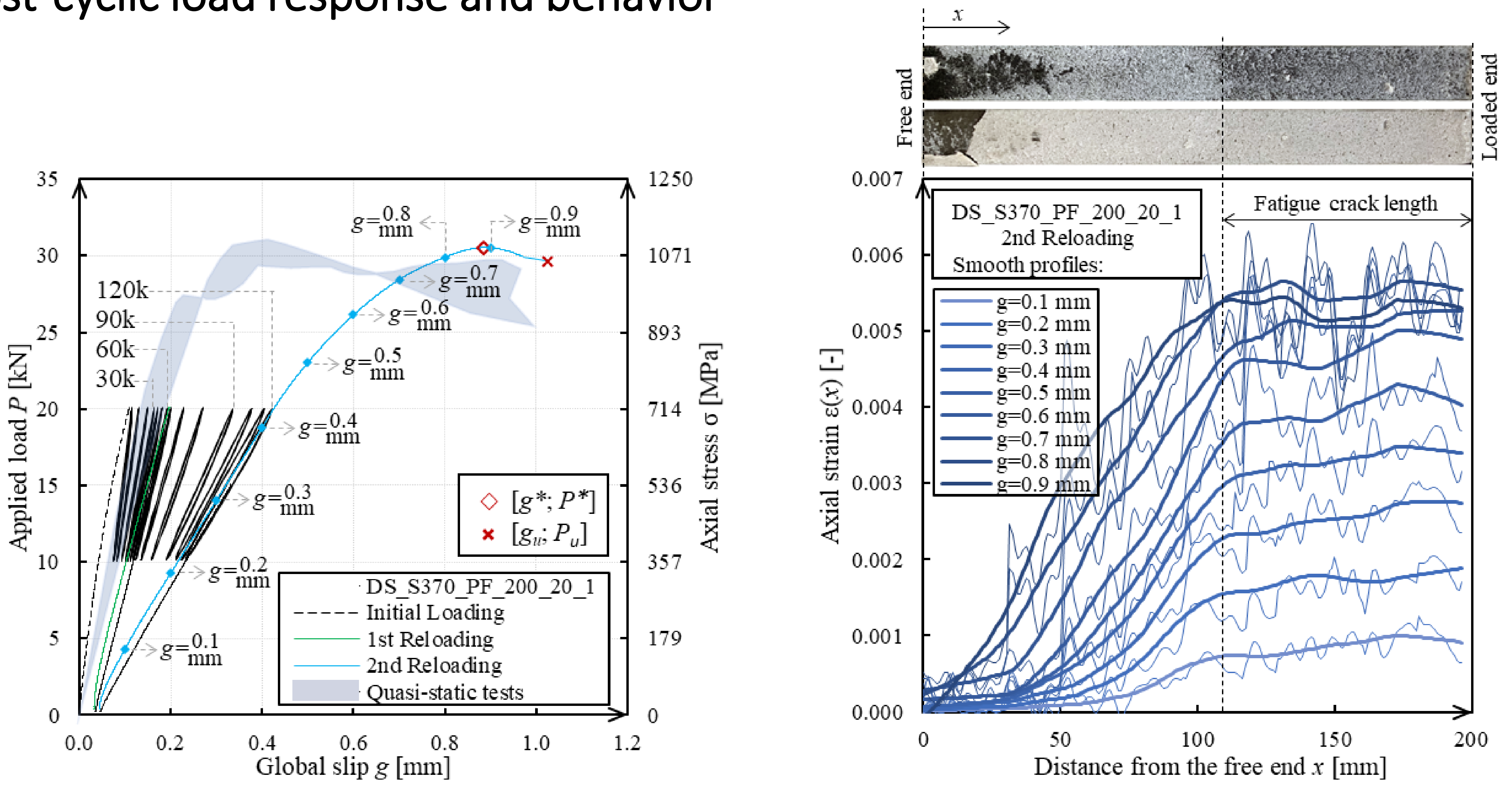


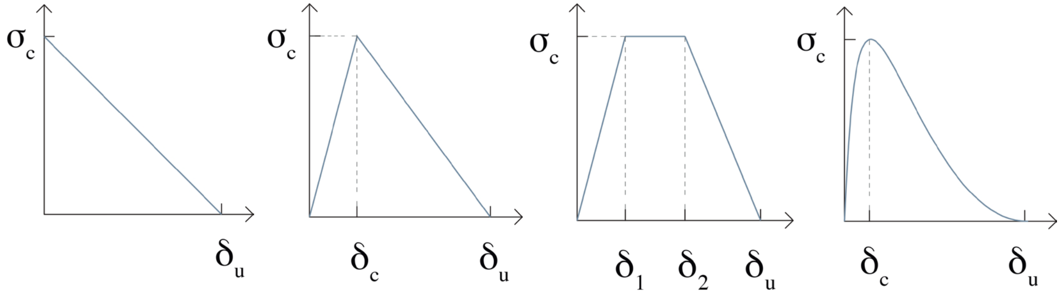


Fatigue behavior of FRP-steel joints:
Post-cyclic load response and behavior



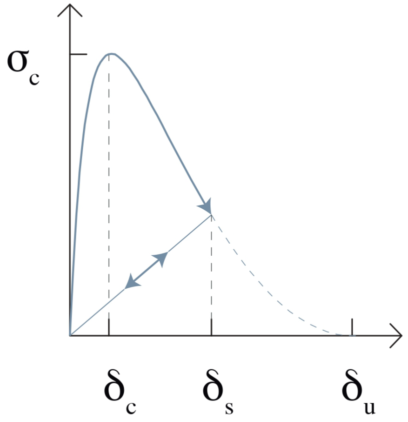
Cyclic cohesive zone models

Analysis of bond:
Cyclic cohesive zone models

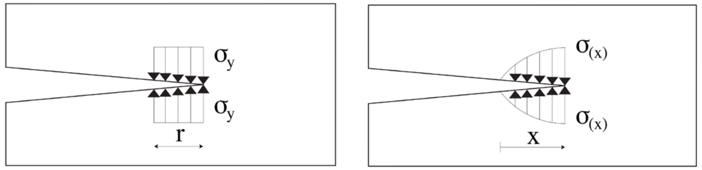


Monotonic Cohesive Models
(Hillerborg et al. 1976)

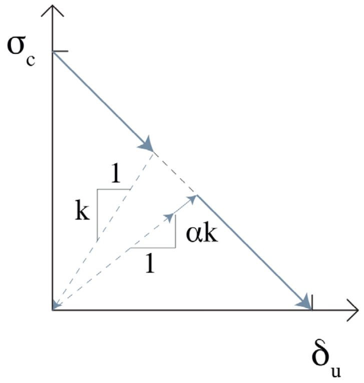
Monotonic Irreversible Cohesive Models
(Tvergaard 1990, Needleman 1992)



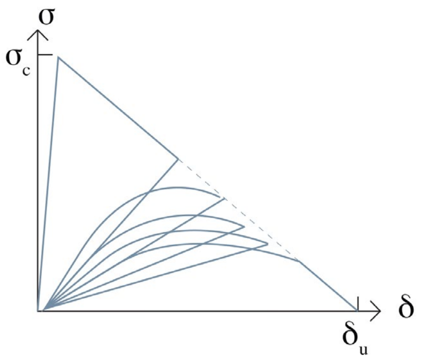
First Cohesive Models
(Dugdale 1960, Barenblatt 1962)



Unloading-Reloading Hysteresis Cohesive Models
(Gylltoft 1984, Horii et al. 1990)



Cyclic Cohesive Models
(Nguyen et al. 2001, Yang et al. 2001)



Analysis of bond:
Cyclic cohesive zone models

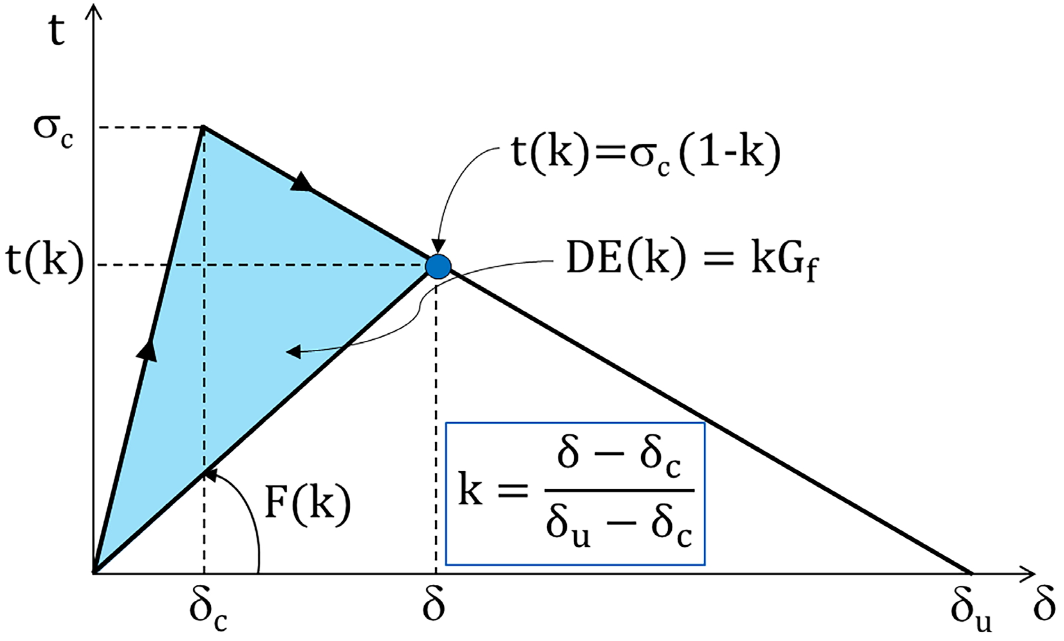
Cyclic Cohesive Zone Models (CCZMs)

Bilinear TSL

$$\mathbf{t} = \begin{bmatrix} t_n \\ t_s \end{bmatrix} = F(k) \begin{bmatrix} \delta_n \\ \eta^2 \delta_s \end{bmatrix} \longrightarrow$$

Elastic: $F(k) = \frac{\sigma_c}{\delta_c}$

Softening: $F(k) = \frac{\sigma_c}{\delta}\left(\frac{\delta_u - \delta}{\delta_u - \delta_c}\right)$



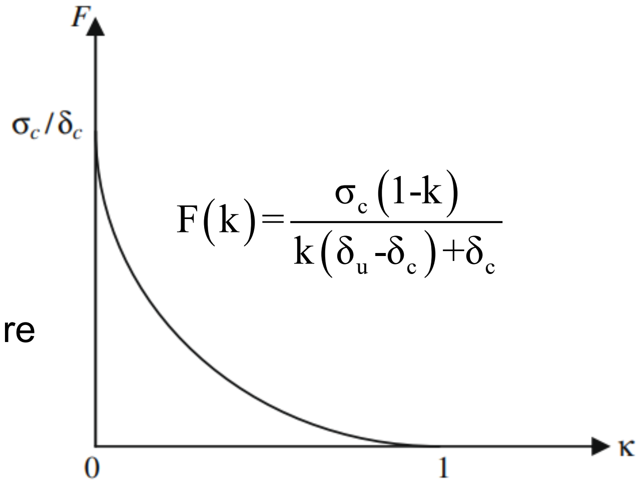
Non-linear degrading stiffness:

$$F(k)$$

Damage variable k:

$$0 \leq k \leq 1$$

No damage — Complete Failure



$$F(k) = \frac{\sigma_c(1-k)}{k(\delta_u - \delta_c) + \delta_c}$$

Analysis of bond:
Cyclic cohesive zone models

Cyclic Cohesive Zone Models (CCZMs) – cyclic loading

During fatigue un- and re-loading cycles, the evolution of the damage variable *k* is governed by a rate equation and the fatigue parameters.

Model Parameters
Crack propagation and damage healing →

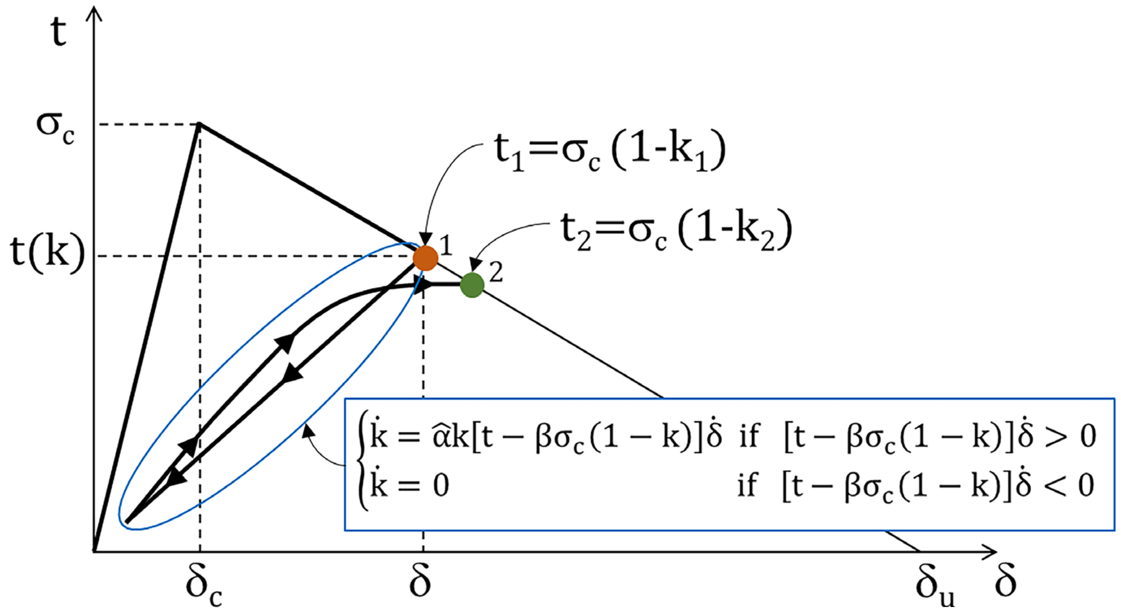
α	*Rate of damage accumulation*
β	*Fatigue threshold*
γ	*Rate of damage recovery*
λ	*Damage evolution*

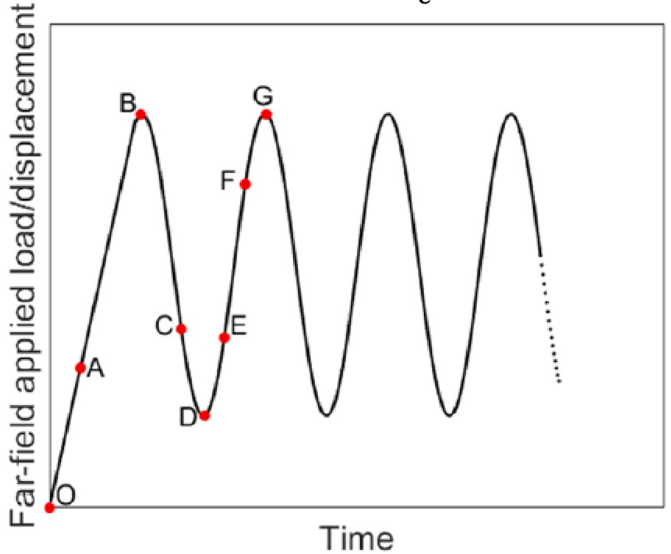
Unloading Phase $\dot{\delta} < 0,\ \hat{\alpha} = -\gamma < 0$

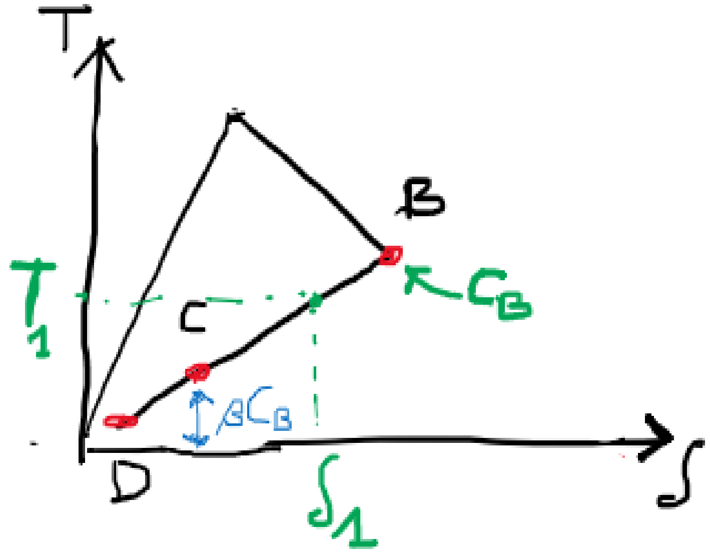
- *Initial unloading stage – branch A-B :* no damage evolution
- *Final unloading stage – branch B-C :* damage healing

Loading Phase $\dot{\delta} > 0,\ \hat{\alpha} = \alpha > 0$

- *Initial loading stage – branch C-D :* no damage evolution
- *Final loading stage – branch D-E :* damage incrementation



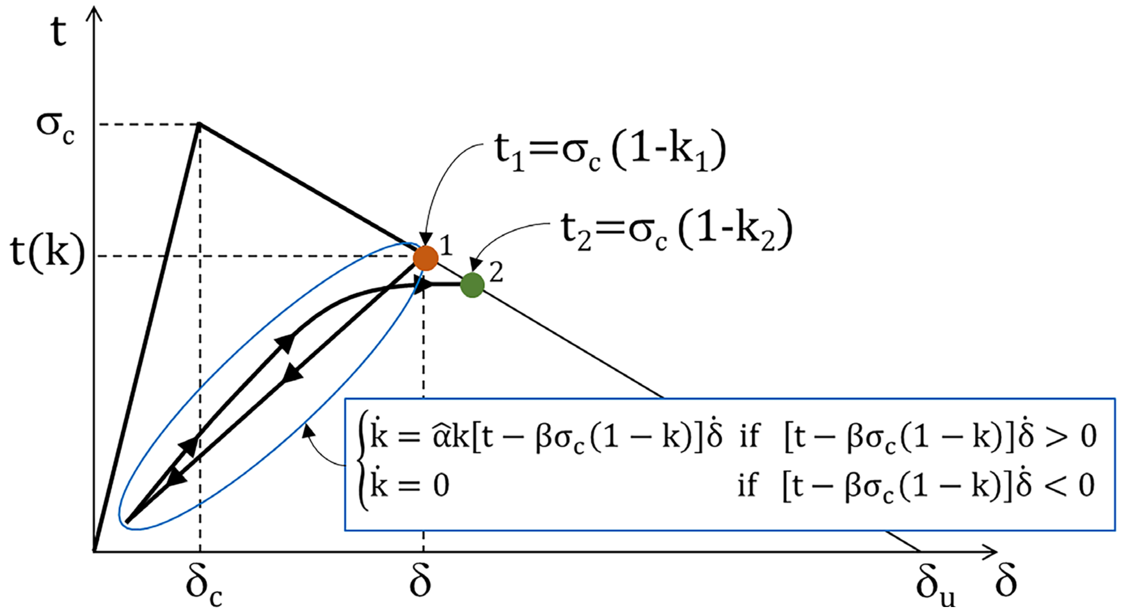


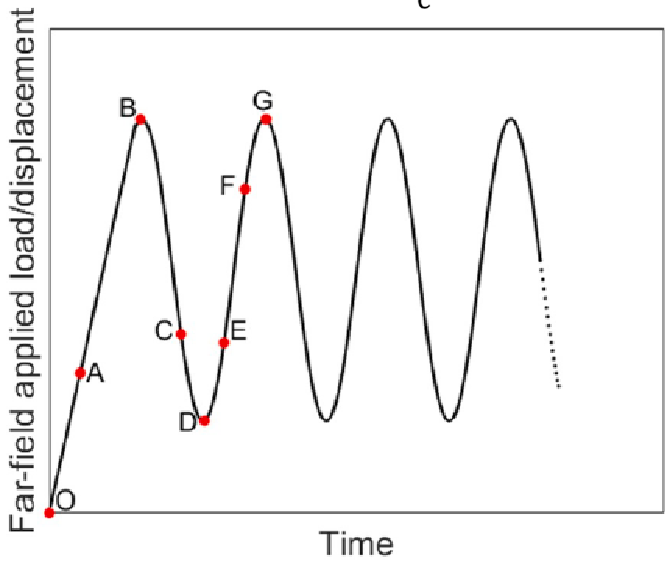


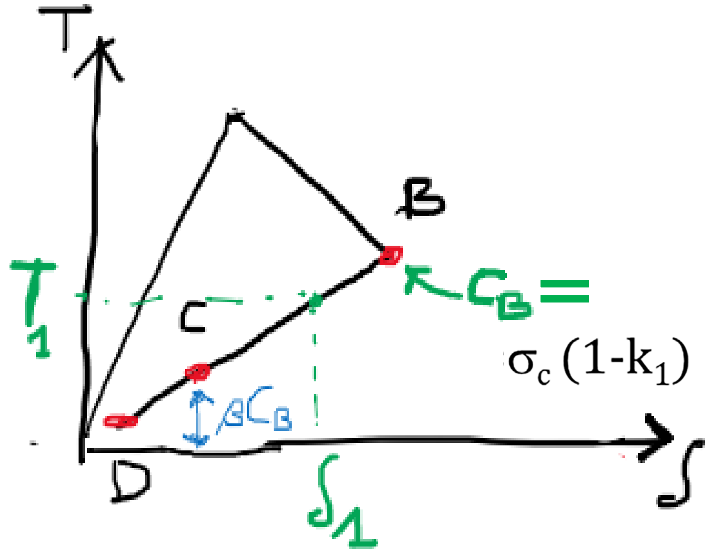
Analysis of bond:
Cyclic cohesive zone models

Cyclic Cohesive Zone Models (CCZMs) – cyclic loading

- Initial unloading stage: $\dot{\delta} < 0$ and $t > \beta C_B$; then $[t - \beta C_B]\dot{\delta} < 0$; and $\dot{k} = 0$, which means no damage evolution.
- Final unloading stage: $\dot{\delta} < 0$ and $t < \beta C_B$; then $[t - \beta C_B]\dot{\delta} > 0$ and $\dot{k} = -\gamma k[t - \beta C_B]\dot{\delta} < 0$, which means damage healing or crack retardation.
- Initial reloading stage: $\dot{\delta} > 0$ and $t < \beta C_B$; then $[t - \beta C_B]\dot{\delta} < 0$ and $\dot{k} = 0$, which means no damage evolution.
- Final reloading stage: $\dot{\delta} > 0$ and $t > \beta C_B$; then $[t - \beta C_B]\dot{\delta} > 0$ and $\dot{k} = \alpha k[t - \beta C_B]\dot{\delta} > 0$, which means damage incrementation.







Analysis of bond:
Cyclic cohesive zone models

Cyclic Cohesive Zone Models (CCZMs) – cyclic loading

K indicates the energy dissipated up to the actual maximum effective displacement attained divided by the total fracture energy.

Linear damaging radial paths considered in the stress versus opening space from the origin to the maximum attainable interface traction.

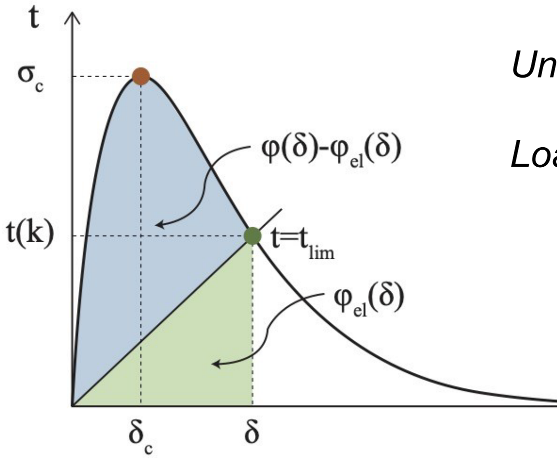
Elasto damage behavior with no residual slip at unloading, different from elasto-plastic damage models allowing for residual plastic deformations

Exponential TSL

$$\phi(\delta) = e\sigma_c\delta_c\left[1-\left(1+\frac{\delta}{\delta_c}\right)e^{-\delta/\delta_c}\right]$$

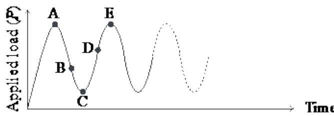
$$F(k) = \frac{\sigma_c}{\delta_c}e^{\left(1-\tilde{\delta}(k)/\delta_c\right)}$$

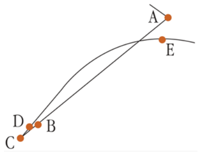
$$k = \left[1-\left(1+\frac{\tilde{\delta}}{\delta_c}+\frac{1}{2}\left(\frac{\tilde{\delta}}{\delta_c}\right)^2\right)e^{-\tilde{\delta}/\delta_c}\right]^{\lambda}$$



Unloading Phase $\dot{\delta} < 0,\ \hat{\alpha} = -\gamma < 0$

Loading Phase $\dot{\delta} > 0,\ \hat{\alpha} = \alpha > 0$





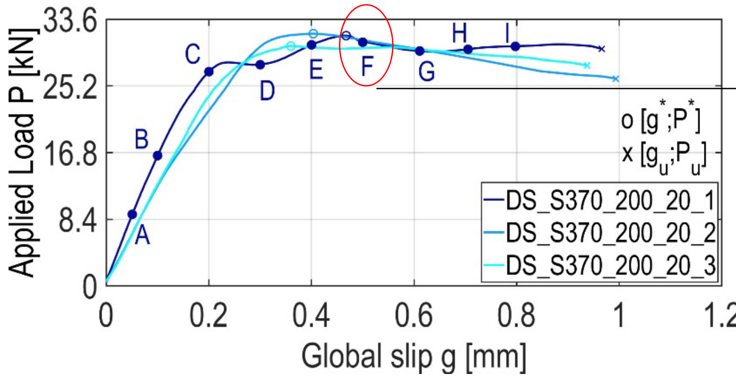
- Initial unloading stage: $\dot{\delta} < 0$ and $t > \beta t^{lim}$; then $\left[t-\beta t^{lim}\right]\dot{\delta} < 0$; and $\dot{k} = 0$, which means no damage evolution.
- Final unloading stage: $\dot{\delta} < 0$ and $t < \beta t^{lim}$; then $\left[t-\beta t^{lim}\right]\dot{\delta} > 0$ and $\dot{k} = -\gamma k\left[t-\beta t^{lim}\right]\dot{\delta} < 0$, which means damage healing or crack retardation.
- Initial reloading stage: $\dot{\delta} > 0$ and $t < \beta t^{lim}$; then $\left[t-\beta t^{lim}\right]\dot{\delta} < 0$ and $\dot{k} = 0$, which means no damage evolution.
- Final reloading stage: $\dot{\delta} > 0$ and $t > \beta t^{lim}$; then $\left[t-\beta t^{lim}\right]\dot{\delta} > 0$ and $\dot{k} = \alpha k\left[t-\beta t^{lim}\right]\dot{\delta} > 0$, which means damage incrementation.

Analysis of bond:
Cyclic cohesive zone models

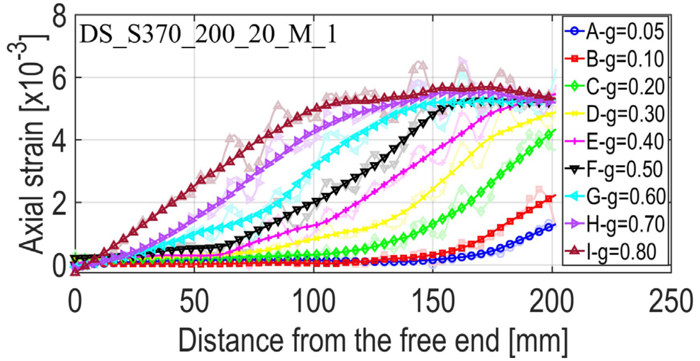
Experimental campaign (MTS laboratory)

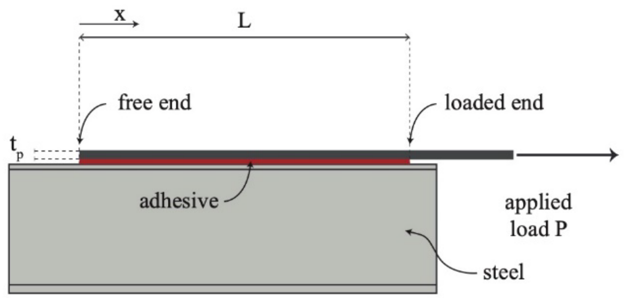
*Single-lap Direct Shear (DS) tests – **Monotonic** Results*

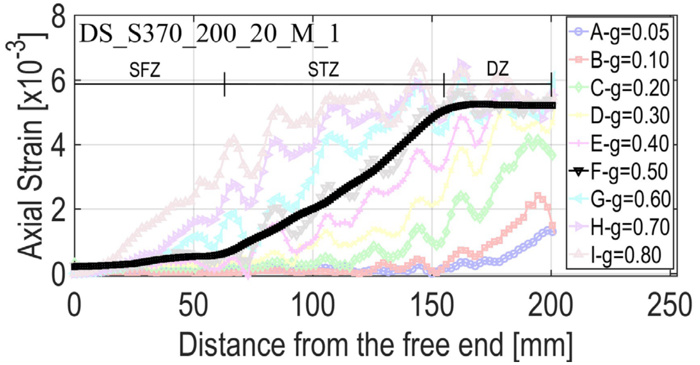
Specimens S370

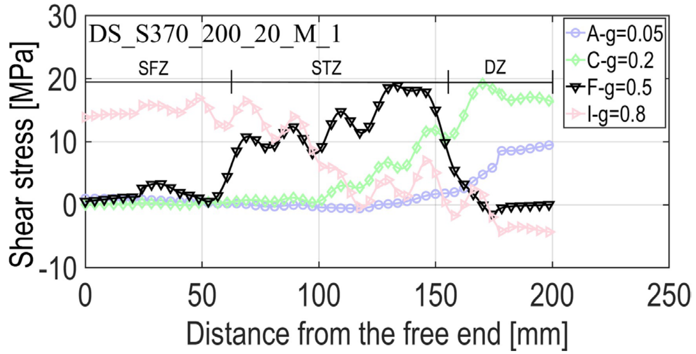


DIC profiles









- Larger peak strain and larger region involved at $P = P_u$
- Larger ultimate load and effective bonded length
- Less sharp peak and larger region involved in shear (trapezoidal shape)

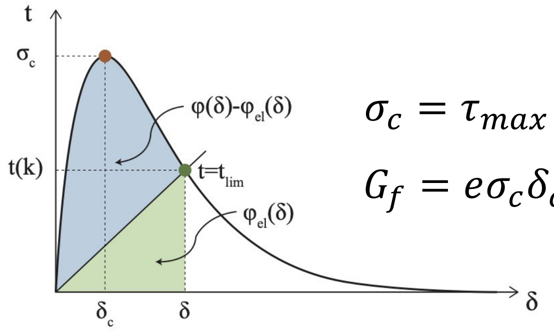
SFZ = Stress Free Zone; STZ = Stress Transfer Zone; DZ = Debonded Zone

Analysis of bond:
Cyclic cohesive zone models

Numerical Results

***Monotonic** results – calibration and comparisons*

Specimen	τ_{max} [MPa]	δ_c [mm]	G_f [N/mm]
DS_S30_200_20_M_1	17.97	0.033	1.62
DS_S30_200_20_M_2	19.16	0.024	1.26
DS_S30_200_20_M_3	24.92	0.021	1.41
Average	20.68	0.026	1.43
CoV	17.97 %	24.45 %	12.68 %
DS_S370_200_20_M_1	19.22	0.080	4.198
DS_S370_200_20_M_2	16.66	0.092	4.168
DS_S370_200_20_M_3	17.01	0.082	3.787
Average	17.63	0.085	4.051
CoV	7.89 %	7.53 %	5.65 %

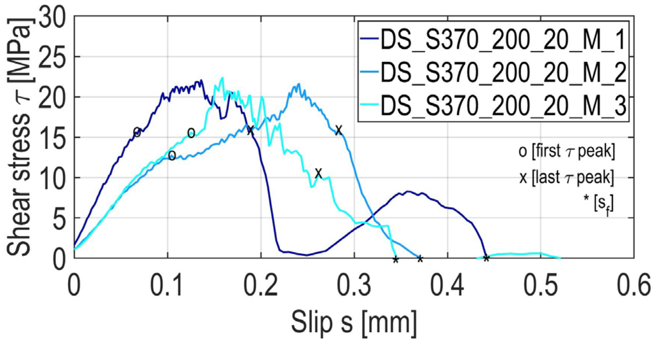


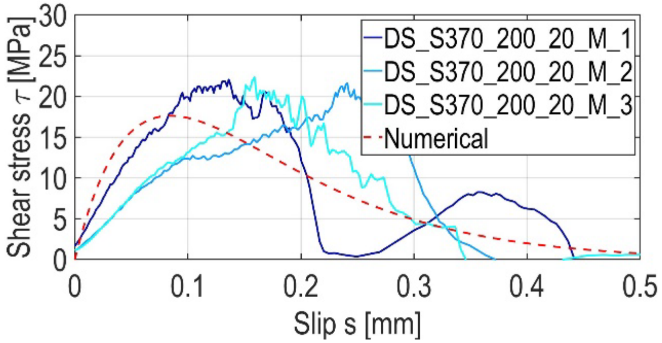
$$\sigma_c = \tau_{max}$$

$$G_f = e\sigma_c\delta_c$$

Exponential cohesive law - monotonic

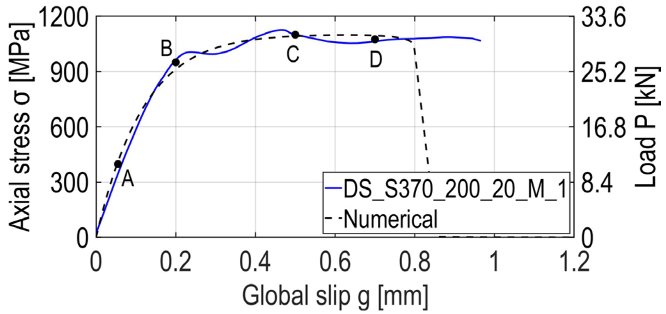
Experimental results

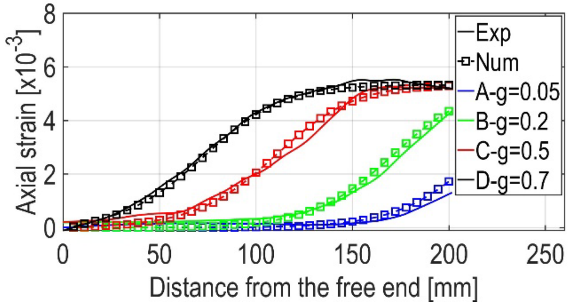


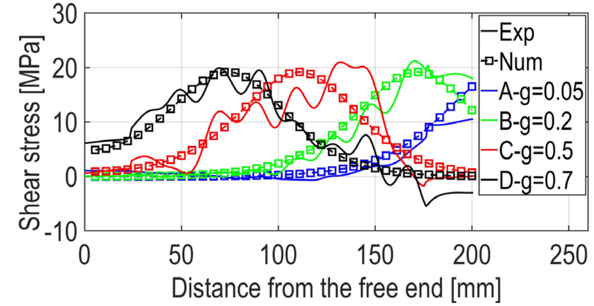


Calibration

Comparison





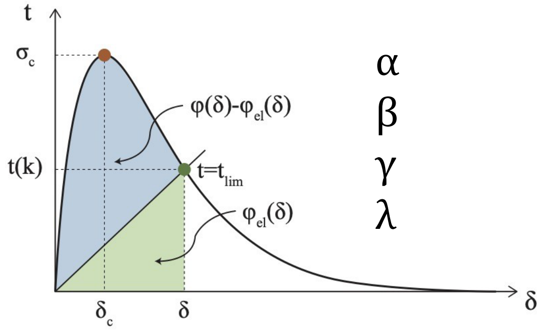


Analysis of bond:
Cyclic cohesive zone models

Numerical Results

Fatigue and Post-fatigue results - comparisons

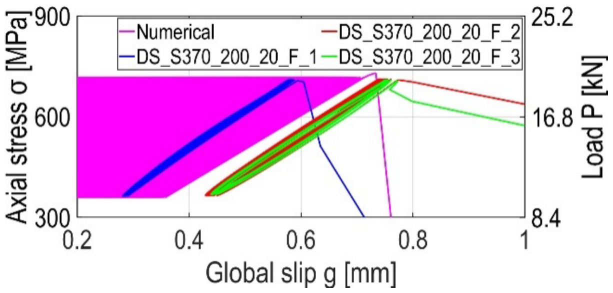
- Calibration of the fatigue model parameters on the F specimens (average behavior)
- Validation of the model with PF specimens (static and cyclic)
- The numerical response is able to capture the ultimate behavior of the system in terms of the overall response and the number of cycles at failure
- Modelling of the reduction of stiffness and damage propagation

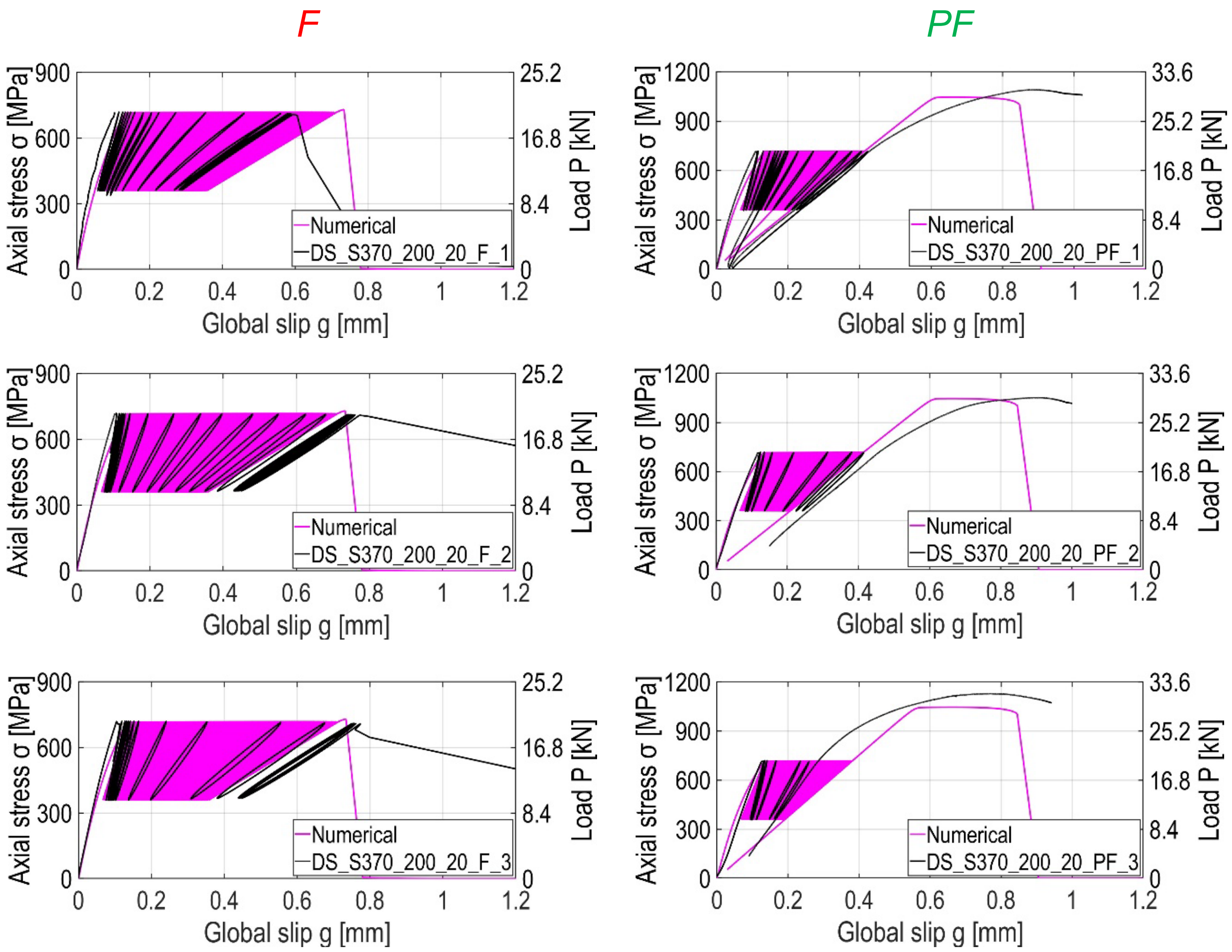


Exponential cohesive law - cyclic

α
β
γ
λ

F Average behavior

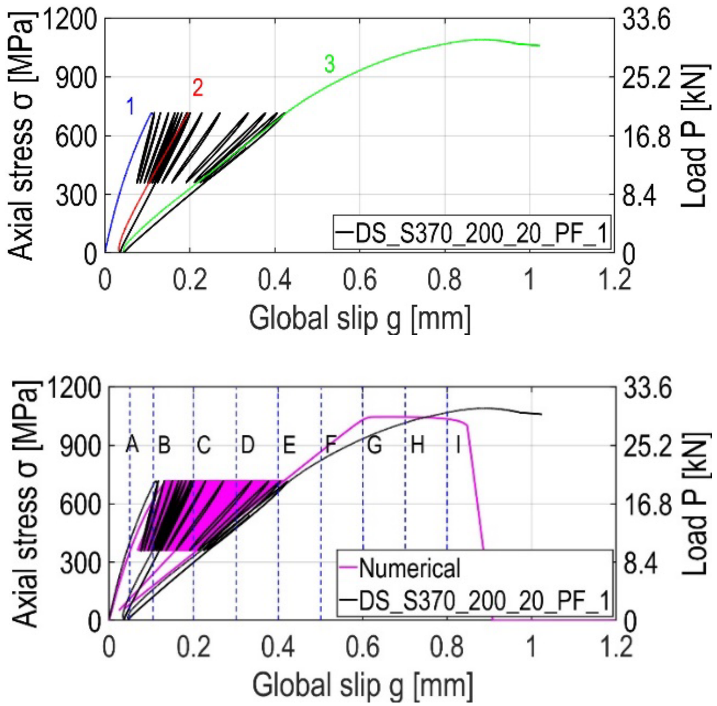




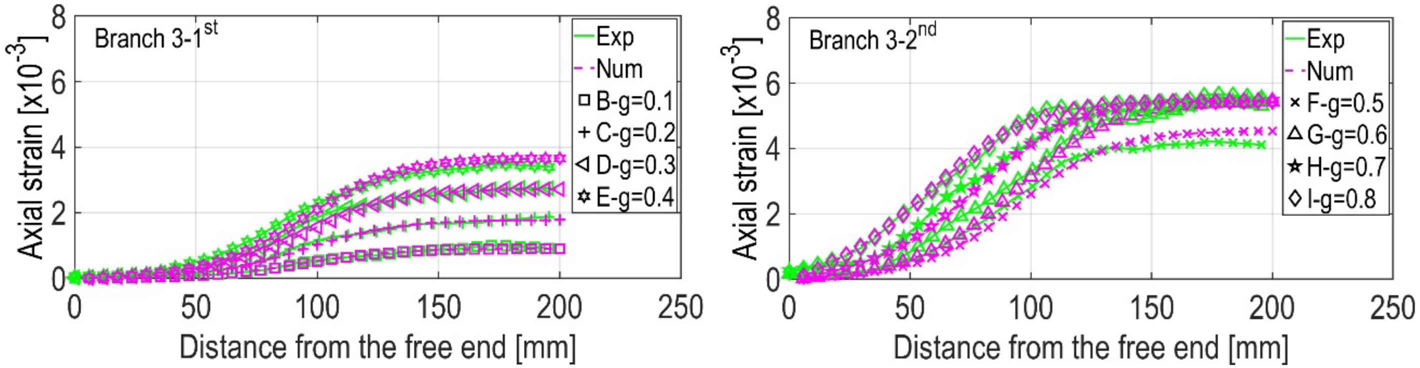
Analysis of bond:
Cyclic cohesive zone models

Numerical Results

Fatigue and Post-fatigue results - comparison



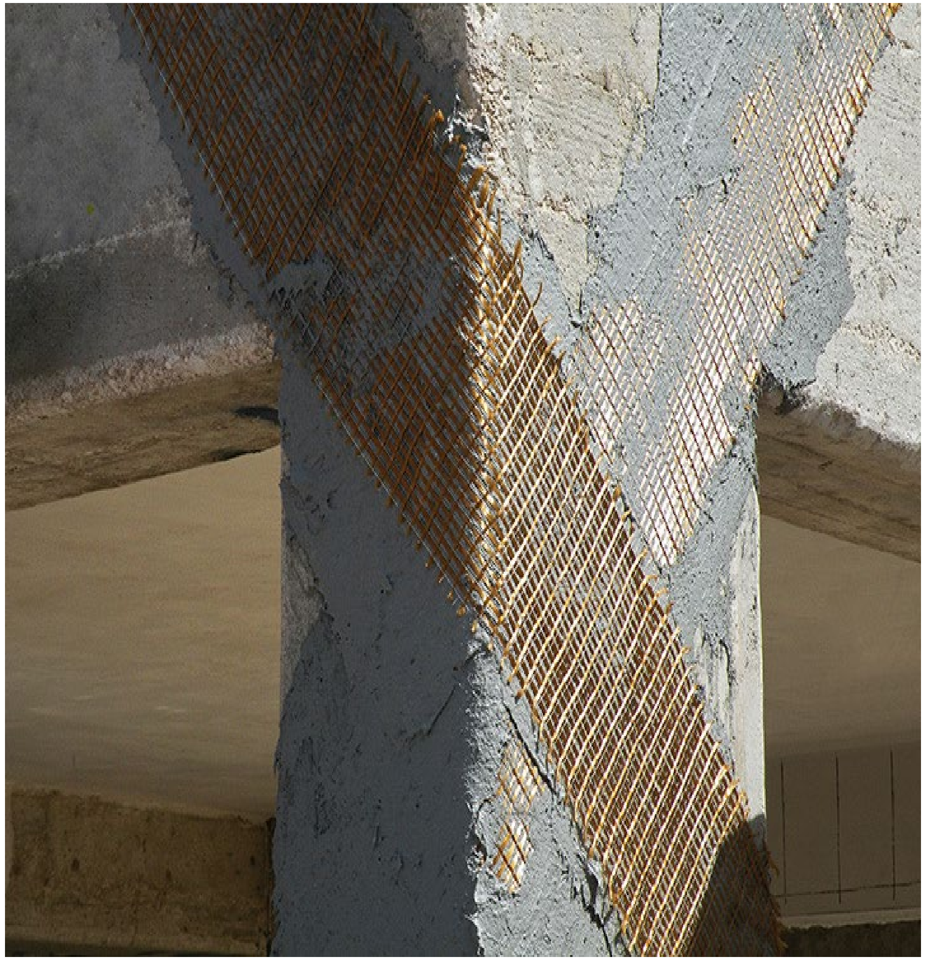
DIC
profiles



- Good agreement in axial strain and shear profiles at different *g*
- Good agreement in profiles belonging to different quasi-static branches
- Modelling of progressive damage propagation and stiffness reduction

Fatigue behavior of inorganic-matrix composites and systems

Fatigue behavior of inorganic-matrix composites:
FRCM-strengthened RC beam under cyclic loading



Nodes

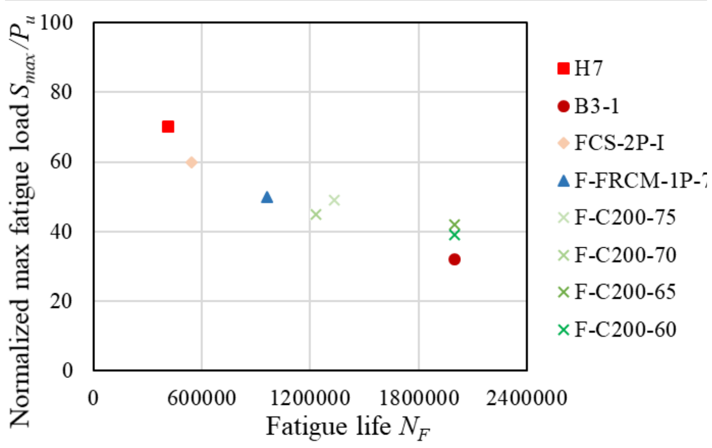
Shear strengthening of RC beams

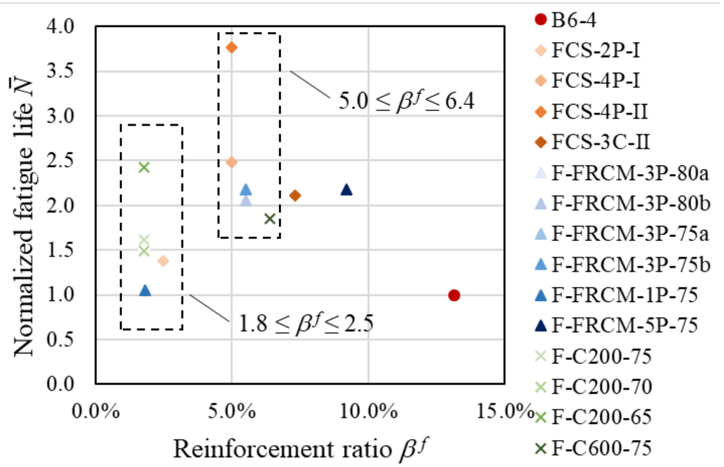
Masonry arch strengthening

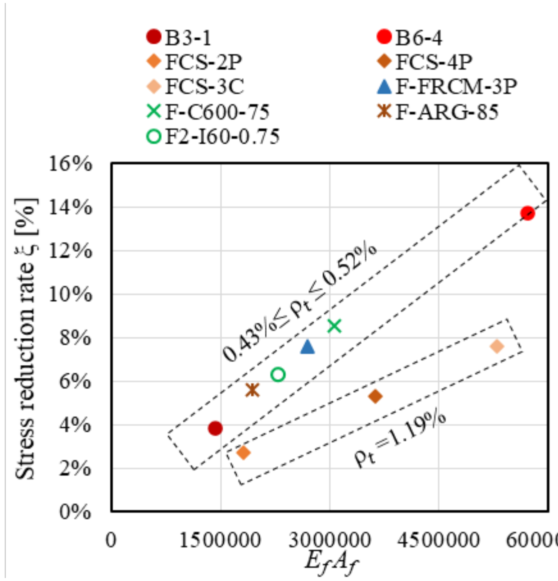
Masonry vaults strengthening

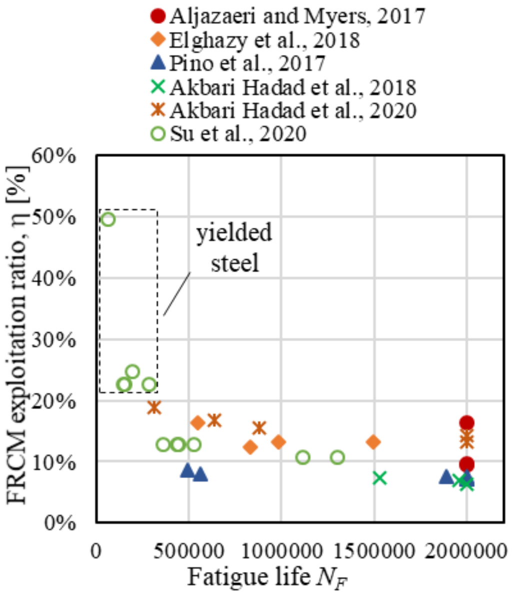
Flexural strengthening of slabs

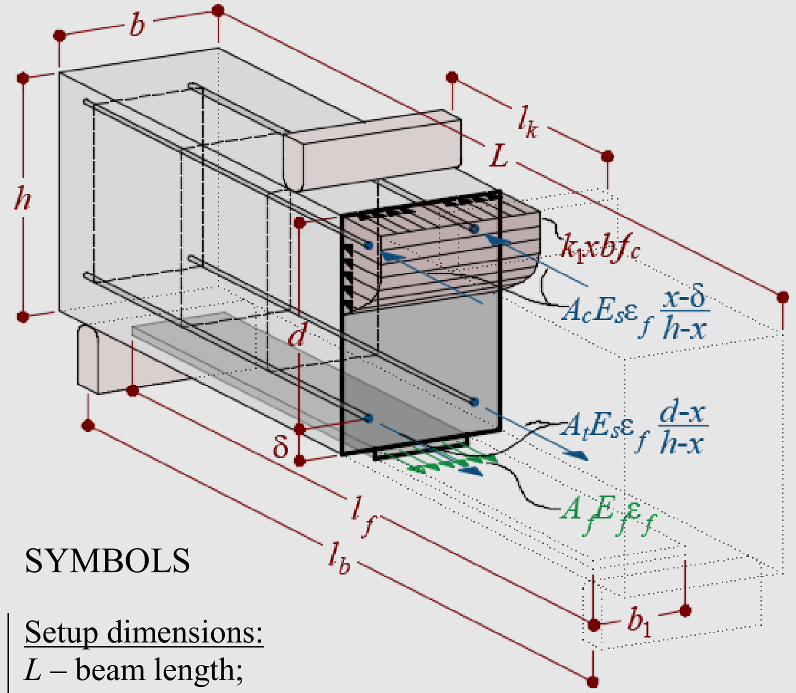
Fatigue behavior of inorganic-matrix composites:
FRCM-strengthened RC beam under cyclic loading











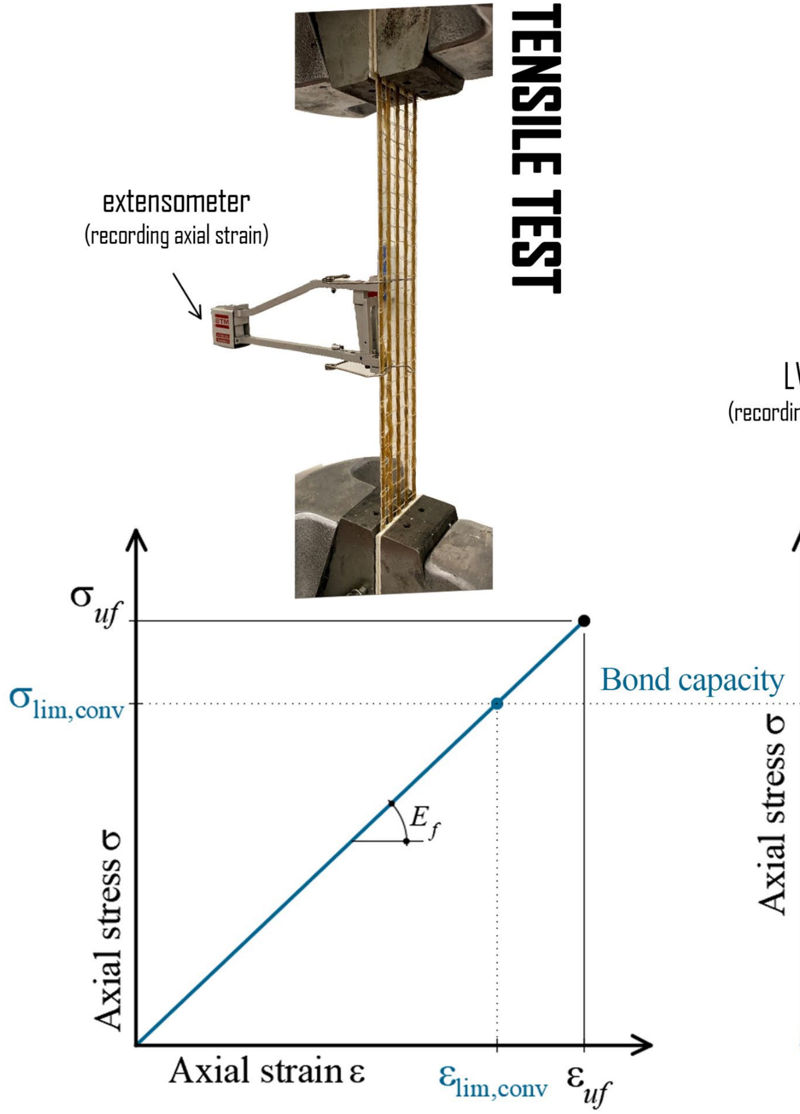
SYMBOLS

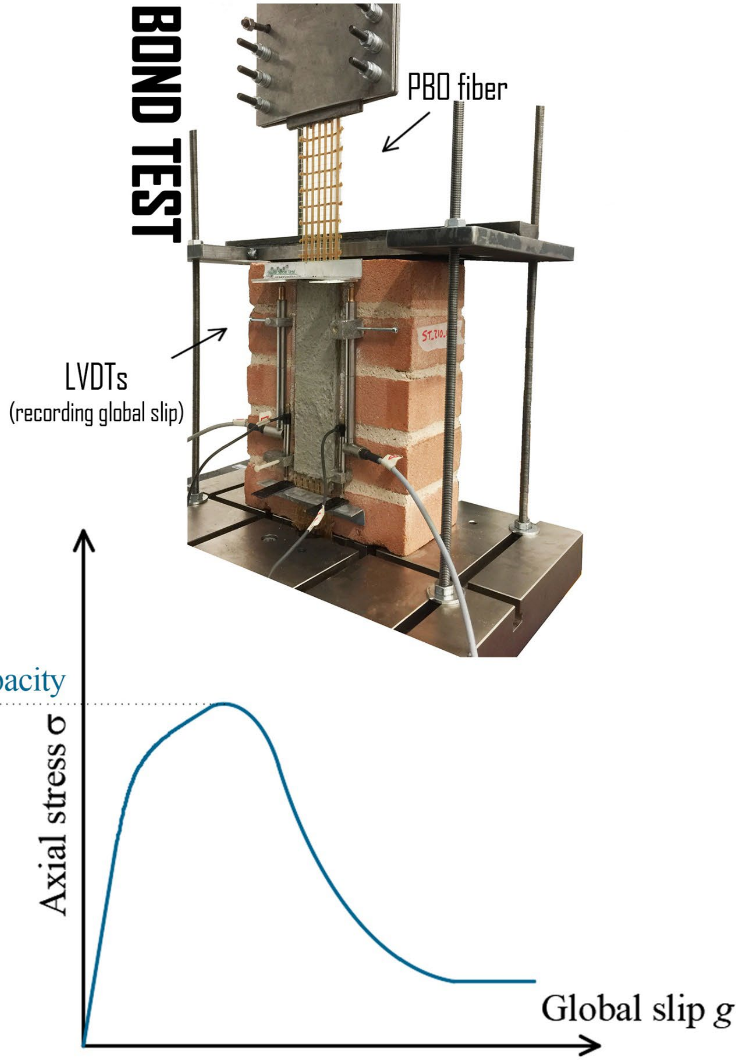
Setup dimensions:
- L – beam length;
- l_f – composite strip length;
- l_b – supporting span;
- l_k – distance between loading points;

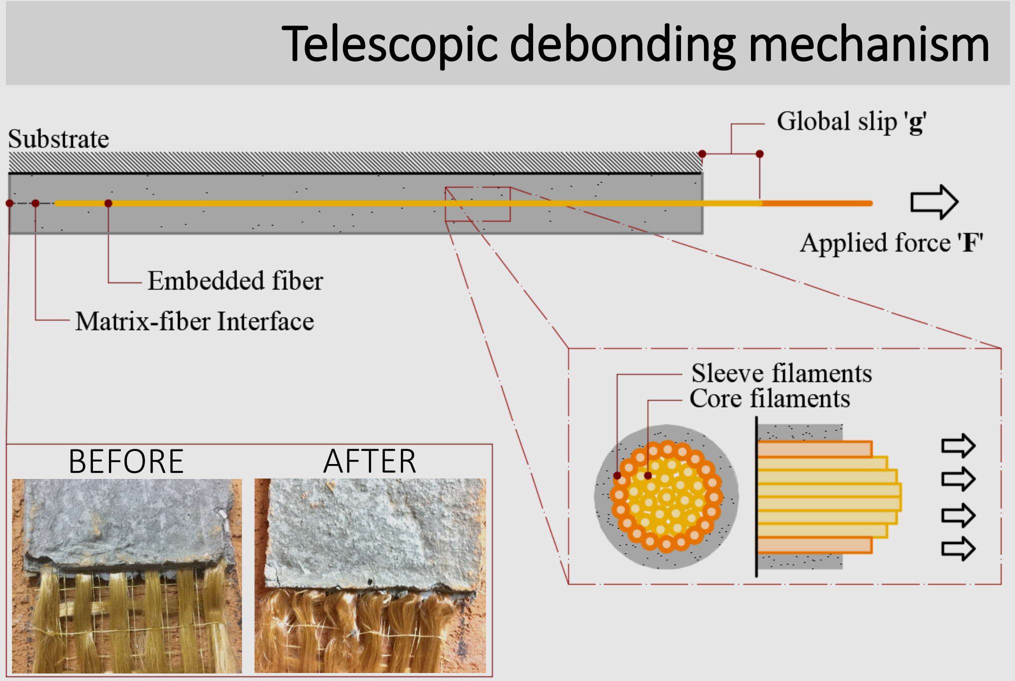
Mechanical parameters:
- f_c – concrete compressive strength;
- E_s – steel bar elastic modulus;
- E_f – composite elastic modulus;
- ε_f – composite axial strain;

Cross-section geometry:
- h – height;
- b – width;
- d – tension bars depth;
- δ – concrete cover;
- b_1 – composite strip width;
- x – neutral axis depth;
- A_c – compression bars area;
- A_t – tension bars area;
- A_f – fiber area;
- k_1 – coefficient defining the concrete stress resultant;

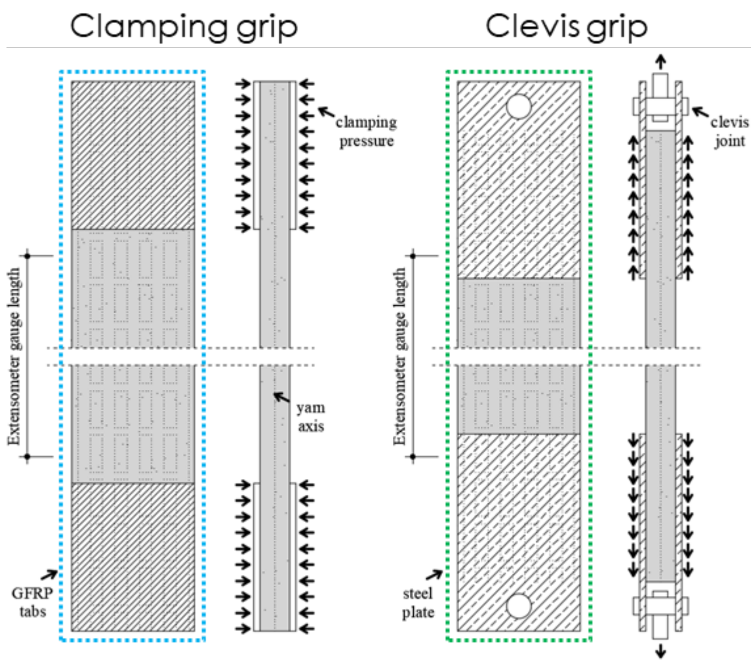
Fatigue behavior of inorganic-matrix composites:
Typical static behavior (benchmark)

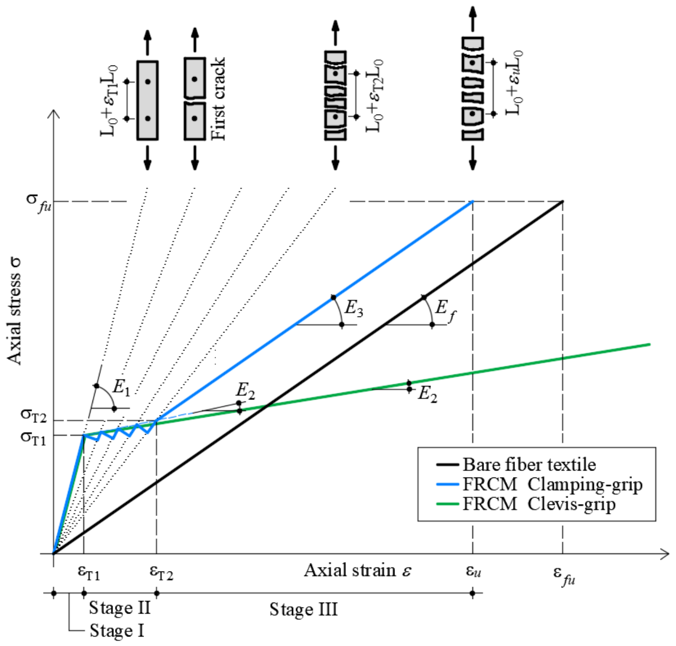






Fatigue behavior of inorganic-matrix composites:
Typical static behavior (benchmark)





Clamping-grip: provides information on the mechanical properties of the FRCM and its component materials.

Clevis-grip provides information on the matrix-fiber stress transfer mechanism.

The European Assessment Document (EAD) 340275-00-0104 “Externally-bonded composite systems with inorganic matrix for strengthening of concrete and masonry structures” requires clamping-grip tensile tests

Fatigue behavior of inorganic-matrix composites:
Typical static behavior (benchmark)

Clamping grip tensile test

The two ends of the specimen are directly clamped by the testing machine and then pulled apart.

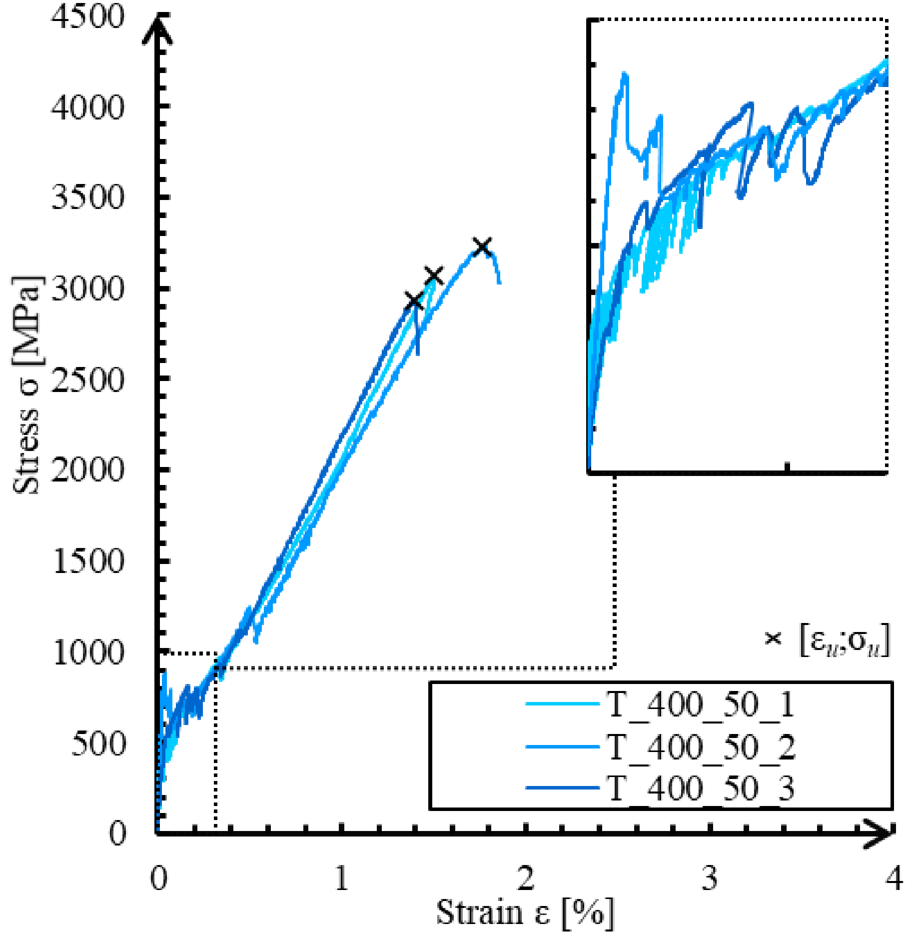
Clevis grip tensile test

Metallic plates are bonded to the specimen lateral faces and then connected to the testing machine with clevis-type joint

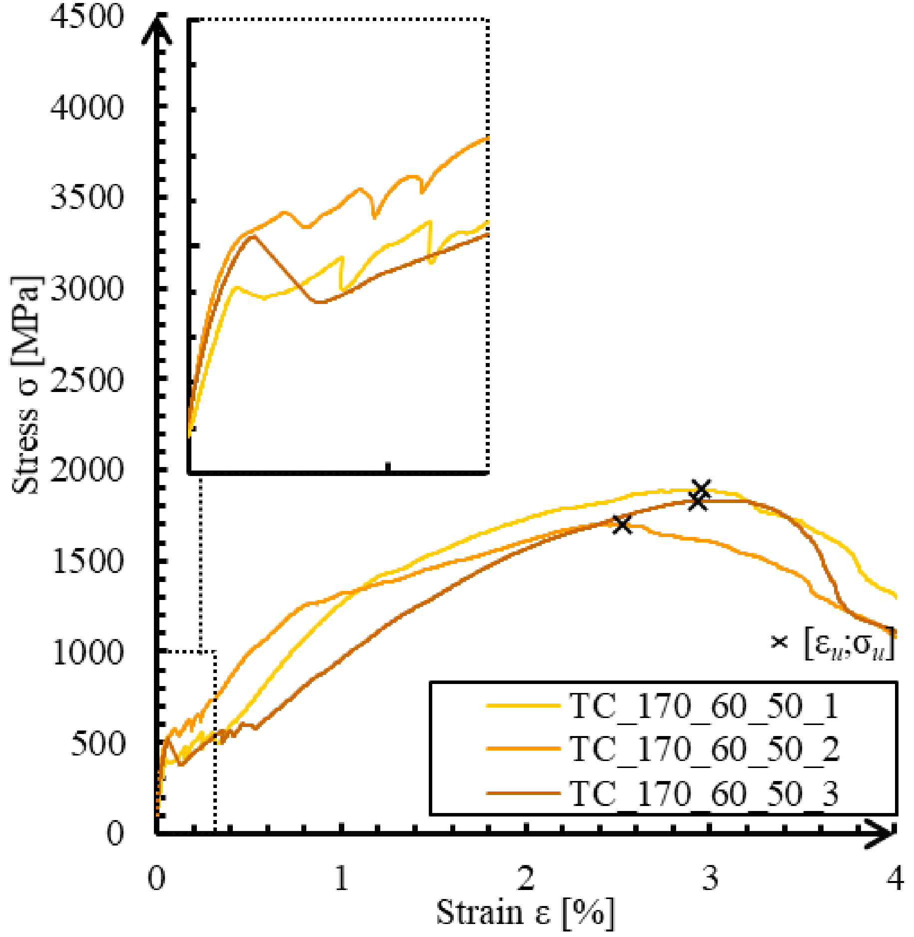
Fatigue behavior of inorganic-matrix composites:

Typical static behavior (benchmark)

Clamping grip tensile test



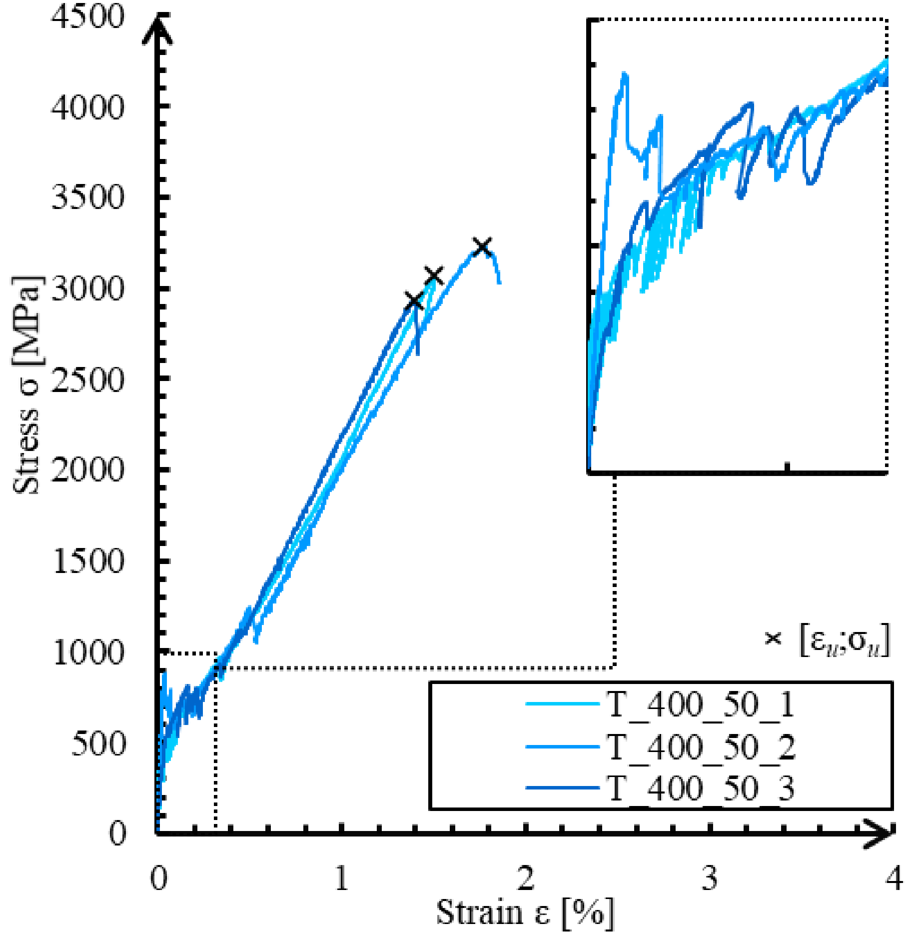
Clevis grip tensile test

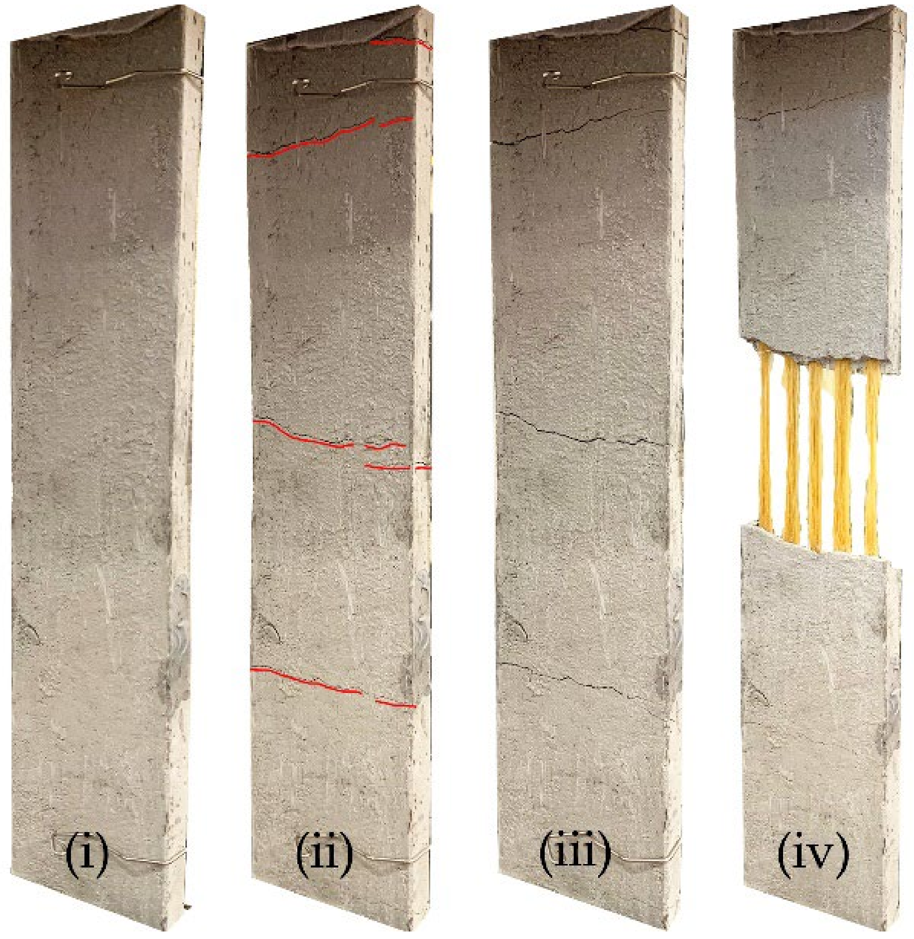


Fatigue behavior of inorganic-matrix composites:

Typical static behavior (benchmark)

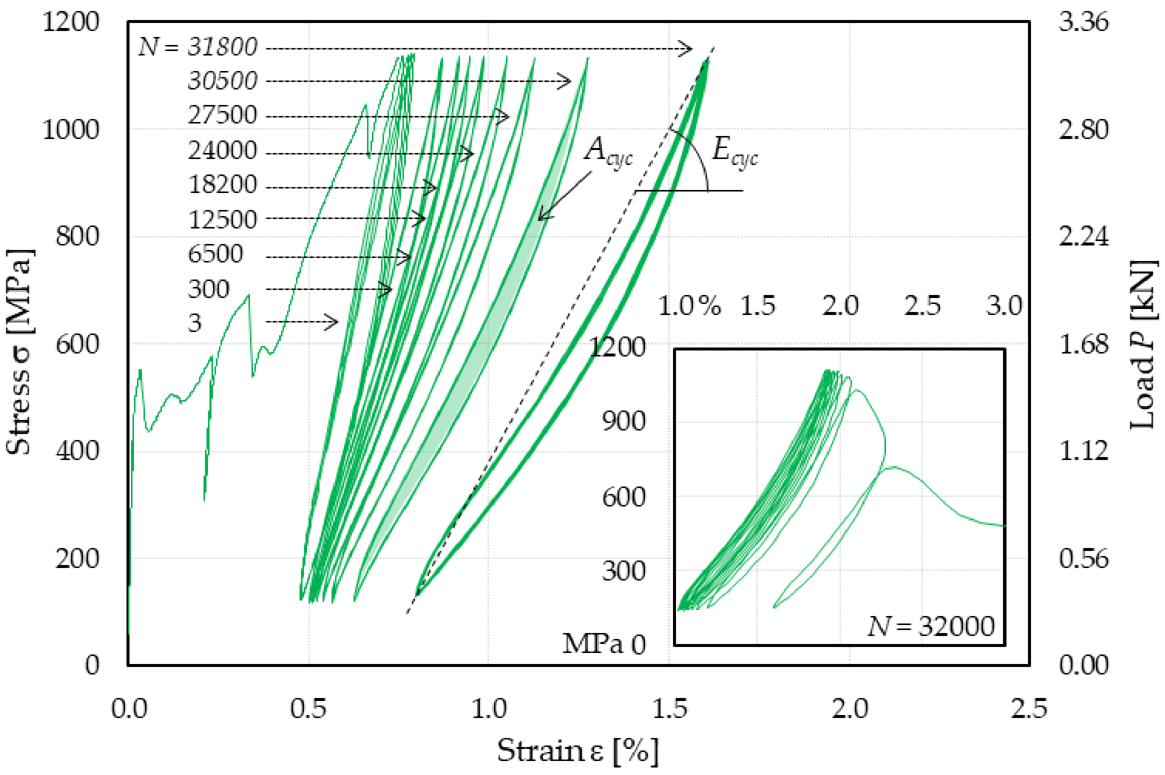
Clamping grip tensile test

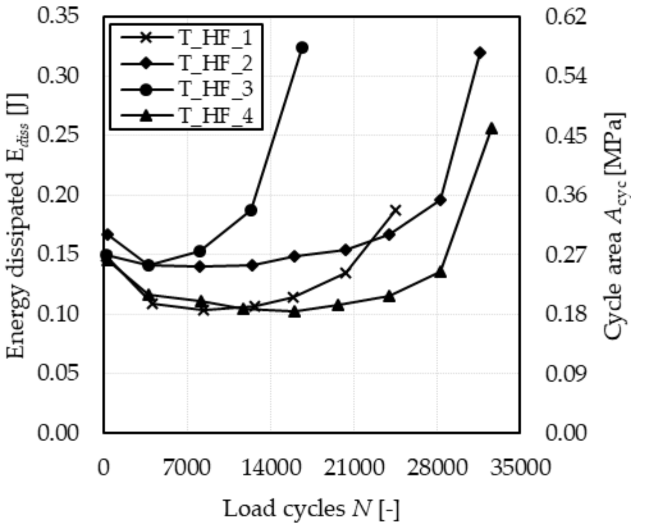


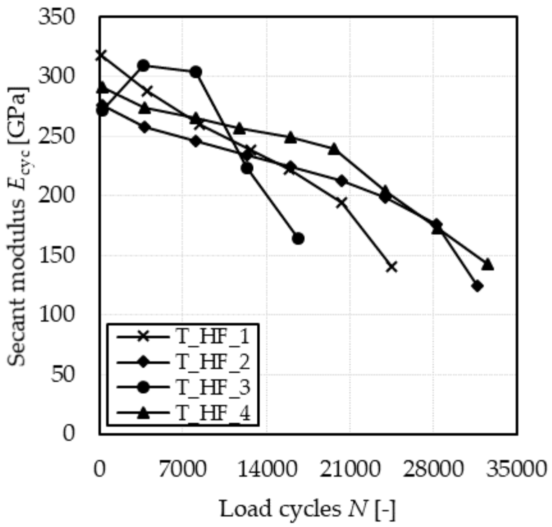


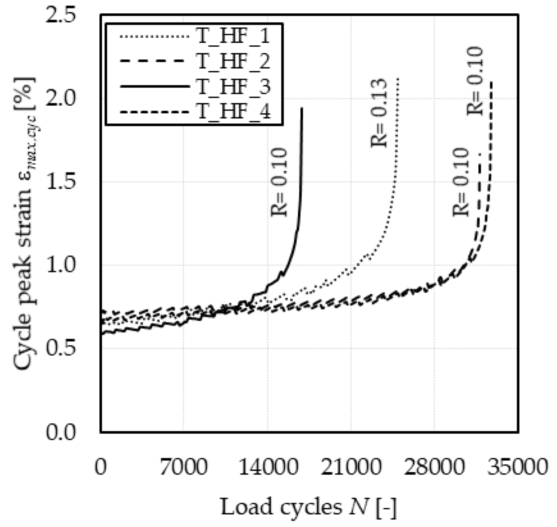
Fatigue behavior of inorganic-matrix composites:
Cyclic tensile behavior (clamping-grip test)

Fatigue actions – High number of cycles (EAD test)





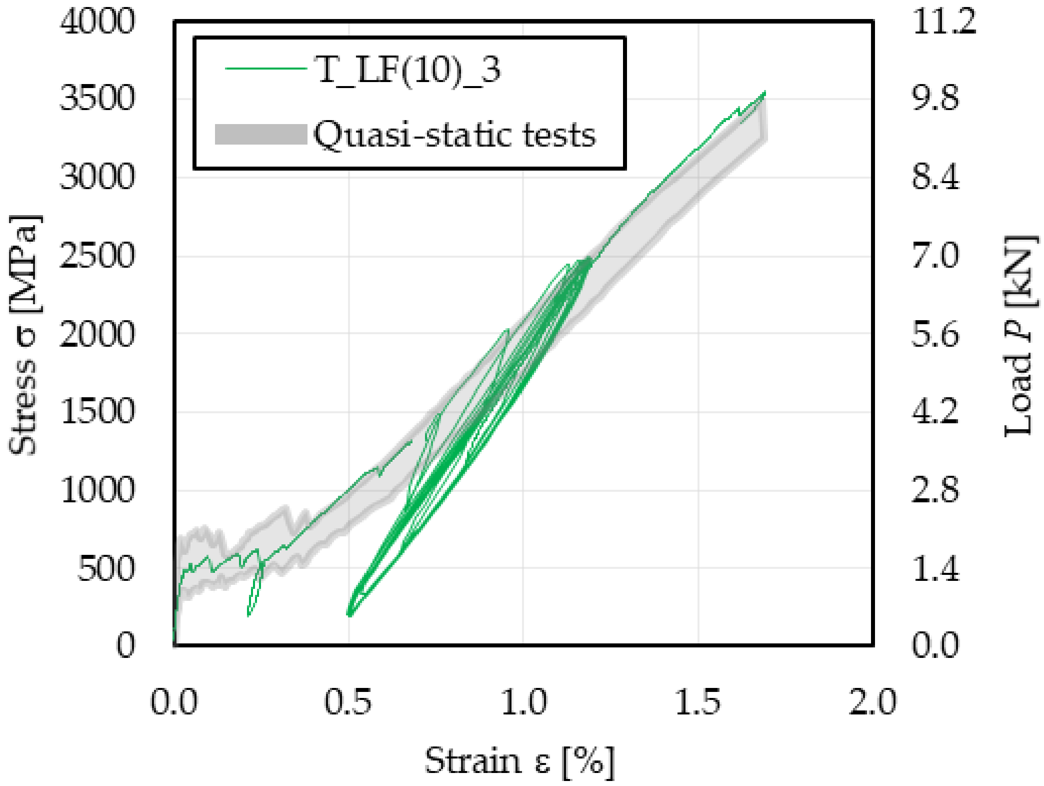


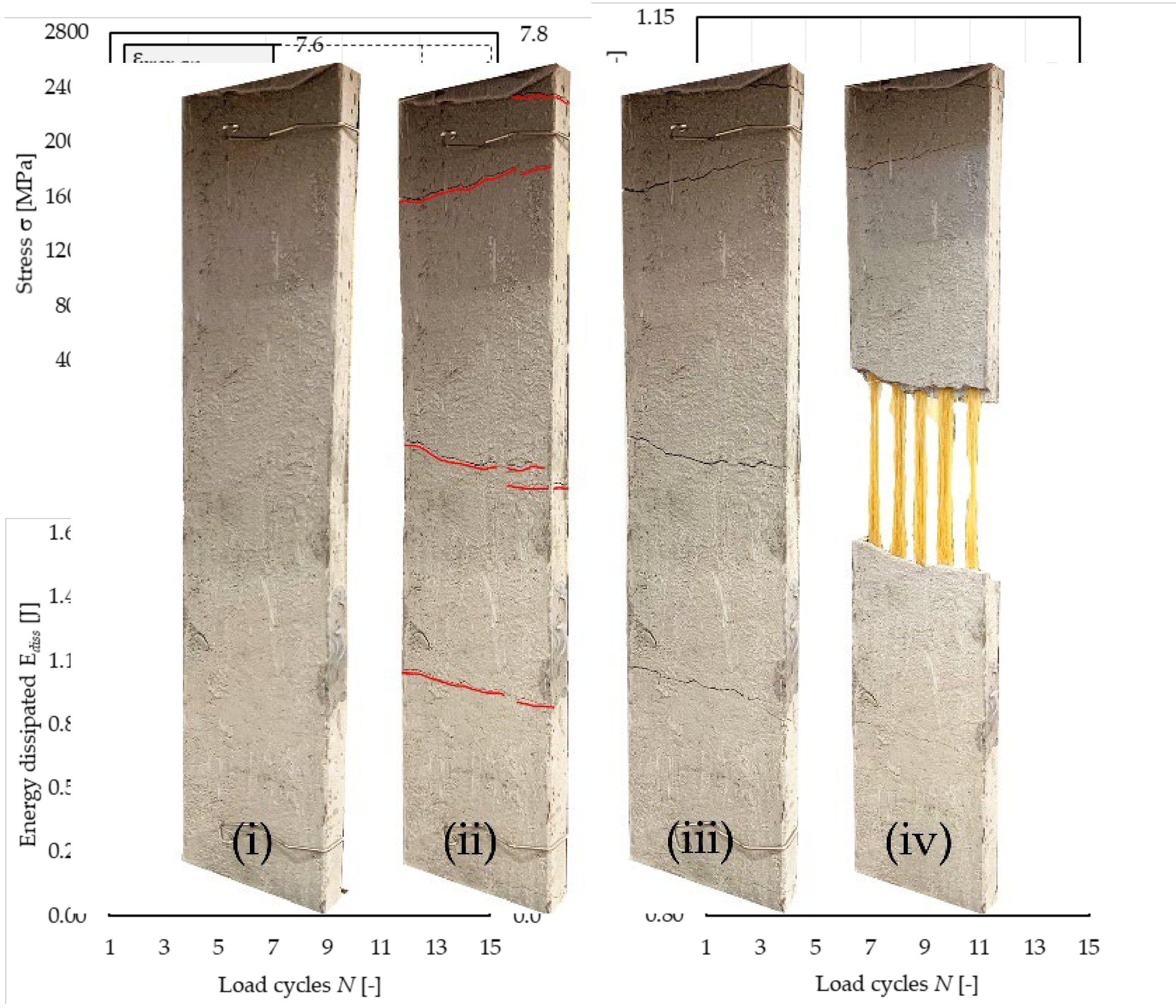


EAD indications: R=0.1 – *f*= 1-3Hz – S_{max}=60% $\sigma_{lim,conv}$

Fatigue behavior of inorganic-matrix composites:
Cyclic tensile behavior (clamping-grip test)

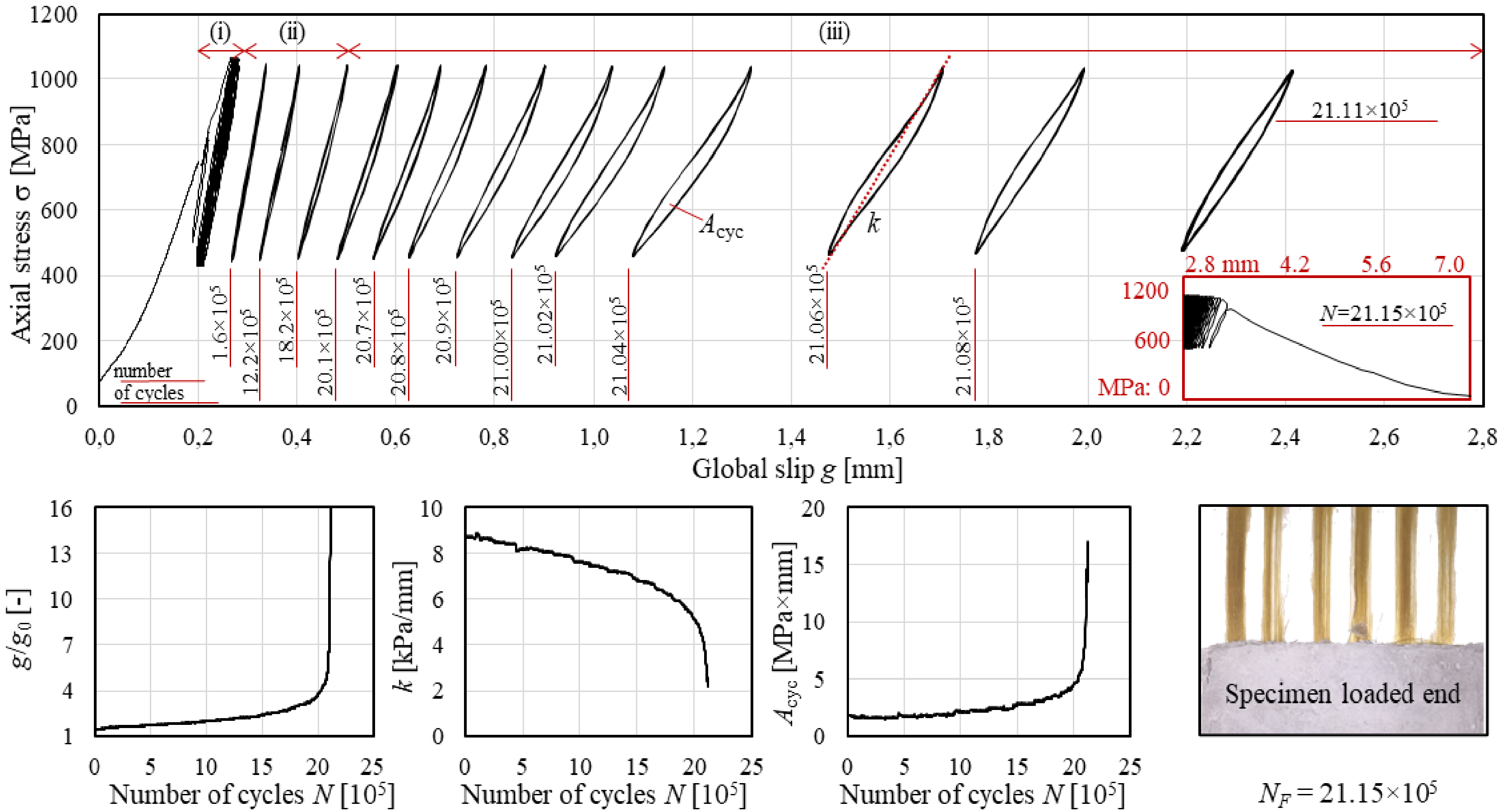
Seismic actions – Low number of cycles (EAD test)

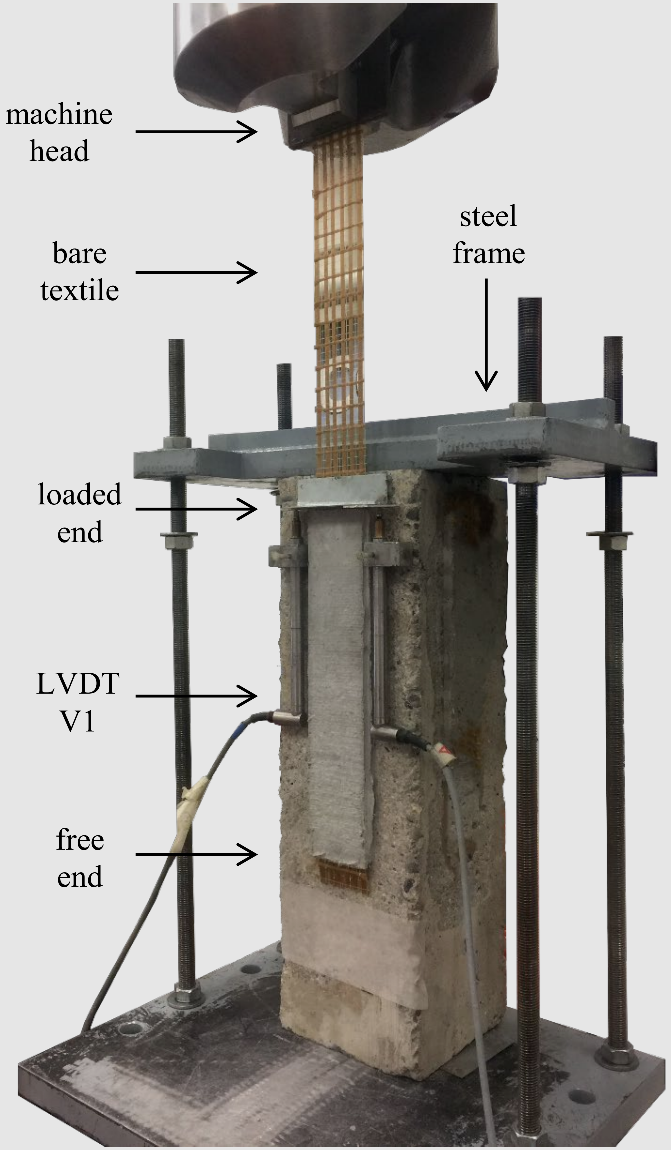




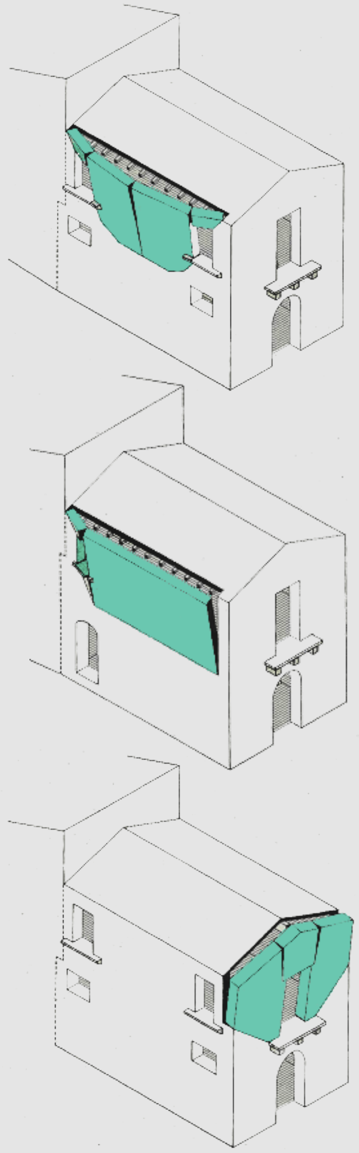
EAD indications: R=0.05 – *f*= 1Hz – S_{max}=90% $\sigma_{lim,conv}$

Fatigue behavior of inorganic-matrix composites:
Cyclic bond behavior (direct-shear test)

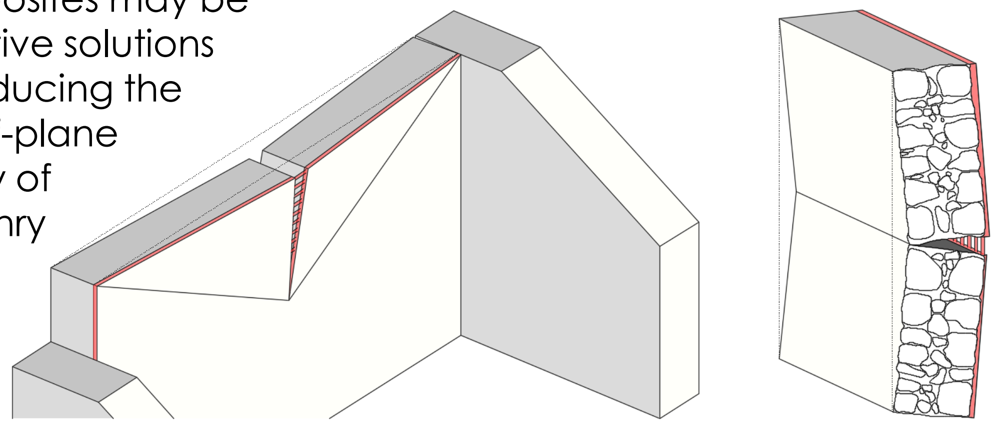




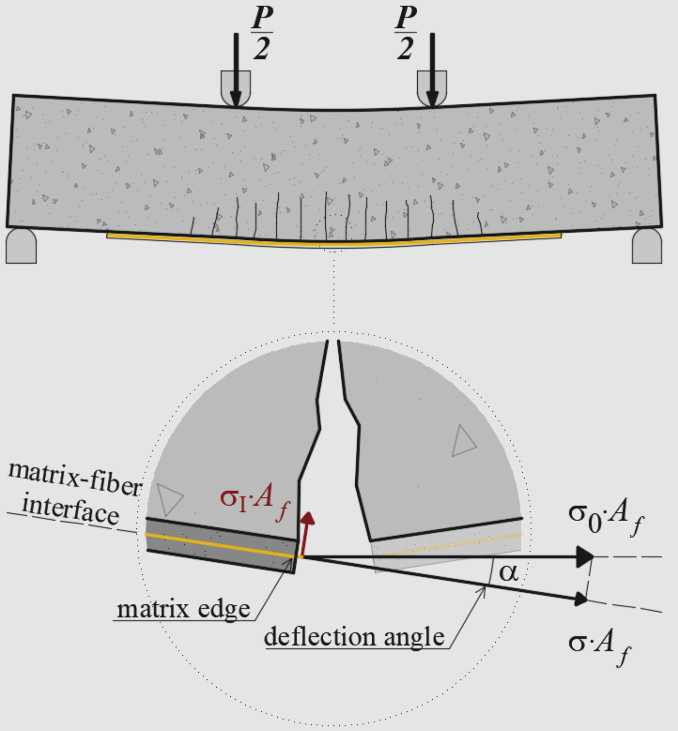
Fatigue behavior of inorganic-matrix composites:
Cyclic bond behavior (INdirect-shear test)



Externally bonded FRCM composites may be effective solutions for reducing the out-of-plane lability of masonry



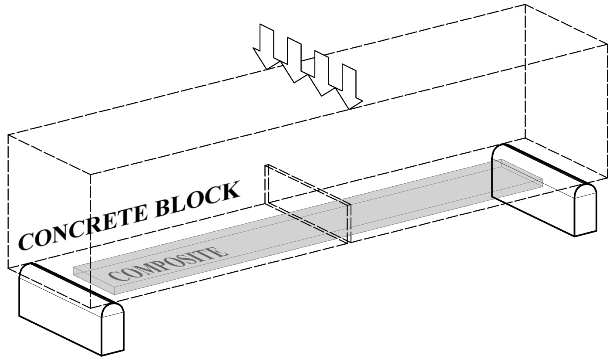
Simplified structural scheme of FRCM-strengthened RC beam test



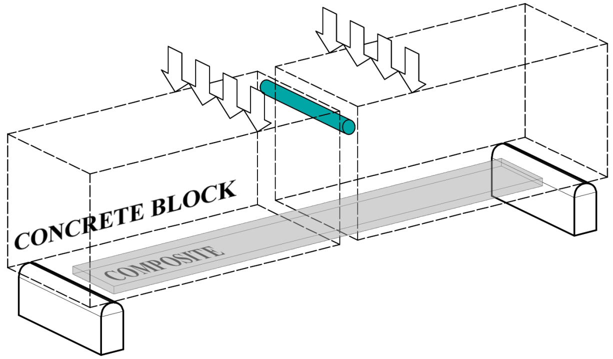
INDIRECT SHEAR TEST SET-UPS

In indirect shear test set-ups the pulling action on the composite is indirectly applied through a flexural scheme:

Notched beam test:



Modified beam test:



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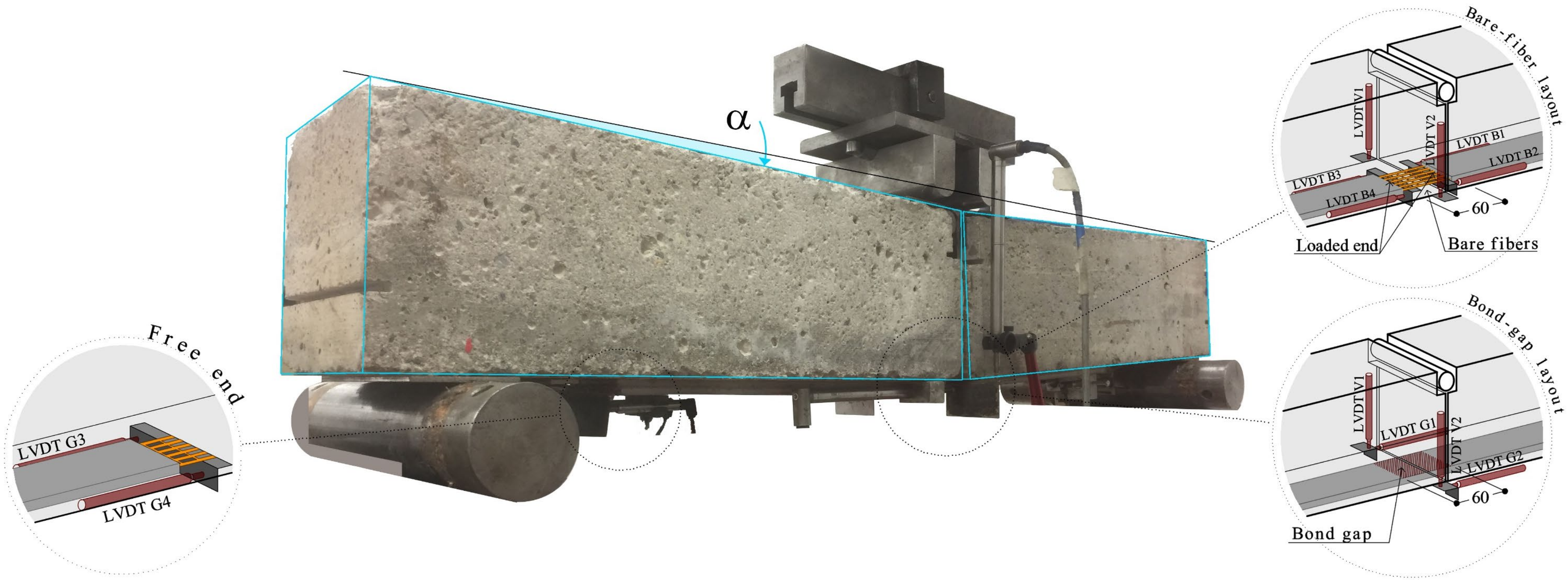


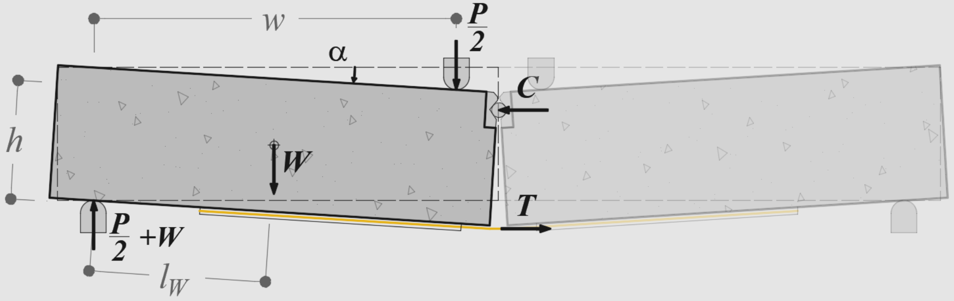
Structural scheme

From the free body diagram:

$$\sigma_0 = \frac{T}{A} = \frac{Pw + 2Wl_W}{2h\cos\alpha} \cdot \frac{1}{A}$$

Blocks opening:

$$g_e = \frac{LVDT_{SX} + LVDT_{DX}}{2}$$



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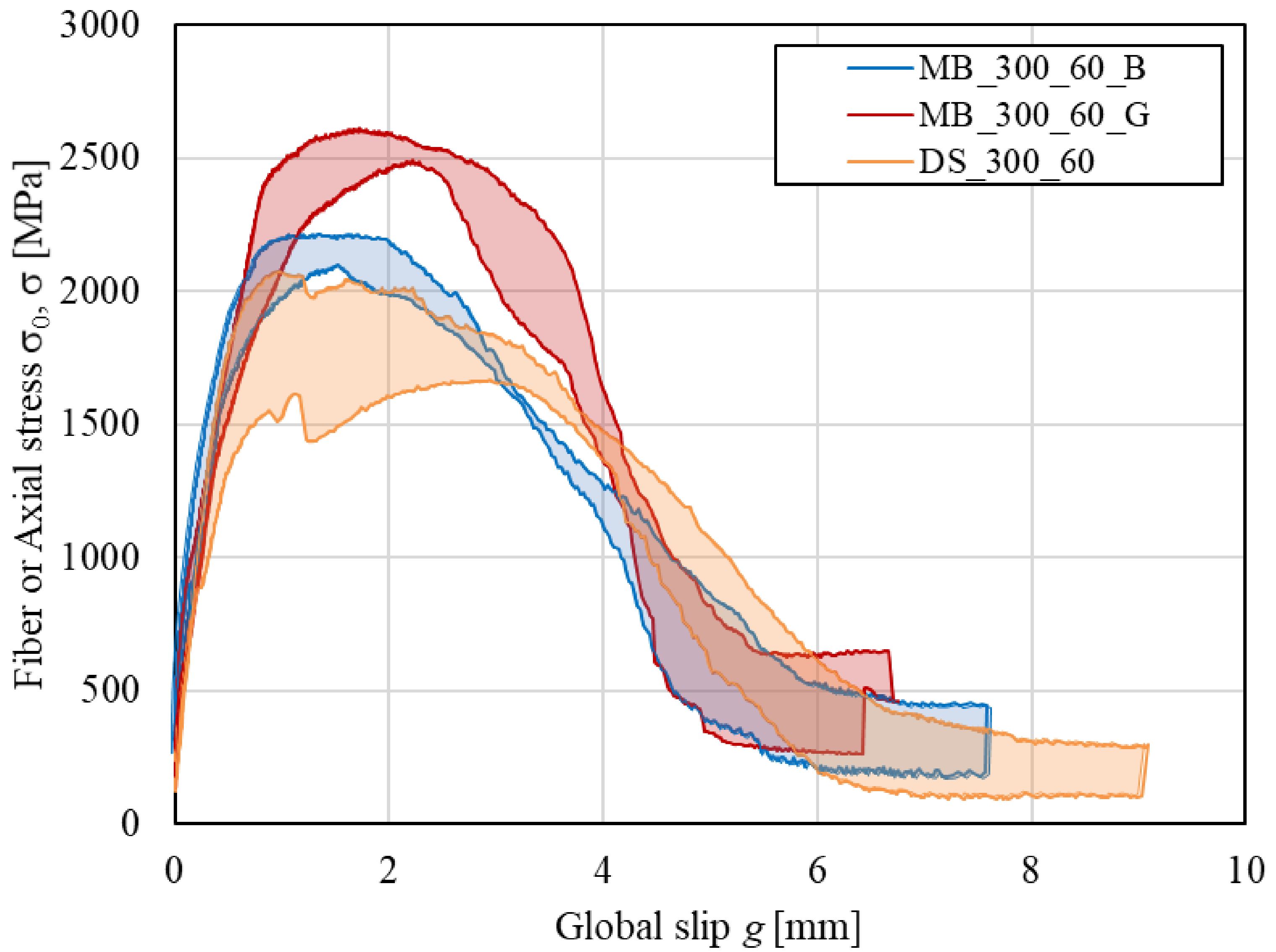
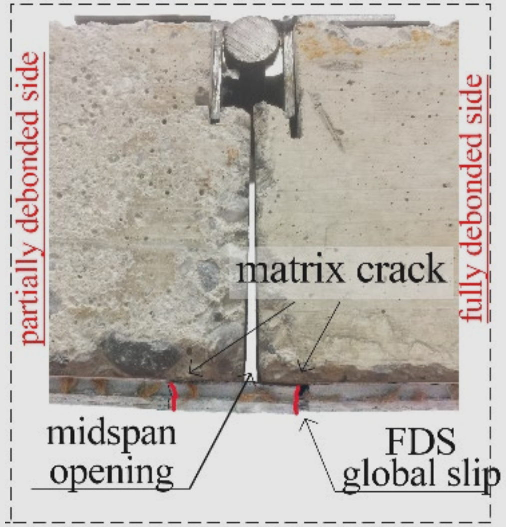
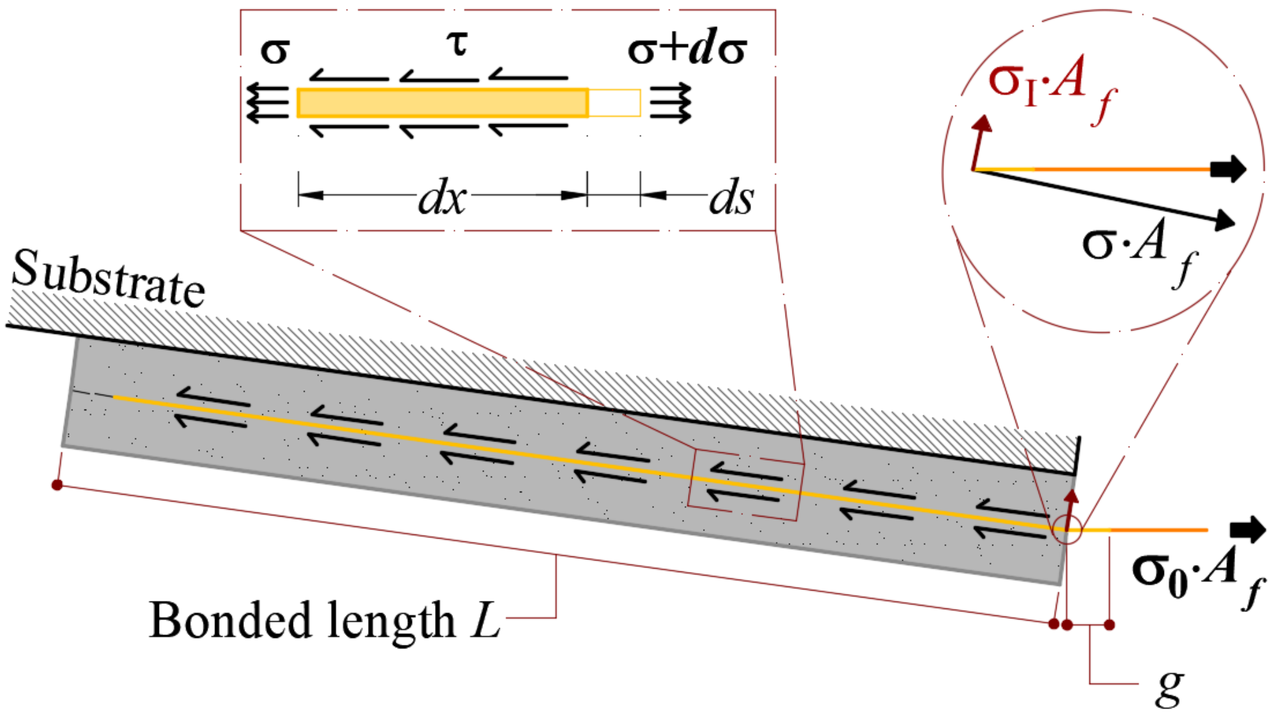


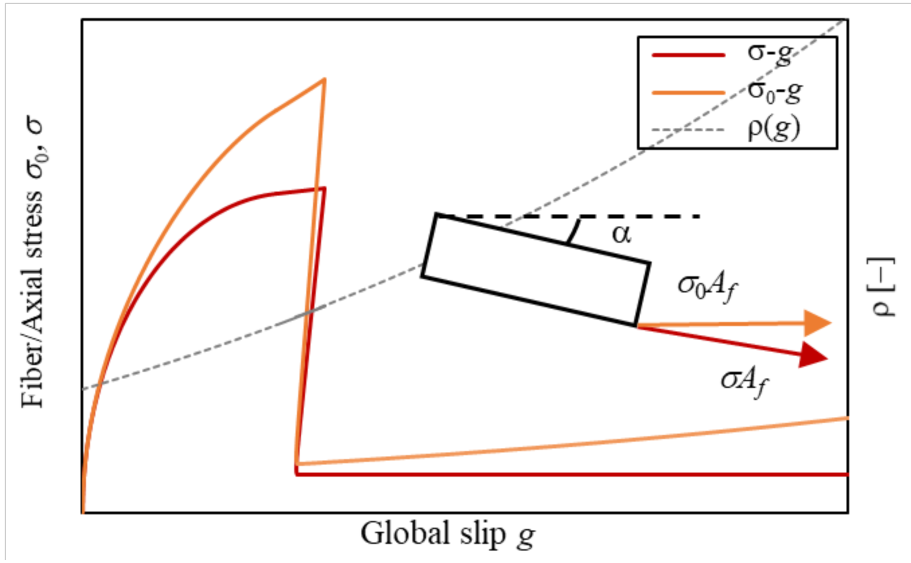
BARE FIBERS LAYOUT

BOND GAP LAYOUT



Fatigue behavior of inorganic-matrix composites:
Cyclic bond behavior (INdirect-shear test)





Bond differential equation

$$s'' - \frac{p}{EA}\tau(s) = 0$$

s : fiber slippage at a generic point of the interface

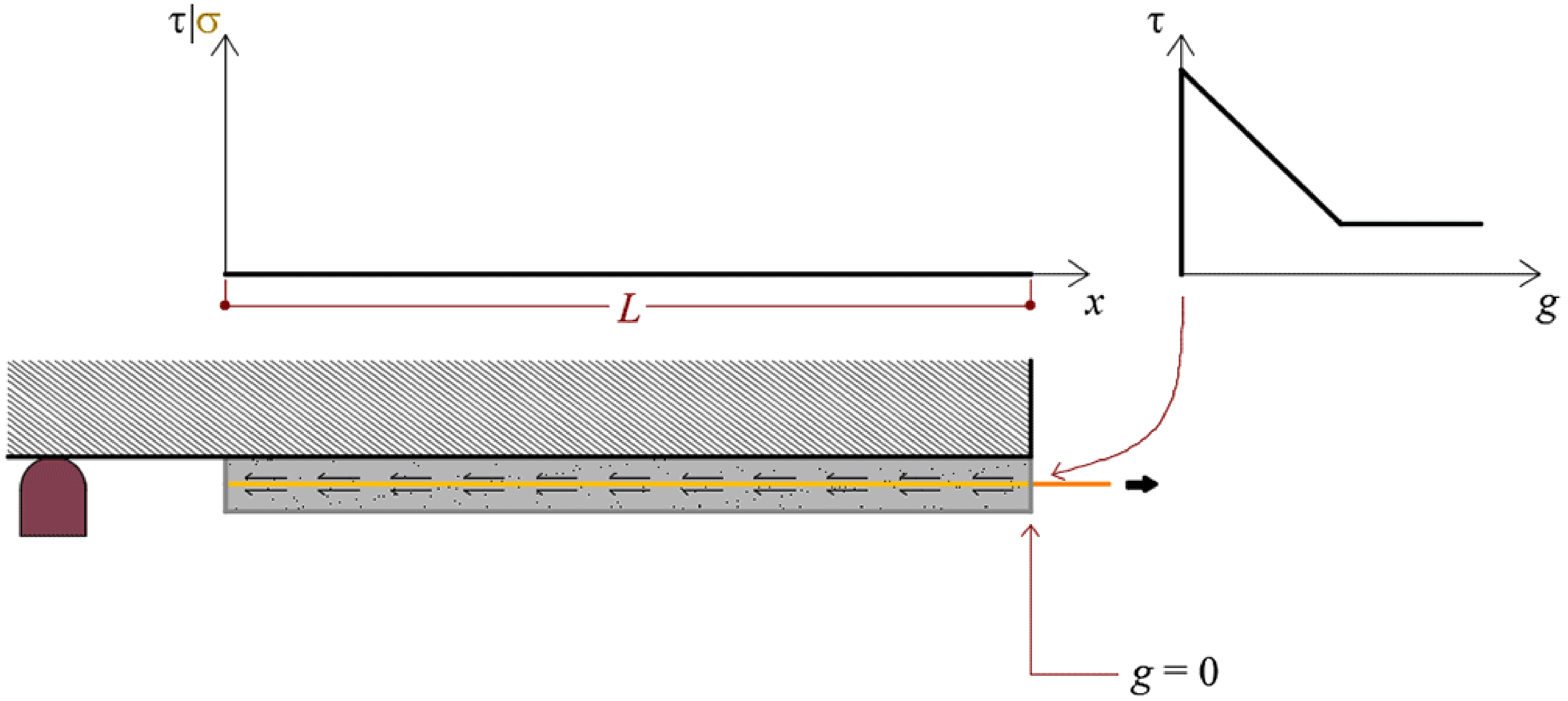
g : slip at the loaded end – $g=s(L)$

p : fiber cross-section perimeter

A : fiber cross section area

τ(s) : cohesive material law or bond-slip relation

Fatigue behavior of inorganic-matrix composites:
Cyclic bond behavior (INdirect-shear test)



LEGENDA

l	: bonded length engaged in the interface softening stage
l_{eff}	: maximum length of the softening stage
a	: debonded portion of the interface
g	: slip at the loaded end
σ_I	: normal stress component to the matrix-fiber interface

Fatigue behavior of inorganic-matrix composites:

Cyclic bond behavior (INdirect-shear test)