Generalized Nonlinear Moment–Curvature Model for flexural fatigue of hybrid reinforced beams

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Introduction

Motivation

- *Increasing Durability And Service Life Of Structures*
- *Performance Under Extreme Conditions*
- *Development Of New Materials*
- *Sustainability*
- *Structural Integrity*
- *Damage Identification Using Non-destructive Methods*
- *Real-time Structural Health Monitoring*

Infante D. Henrique Bridge (PT)

Carolabrücke, Dresden (Germany)

Fortim wind tower complex – CE (BR)

Coxilha Negra wind tower complex – RS (BR)

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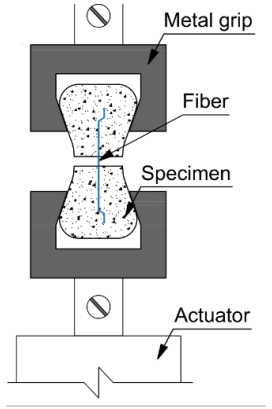
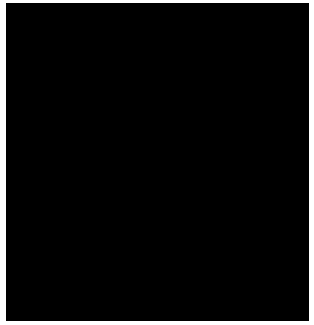
Introduction

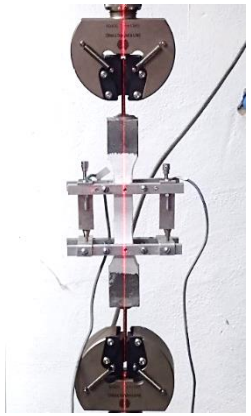
Current research at PUC-Rio

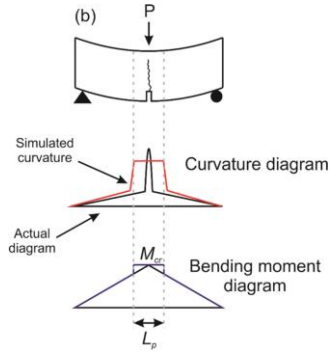
Mechanical behavior of FRC under fatigue loading

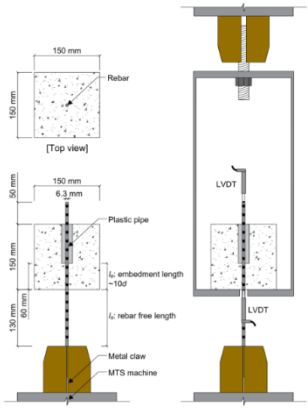
- *Fatigue mechanical characterization of FRC*
- *Fiber-matrix interface degradation under fatigue loading*
- *Dynamic analysis and damage identification*
- *Fatigue mechanical characterization of SHCC*
- *Development of novel models for FRC fatigue*
- *Bond-slip behavior under fatigue loading*
- *Influence of fibers on the degradation of R/SFRC structures*











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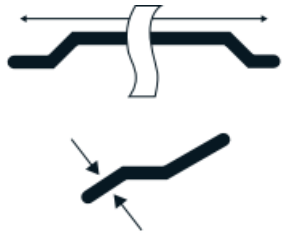
Experimental program

Materials

Materials	Composition
Aggregate (kg/m³)	492
Sand (0,15<A1<0,85 mm) (kg/m³)	826
Sand (0,85<A2<4,80) (kg/m³)	100
Silica #325 (kg/m³)	70
Cement (kg/m³)	360
Fly ash (kg/m³)	168
Silica flour (kg/m³)	45
Water (kg/m³)	164
Superplasticizer (%)	5,5
Viscosity Modifier (%)	0,75
Water/cement	0,50

Steel fibers

Dramix 3D 45/30



C20SF — *20 kg/m³*

C40SF — *40 kg/m³*

C60SF — *60 kg/m³*

fc = 50 MPa

Fiber mass fractions

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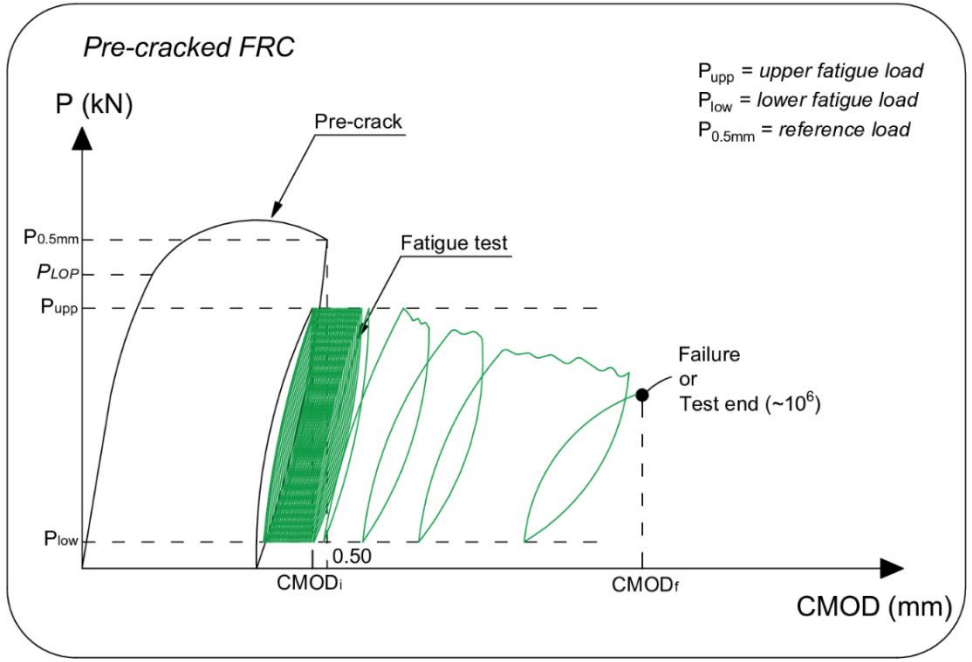
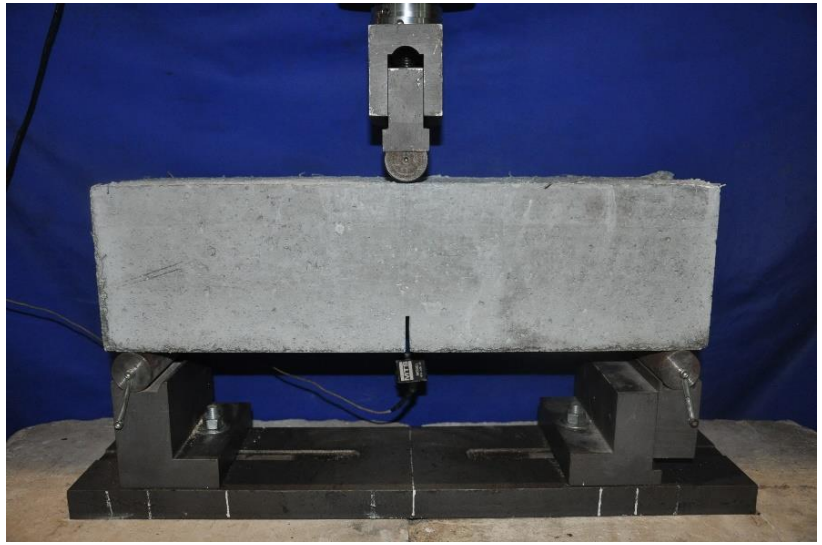
Experimental program – Material Level

Mechanical tests (material level)



Frequency = 6hz
Load controlled at 70%, 80% and 90% of P0.5mm ($f_{R,1}$)



- *Beam pre-crack until reaching 0.50 mm of CMOD*
- *Fatigue test until reaching 1,000,000 cycles or beam rupture*
- *Pre-notched beams in accordance with EN14651*

- *Load level (S) = Pupp/P0.50mm*
- *CMOD monitored by clip-gauge*
- *Mechanical degradation along the cycles*

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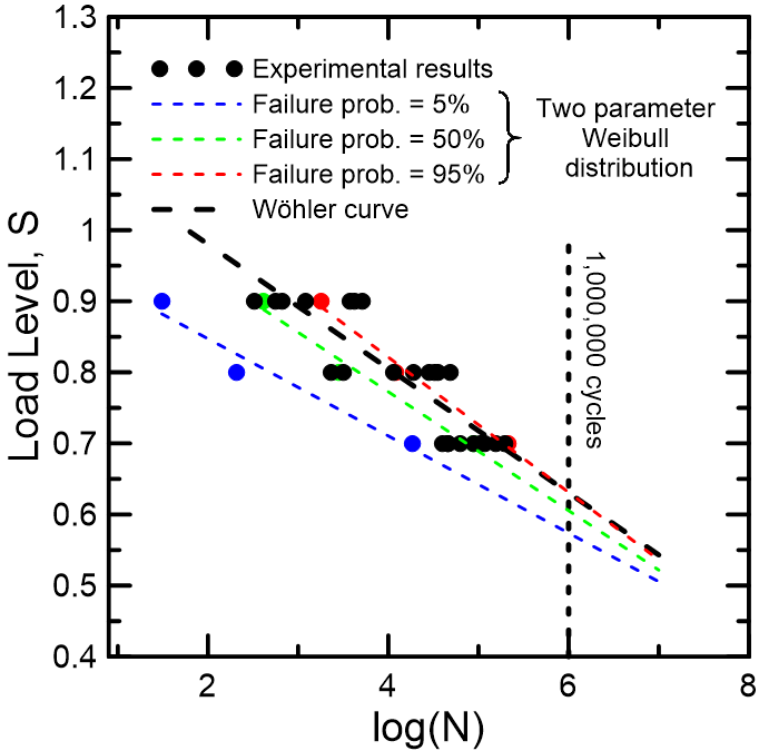
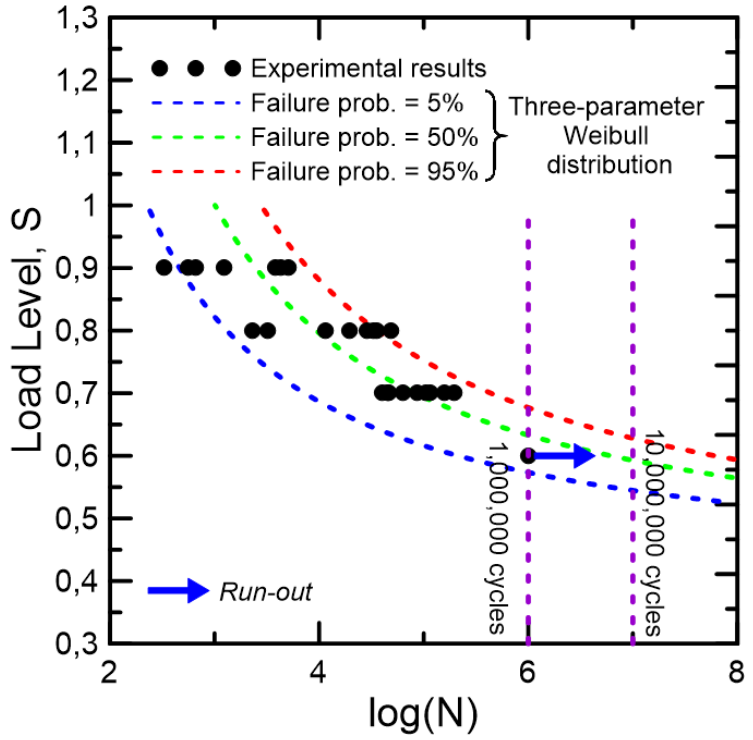
Discussion and analysis

Weibull distribution for fatigue failure probability



Two-parameter Weibull distribution

$$F(x;u;\alpha) = 1 - e^{\left(\frac{x}{u}\right)^{\alpha}}$$

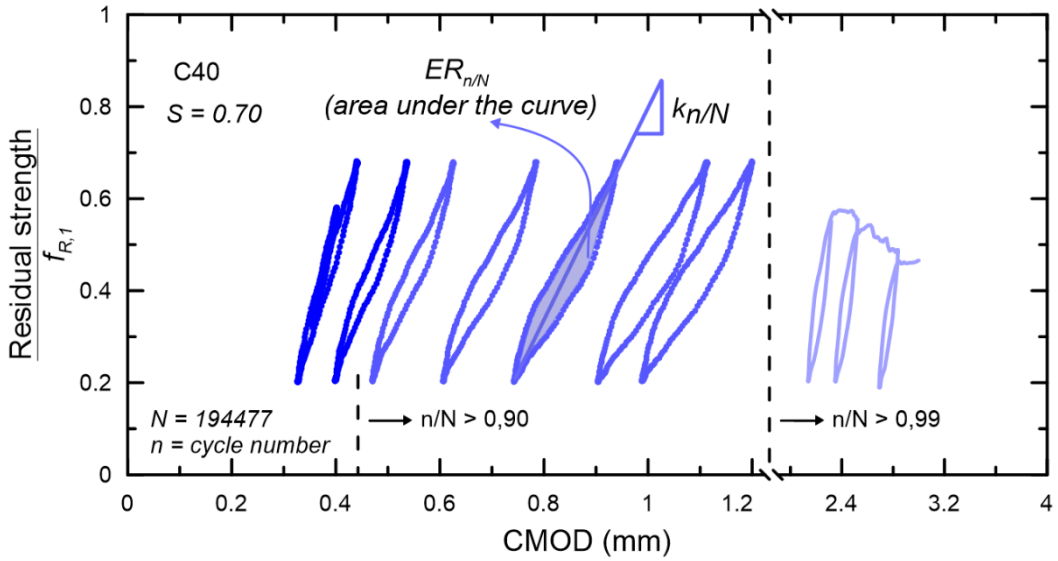


Three-parameter Weibull distribution

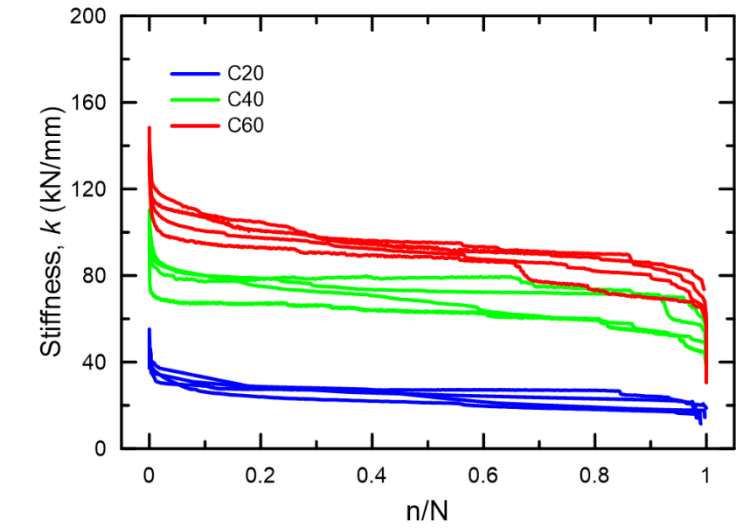
$$F(x;\lambda;u;\alpha) = 1 - \exp\left(-\left(\frac{x-\lambda}{u}\right)^{\alpha}\right)$$

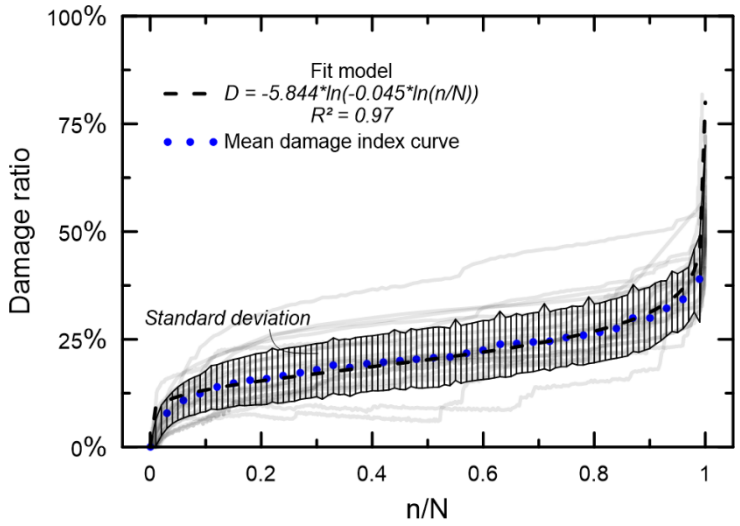
Discussion and analysis

Material pre-crack and fatigue test



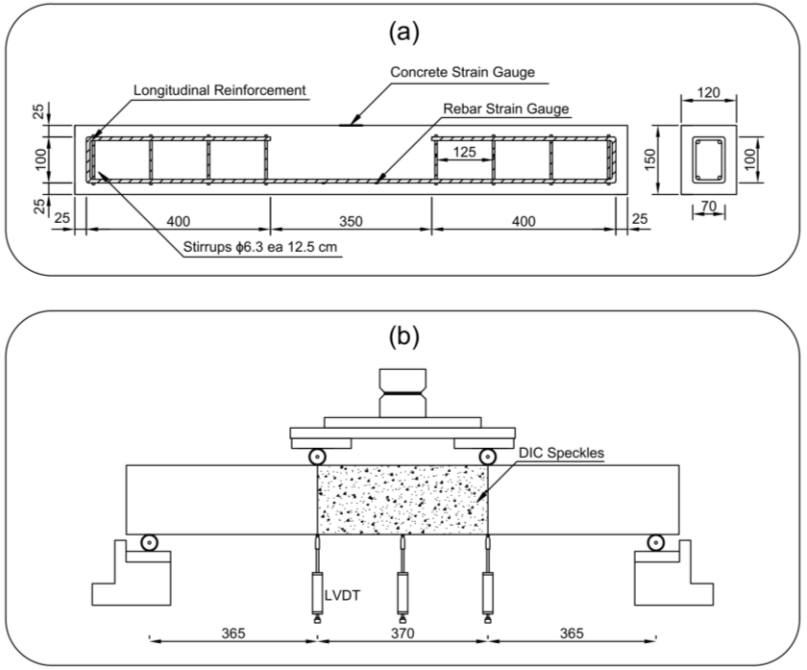
- *Stiffness as hysteresis cycle slope*
- *Stiffness degradation along the fatigue test*
- *Proposal of damage evolution empirical equations*
- *Influence of fibers on the stiffness results*
- *Damage ratio* $= 1 - \frac{k_n}{k_0}$

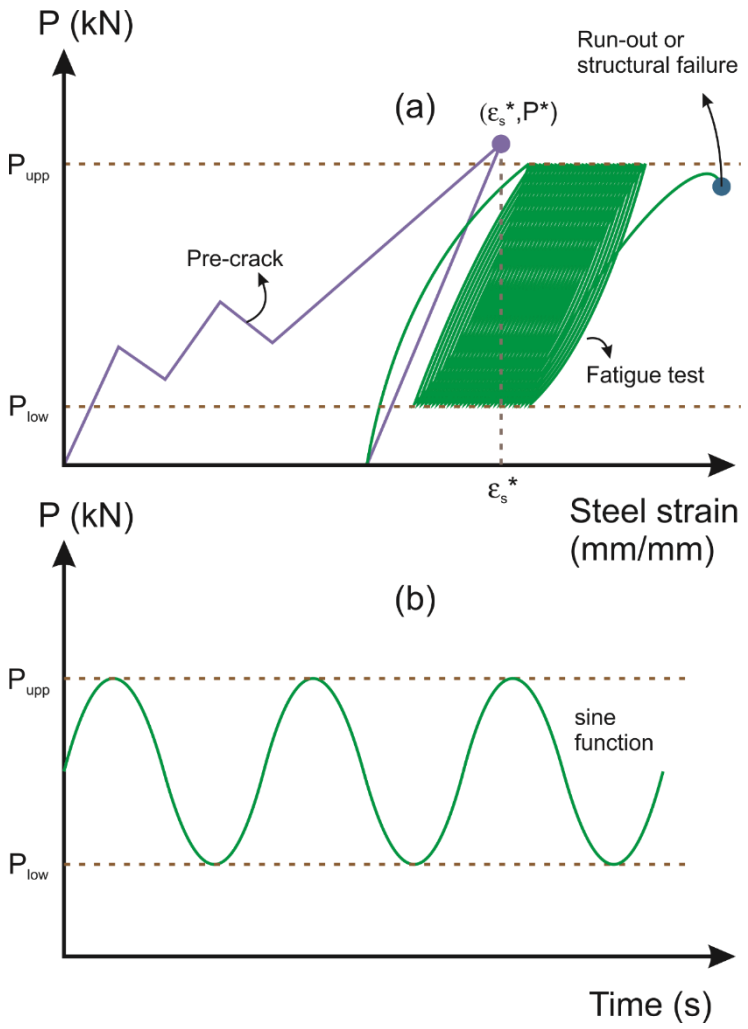




Structural Analysis

Mechanical tests (structural level)

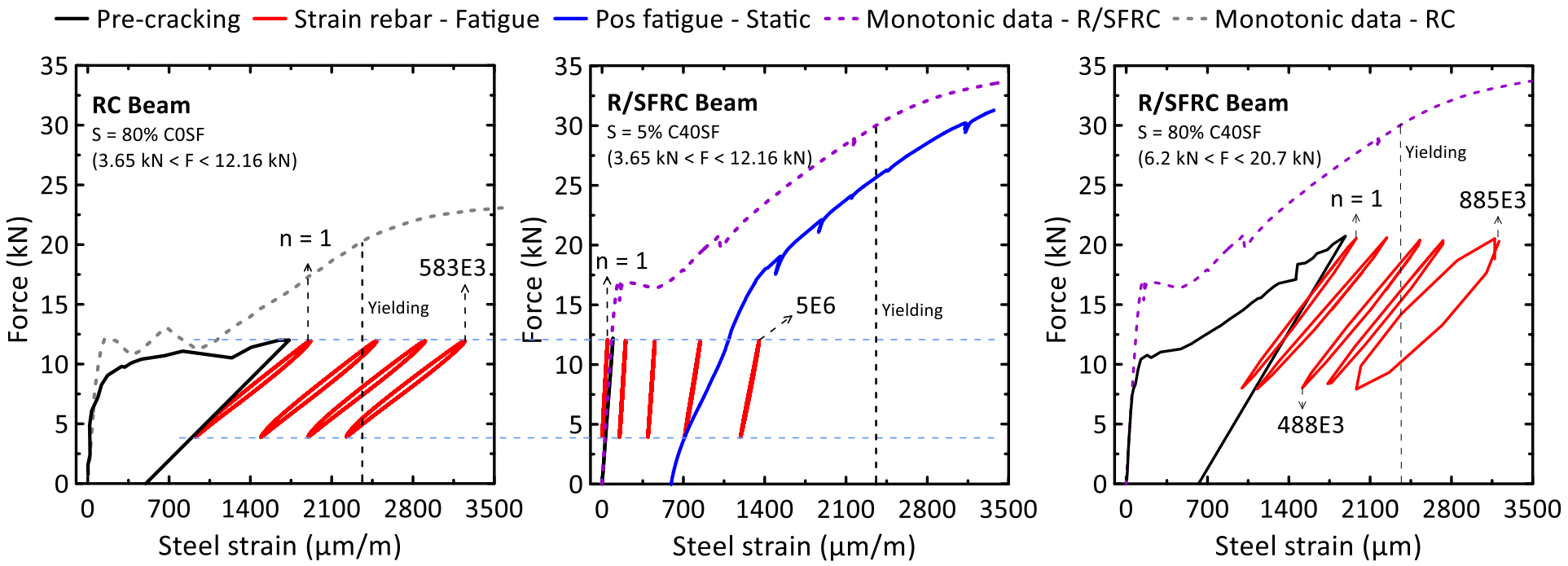




- *Beam pre-crack until reaching rebar strain level of 1900 μm/mm (80% of the rebar yielding strain)*
- *Beam pre-crack until reaching 12.16 kN (equivalent to the force of 80% of the rebar yielding strain for the RC beam)*
- *Fatigue test until reaching 5,000,000 cycles or beam rupture*
- *Stress ratio (F_{min}/F_{max}) = 0.3*

Structural Analysis

Longitudinal rebar strain evolution



RC beam	*R/SFRC beam*	*R/SFRC beam*
80% of the rebar yielding strain (1900 µm/m)	*Reached 12.16 kN (5% of the rebar yielding strain)*	*80% of the rebar yielding strain (1900 µm/m)*

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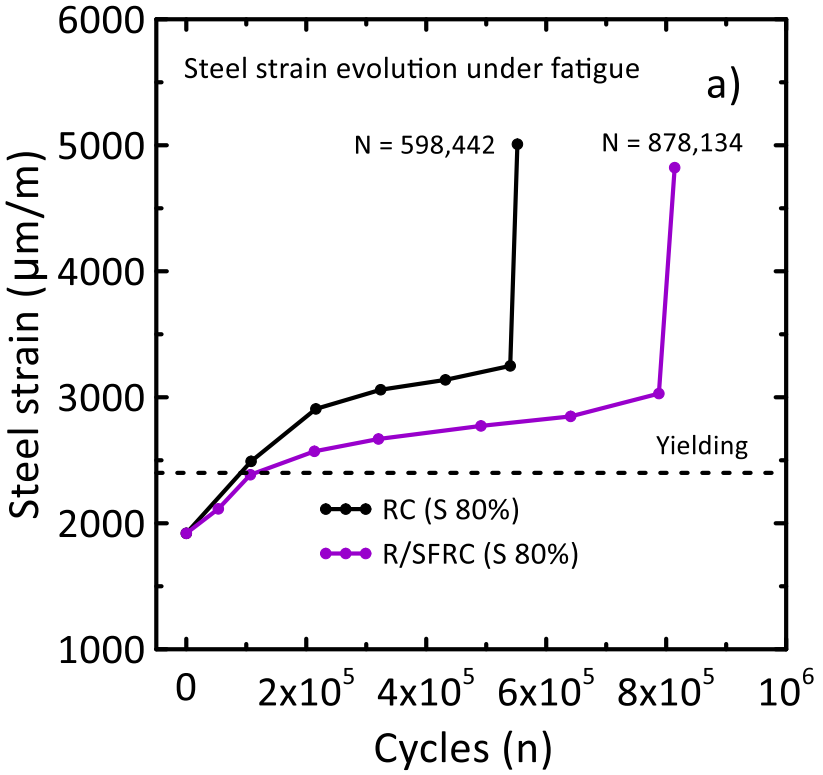
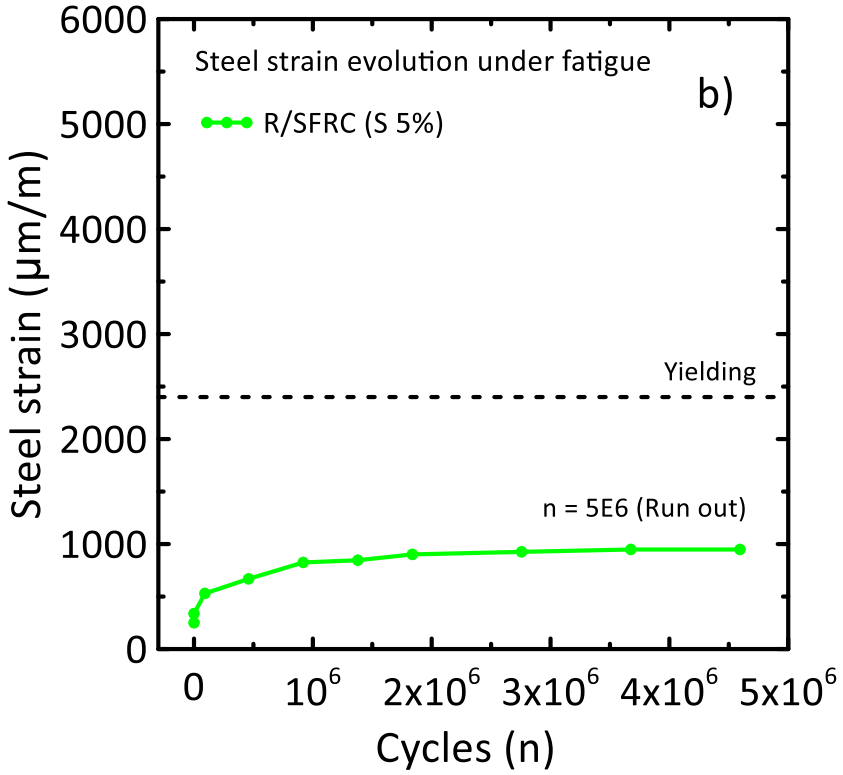
Structural Analysis

Strain evolution along the cycles





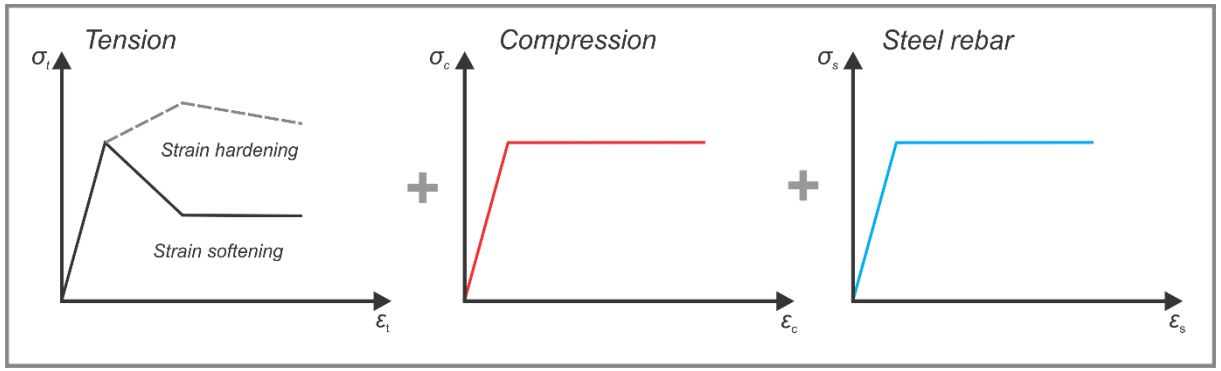
Stress level of 80%
Stress steel range ($\Delta\sigma_s$) = 225 MPa

Stress level equivalent of 5%
Stress steel range ($\Delta\sigma_s$) = 50 MPa

Structural Analysis

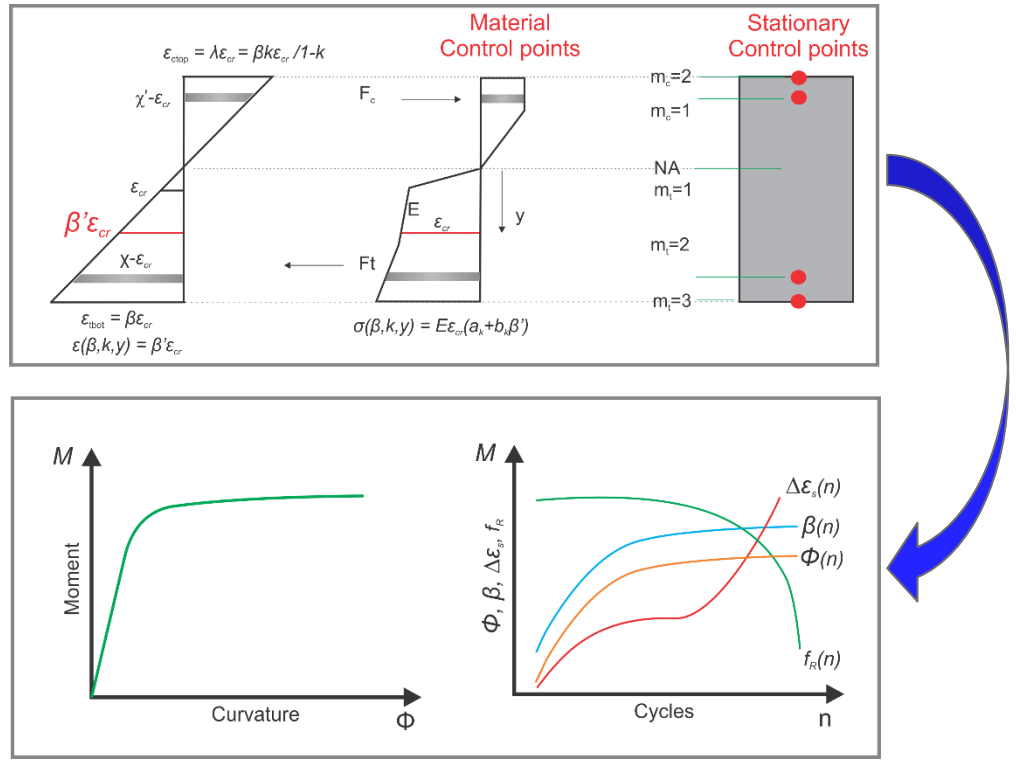
Fatigue Model Development

Material Constitutive Relationship



Fatigue life and mechanical degradation of structural beams

Strain Compatibility in the Concrete and Steel Reinforcement



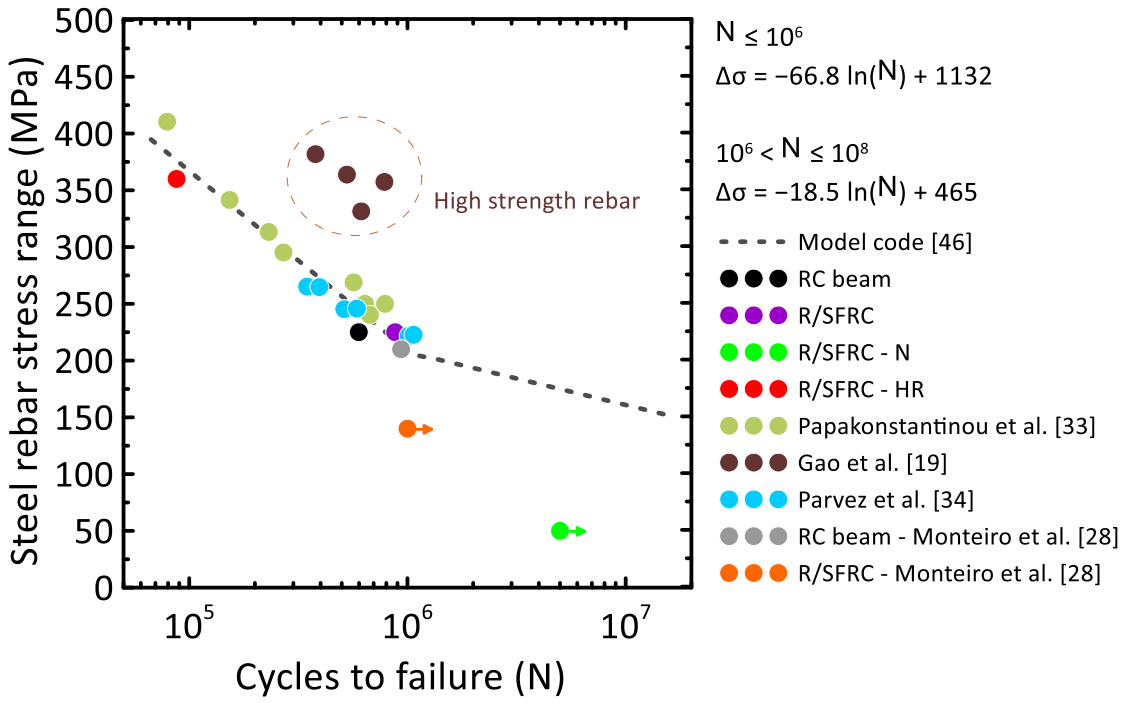
Progression of Rebar Steel Strain, Residual Strength, Moment and Curvature

Model workflow from defining the FRC quasi-static response until its mechanical degradation under flexural fatigue for structural beams.

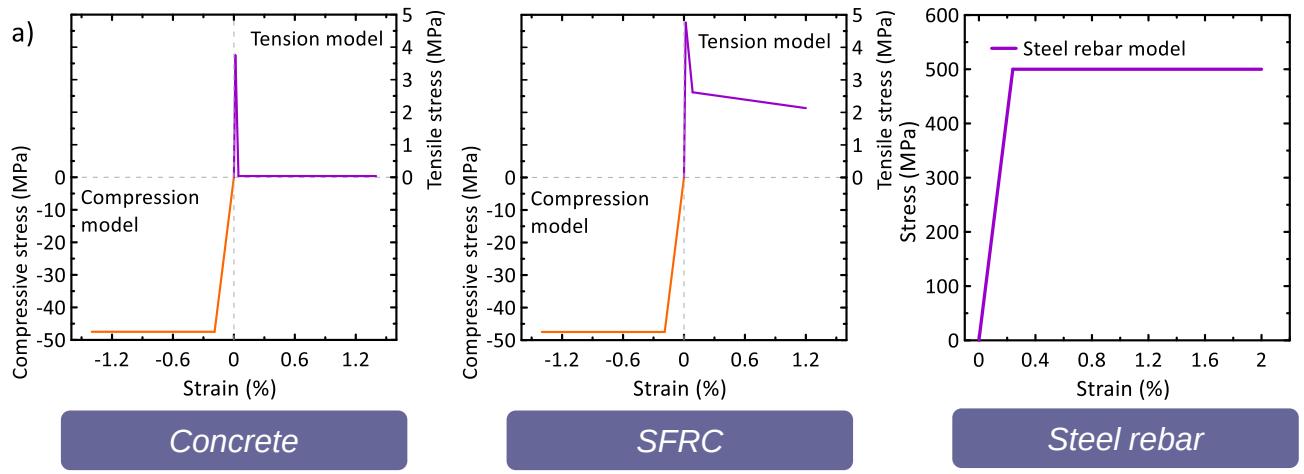
Structural Analysis

Fatigue Life and Material Constitutive Relationship

Rebar S-N curve



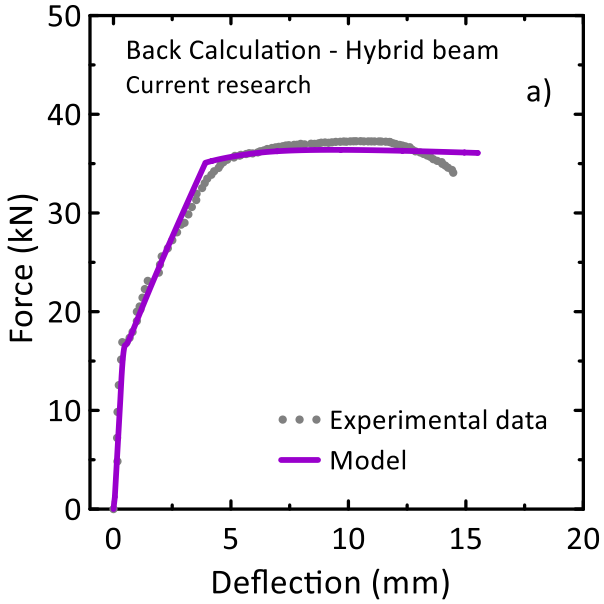
Material Constitutive Relationship



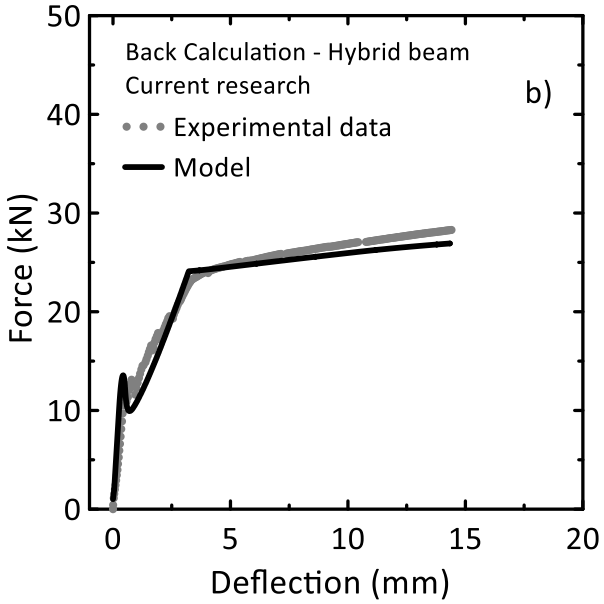
Structural Analysis

Quasi-static results

Force x deflection

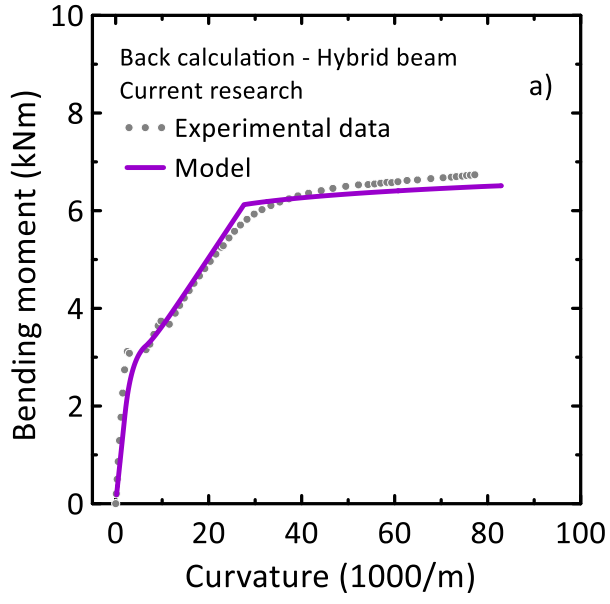


R/SFRC beam

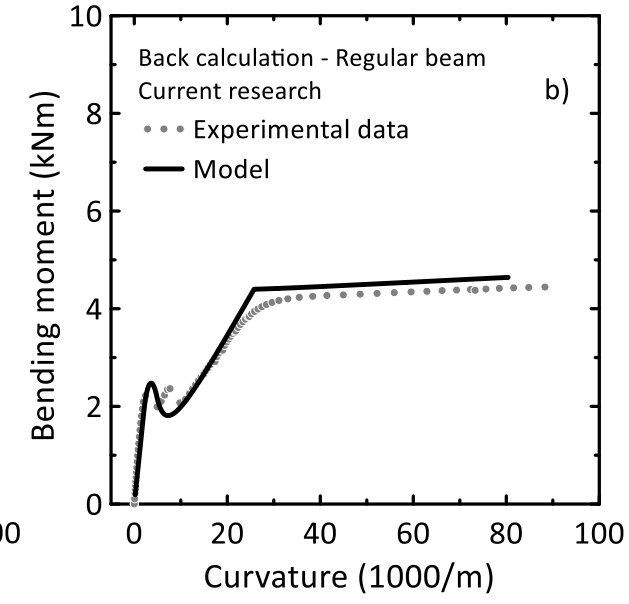


RC beam

Moment x curvature



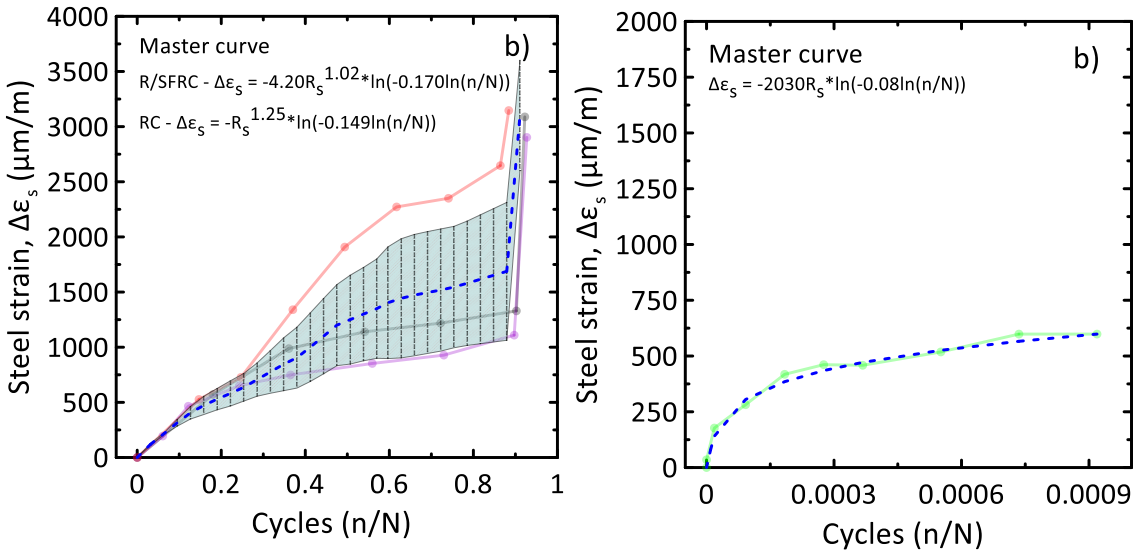
R/SFRC beam



RC beam

Structural Analysis

Steel rebar strain evolution under fatigue flexural loading



Legend

$$R_s = \frac{\Delta\sigma}{\sigma_y} = \frac{stress\ amplitude}{yielding\ strength}$$

n/N - referred cycle number

Master curve evolution law

Rebar strain evolution for different stress level and stress range (S = 80% and preload at 5%)

Rebar Strain Evolution Law

RC S80%

$$\Delta\varepsilon_s = -R_s^{1.25}\ln\left(-0.149 * \ln\left(\frac{n}{N}\right)\right)$$

R/SFRC S80%

$$\Delta\varepsilon_s = -4.20 * R_s^{1.02}\ln\left(-0.170 * \ln\left(\frac{n}{N}\right)\right)$$

Uncracked state

$$\Delta\varepsilon_s = -2030 * R_s^{1.02}\ln\left(-0.08 * \ln\left(\frac{n}{N}\right)\right)$$

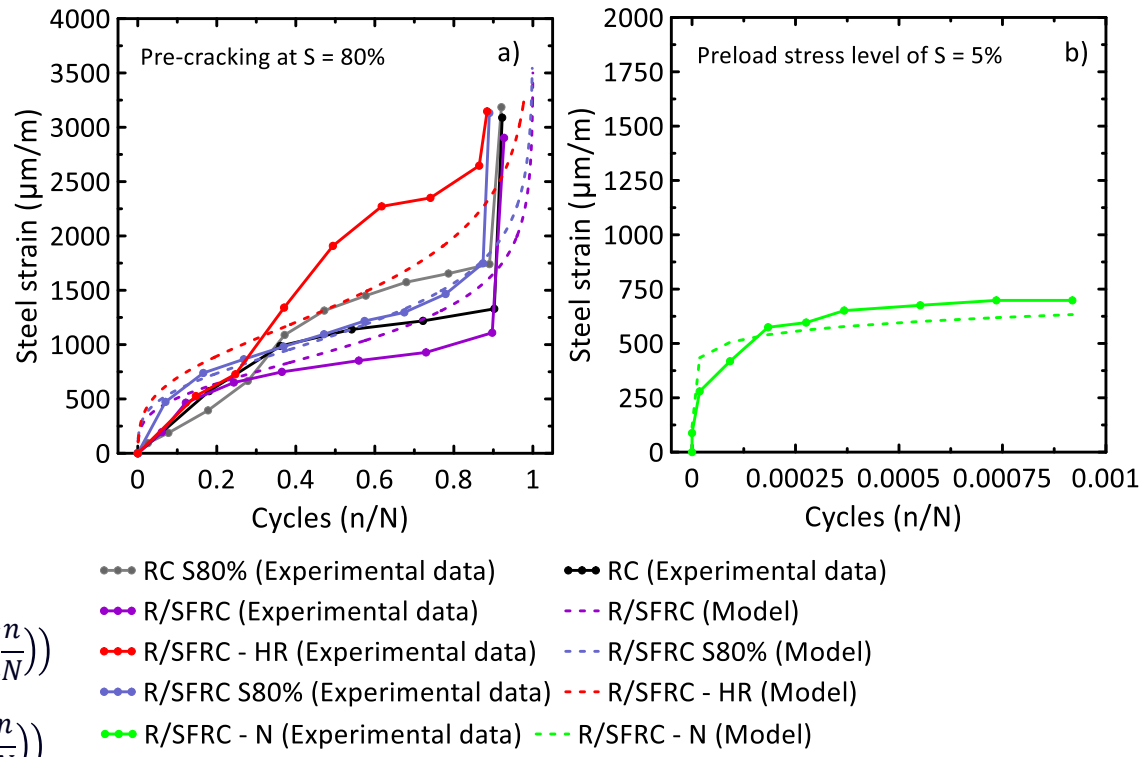
Legend

R/SFRC - Hybrid reinforced beam

RC - Conventional R/C beam

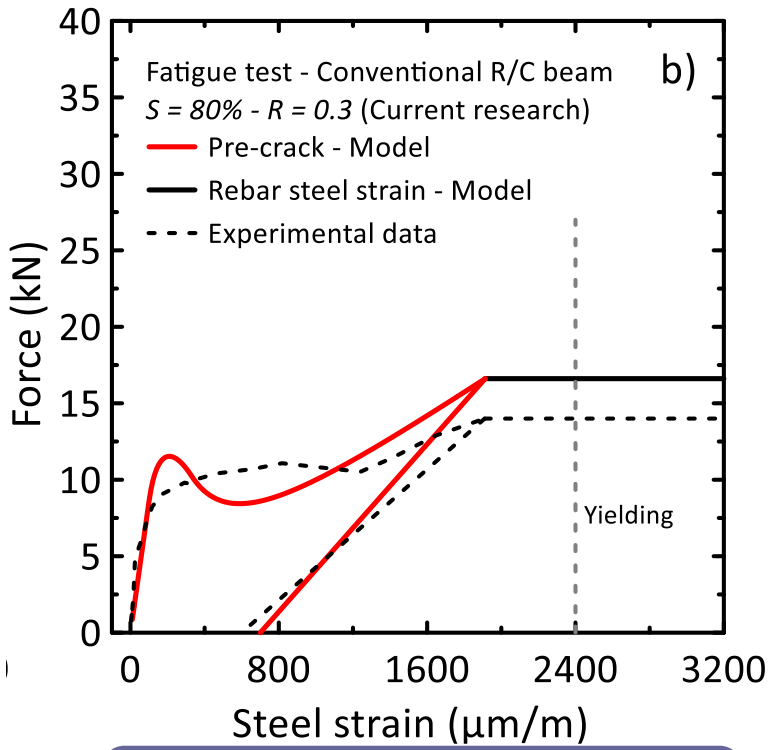
S - Stress level

Model Application



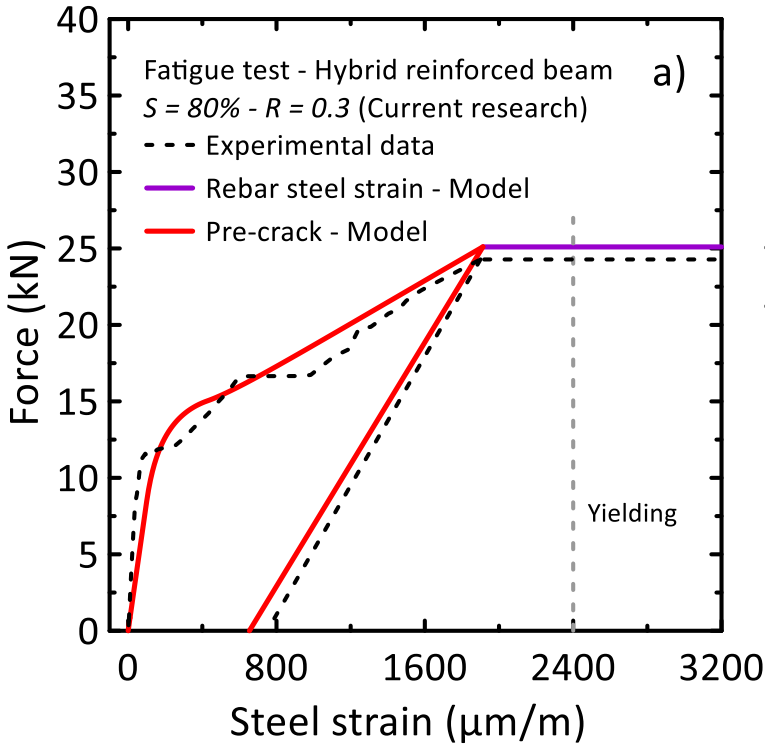
Structural Analysis

Mechanical degradation under fatigue flexural loading – Pre-crack stage (monotonic) and fatigue



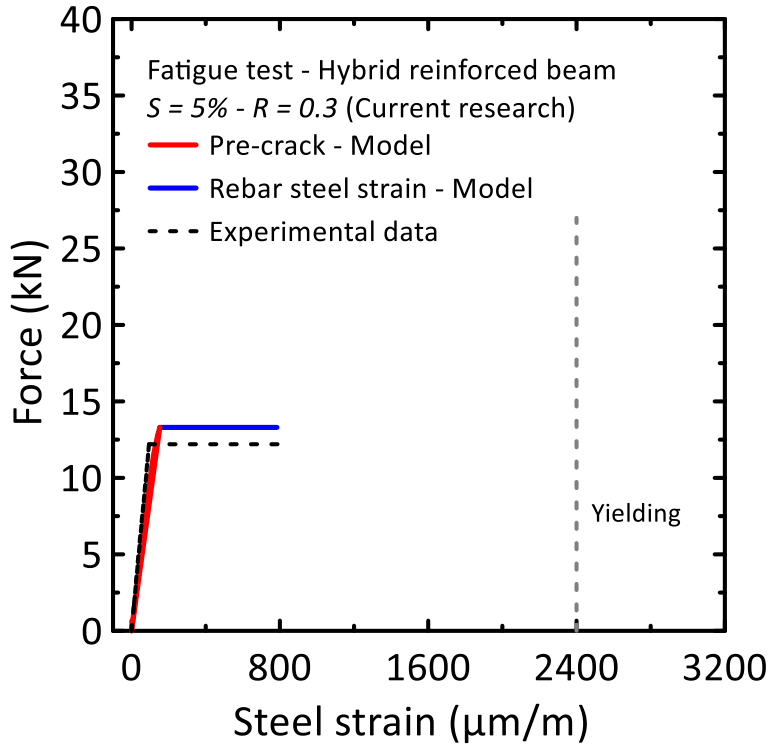
RC beam

80% of the rebar yielding strain (1900 µm/m)



R/SFRC beam

80% of the rebar yielding strain (1900 µm/m)



R/SFRC beam

Reached 12.16 kN (5% of the rebar yielding strain)

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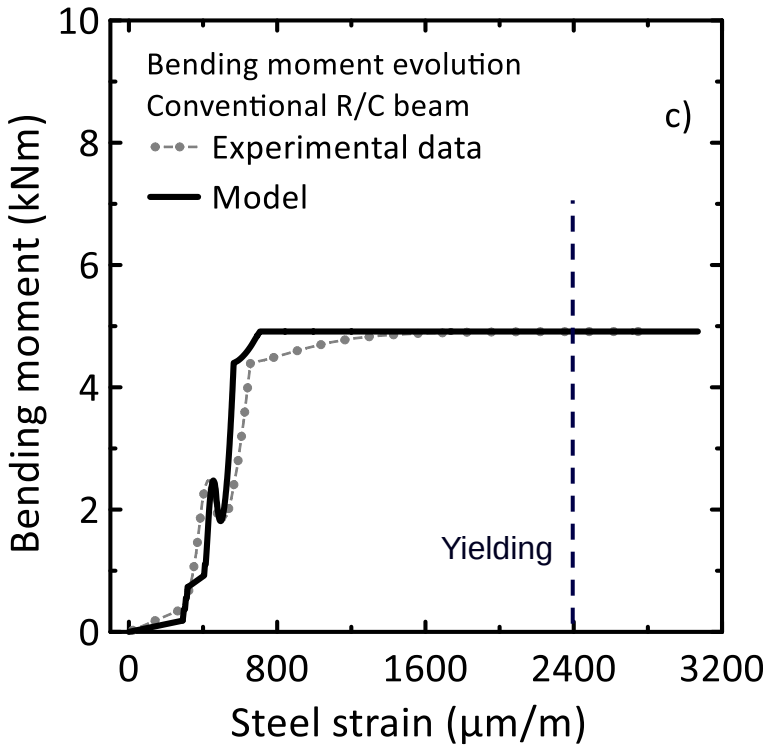
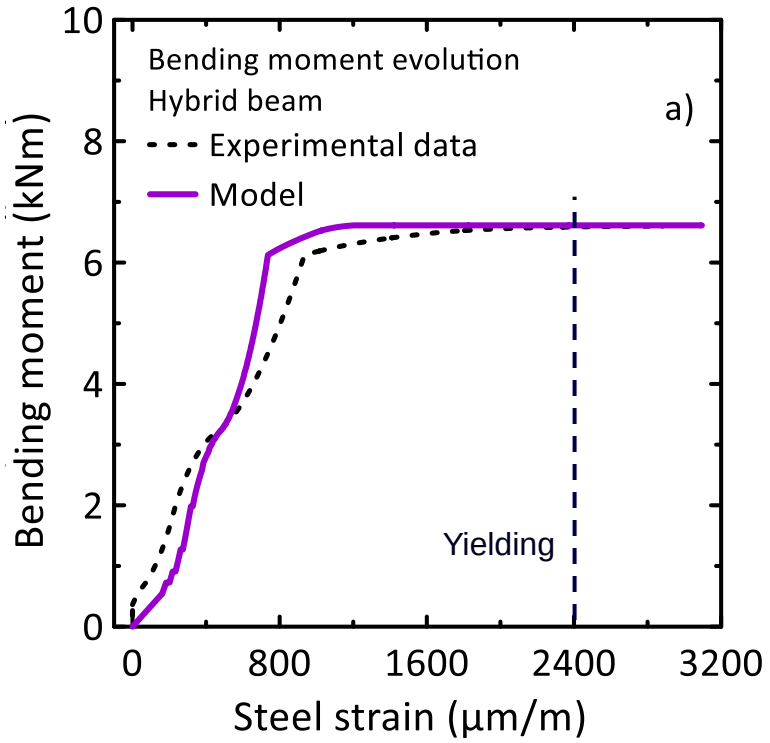
Structural Analysis

Nonlinear Moment–Curvature model for Hybrid reinforced beams under fatigue



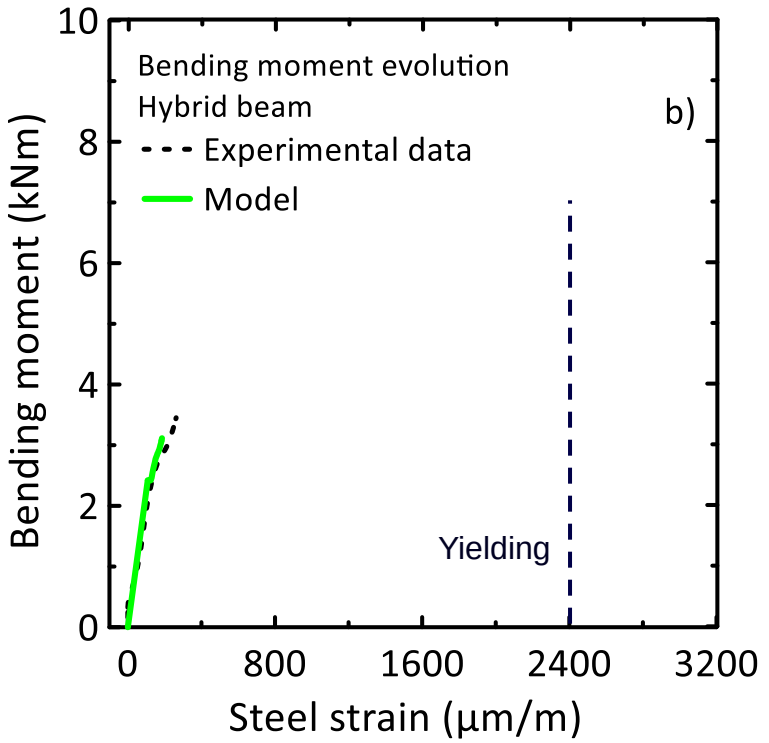
RC beam

80% of the rebar yielding strain (1900 µm/m)



R/SFRC beam

80% of the rebar yielding strain (1900 µm/m)



R/SFRC beam

Reached 12.16 kN (5% of the rebar yielding strain)

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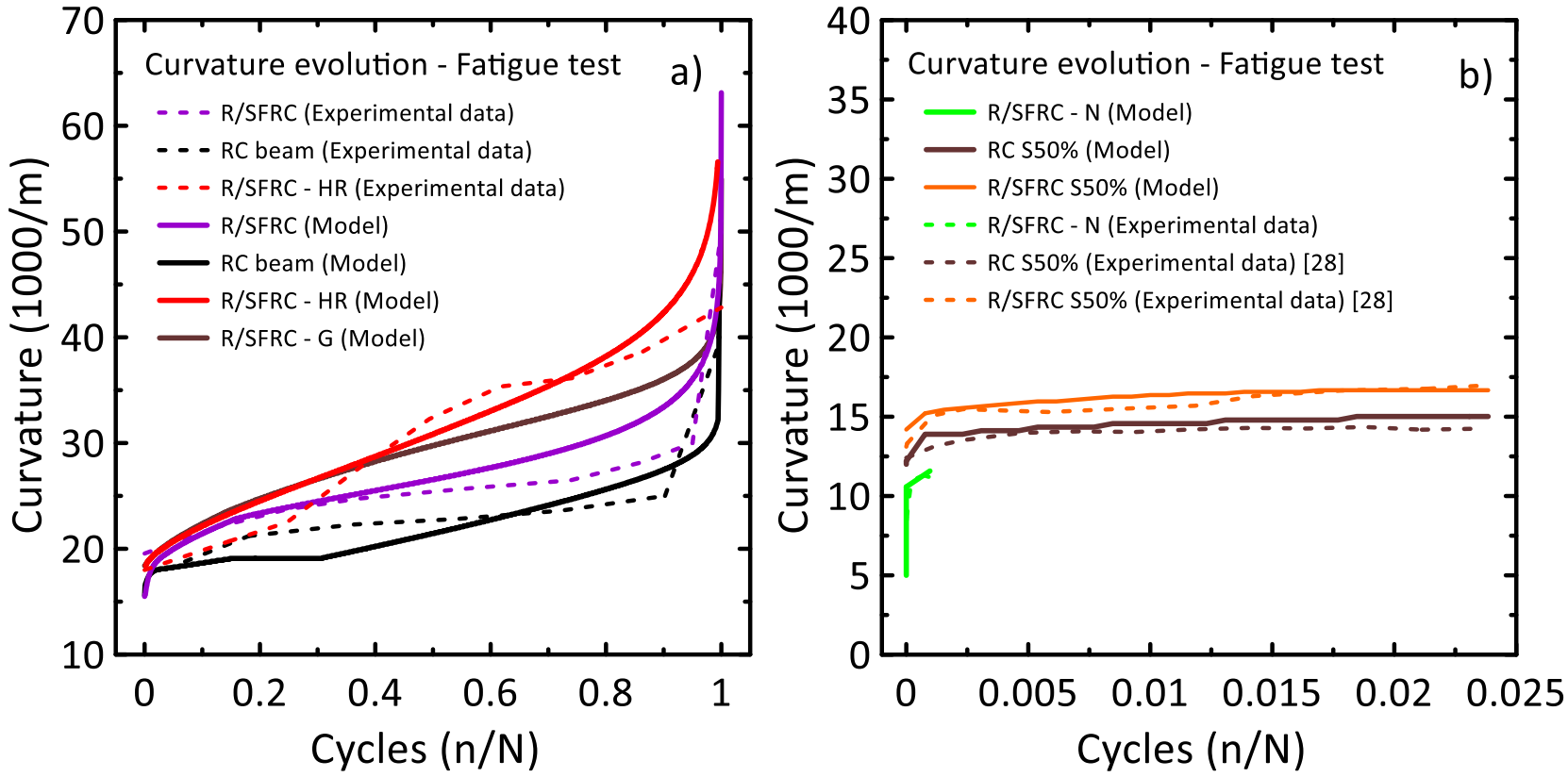
Structural Analysis

Curvature model evolution for Hybrid reinforced beams



R/SFRC beam

Stress level (S) of 80%

RC beam

Stress level (S) of 50% and preload at 5%

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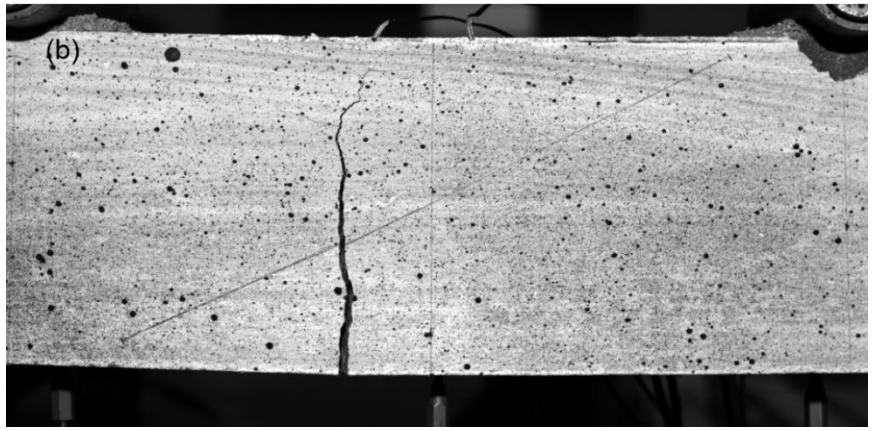
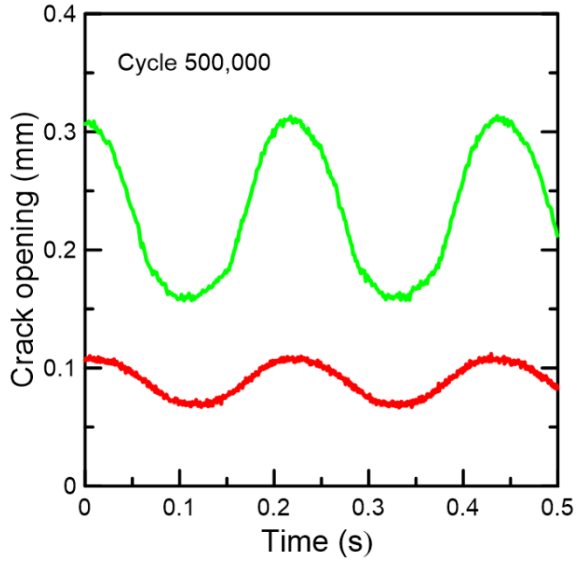
Structural Analysis

Crack width oscillation with DIC





Conclusions

- *There is a positive influence on the fiber addition on fatigue life of the fiber reinforced concretes;*
- *The evolution of dynamic properties allowed to verify how damage affect the mechanical parameters in the fatigue life of SFRC;*
- *Steel fiber reinforced concrete structural beams reported much lower rebar strain values along the fatigue test;*
- *The fatigue life of rebars is a critical determinant in the fatigue behavior of structural beams;*
- *The addition of fibers will significantly modify the fatigue life of structural elements.*

Acknowledgments

CAPES

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Eletrobras

CNPq

belgo
arames

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