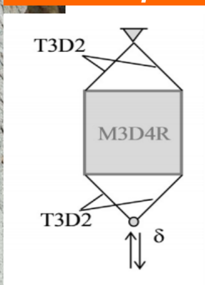
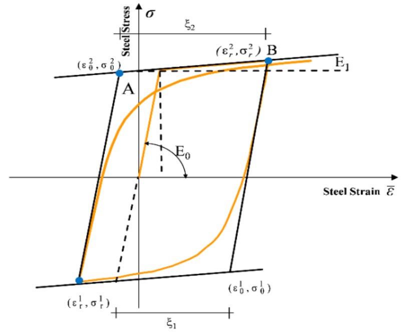
PARC_CL 2.1 crack model

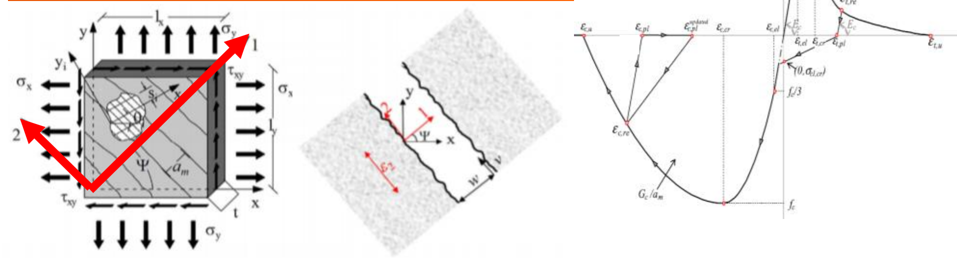
PROPOSE a reliable numerical model for the **cyclic and dynamic response** prevision of **EXISTING** Reinforced Concrete structures subjected to **CORROSION**

NLFEA Setup



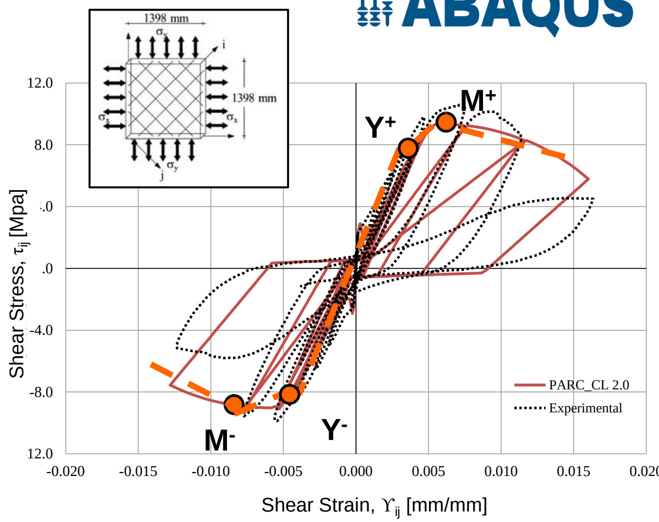


A Smeared Fixed Crack Model



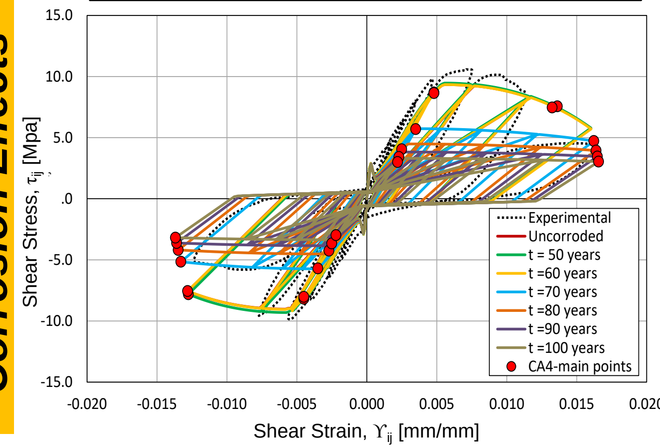
ABAQUS

Model Validation



Corrosion Effects

Response of Corroded Panel over the time



CMDWC 2021

corrosion and materials degradation

MDPI

Modelling of Time-Dependent Behaviour of Corroded RC Elements

1st Corrosion and Materials Degradation Web Conference

17-19 May 2021 | International Workshop Online

Francesca Vecchi, **Lorenzo Franceschini**, Beatrice Belletti

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Outline of the research

- ❖ **Introduction**
  - ❖ **Aims of the study**
    - ❖ **PARC_CL 2.1 crack model**
      - General overview of the model;
      - ❖ **Effects of corrosion**
        - Corrosion rate evaluation based on different exposure classes;
        - Mechanical properties reduction;
        - ❖ **Model Validation**
          - ❖ **Main results**
            - ❖ **Conclusions and Further research**

Introduction:
Significant Attention from researchers all over the world

Corrosion is recognised has one of the main factors that leads RC structures to premature unexpected failure.

- An accurate study on the serviceability, durability and safety performance needs to be carried out.

RC structures designed and built before the entry into force of seismic codes represent a source of seismic risk worldwide due to their vulnerability

AIMS OF THE STUDY

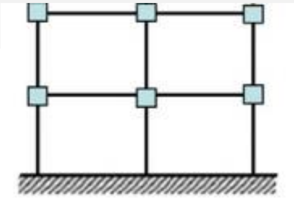
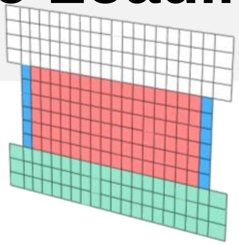
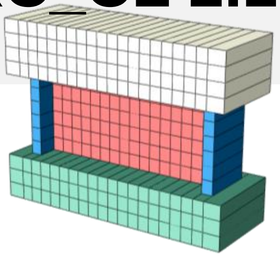
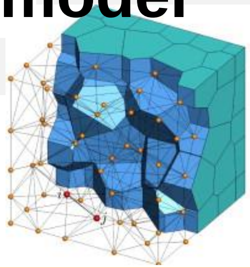
1 TO PROPOSE a reliable numerical model:

- for the cyclic and dynamic response prevision of **EXISTING** Reinforced Concrete structures subjected to **CORROSION**;

2 TO VALIDATE the model by means of the comparison with experimental results.

3 TO APPLY the validated model for the prediction of the **ULTIMATE RESISTANCE and DUCTILITY** of corroded RC structures over the time.

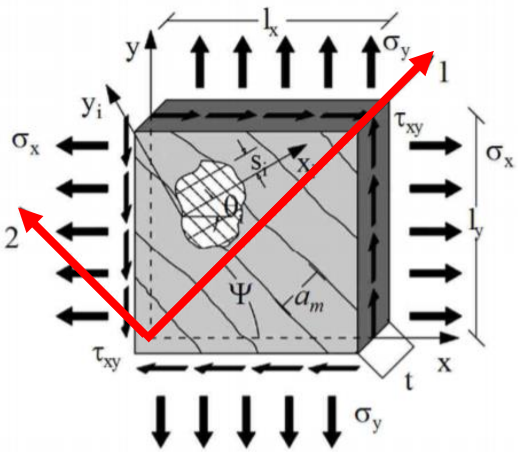
Physical Approach for Reinforced Concrete subjected to Cyclic Loading: PARC_CL 2.1 crack model

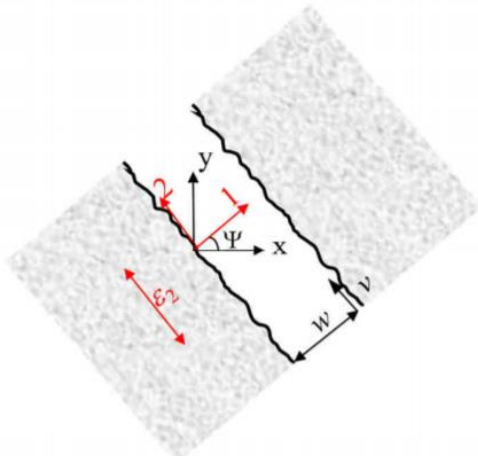





	Beam elements	2D elements	3D elements	Discrete
	The structure is divided in **one-dimensional** elements. -lumped plasticity or -distributed plasticity (fibre model)	The structure is characterised by **two-dimensional elements** with translational and rotational degrees of freedom.	The structure is divided by **three-dimensional elements** with translational degrees of freedom.	The structure is idealized as a set of rigid part (**aggregates**) interconnected by springs with axial and tangential stiffness (**cement past**).
PROS	**Limited computational costs**	**Limited computational costs** and uncertainties respect to 3D modelling.	Possibility to analyze complex structural typologies	Capability to catch physical and mechanical phenomena in detail.
CONS	**Only flexural failure** of thin elements: no shear or torsional effects.	Shortcomings in evaluating shear behaviour along the thickness of the element	**Elevated computational costs** Uncertainties due to modelling choices	Elevated computational costs which reduce the scope of these models to limited parts of a structure.

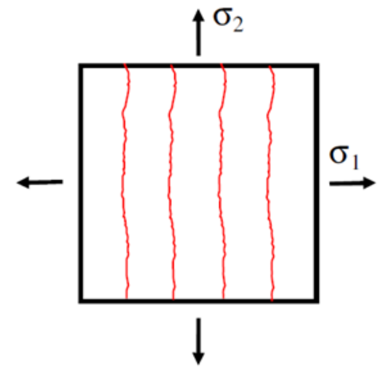
COMPLEXITY – COMPUTATIONAL EFFORTS

Physical Approach for Reinforced Concrete subjected to Cyclic Loading: PARC_CL 2.1 crack model





Smeared Fixed Crack Model



Implemented in a user subroutine UMAT.for for the software

ABAQUS

It treats the cracked solid as a continuum by reducing stiffness properties.

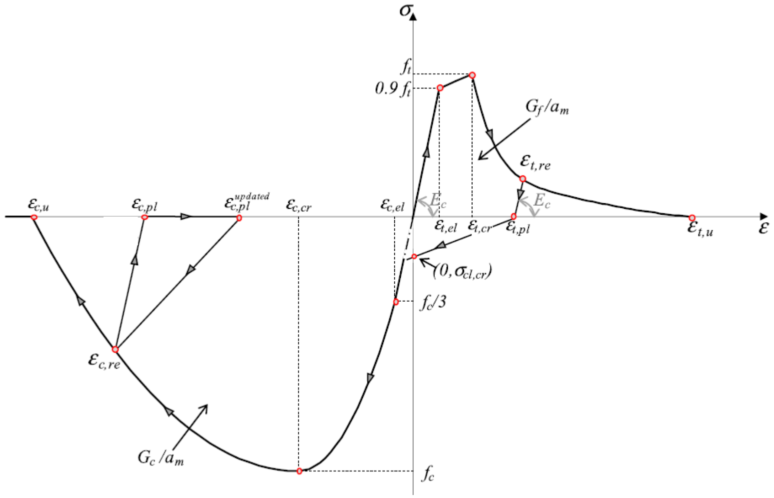
It hypotheses the starting crack pattern as fixed during the analyses

the prediction of **shear stresses** generated along the cracks becomes very important

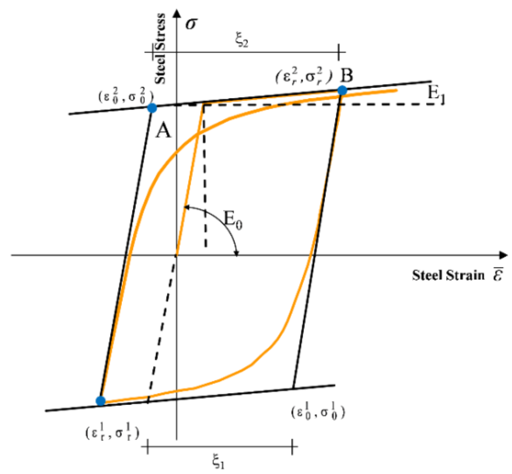
Physical Approach for Reinforced Concrete subjected to Cyclic Loading: PARC_CL 2.1 crack model

Belletti B., Scolari M., Vecchi F. (2017a). PARC_CL 2.0 crack model for NLFEA of reinforced concrete structures under cyclic loadings. Computers and Structures, 191(2017):165–179.

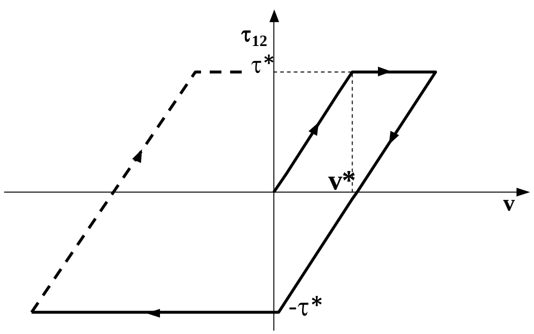
Uniaxial model for concrete:
He-Wu



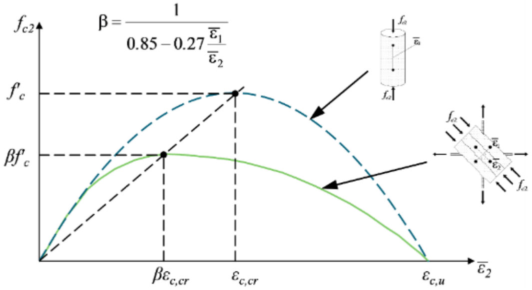
Uniaxial model for steel:
Menegotto -Pinto



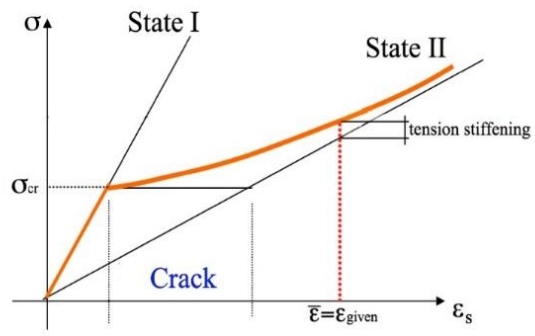
Aggregate interlock:
Gambarova



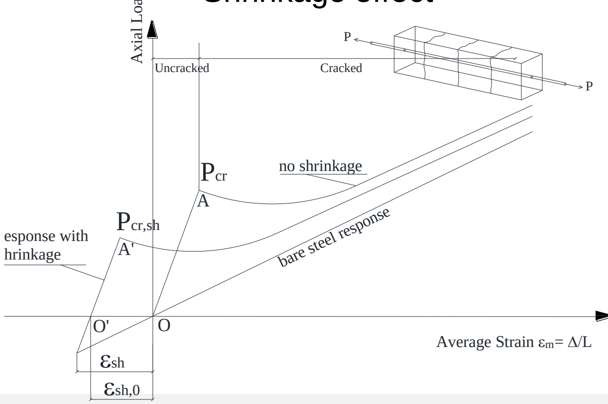
Biaxial state for concrete in compression:
Vecchio - Collins



Tension Stiffening:
MC2010



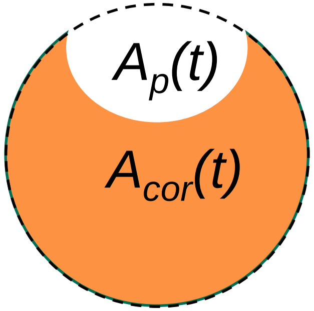
Shrinkage effect

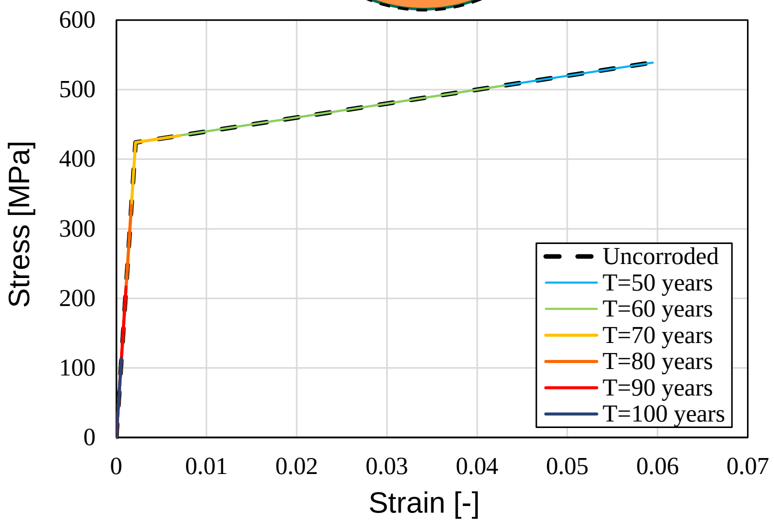


EFFECTS OF CORROSION

The corrosion process can drastically:

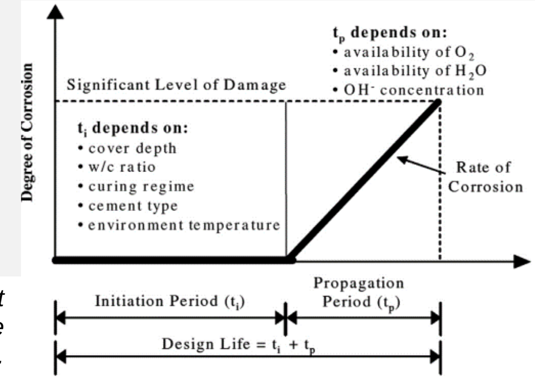
- reduce the resisting section of the reinforcement
- modify the mechanical response of the reinforcement
- determine the cracking of the surrounding concrete
- influence the bond between steel and concrete





All these effects are to be included in NLFEA in order to obtain a reliable prediction of the RC element behaviour

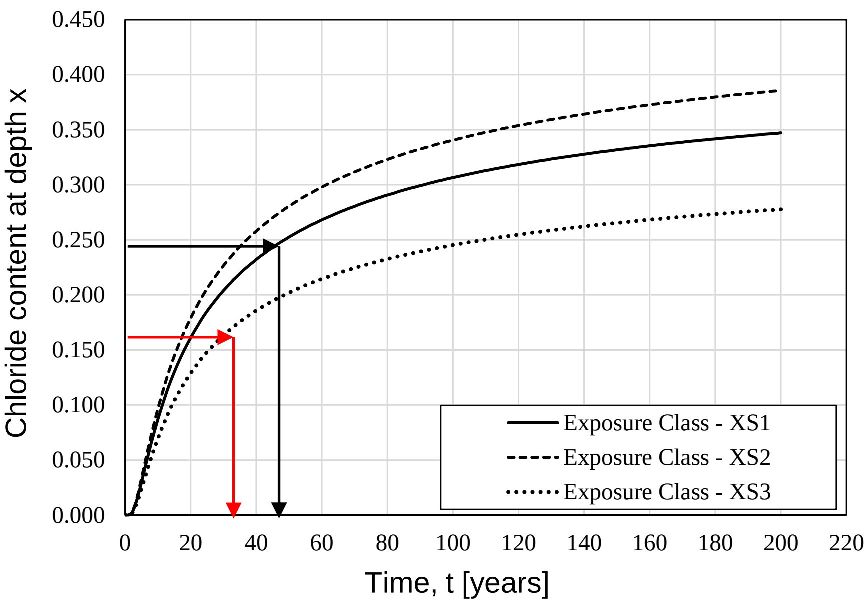
EFFECTS OF CORROSION



Tuutti K. Corrosion of Steel in Concrete Report 4-82. Swedish Cement and Concrete Research Institute, Sweden,(1982).

Evaluation of the **Initiation Period**

$$C(x,t) = C_i + (C_{sa} - C_i)\left[1 - erf\left(\frac{x}{2\sqrt{D_{cl}t}}\right)\right]$$



Input Parameter			
Exposure Class	**XS1**	**XS2**	**XS3**
Cover, x [mm]	45.00	45.00	45.00
Initial Chloride Content, C_i [%]	0.00	0.00	0.00
Diffusion Coefficient, D_{cl} [cm²/year]	0.61	0.61	0.61
Critical Chloride Content, C_{cr} [%]	0.25	0.25	0.17
Cloride Content at surface, C_{sa} [%]	0.45	0.50	0.36

Steel			
Exposure Class	XS1	XS2	XS3
Initiation Period, t_i [years]	48	37	33

CONTECVET IN30902I. A validated user's manual for assessing the residual life of concrete structures. (2001). DG Enterprise, CEC.

Evaluation of the **Propagation Period**

$$t_p = t - t_i$$

t_i : Initiation period – Depassivation time
t : Time of the assessment
t_p : Propagation period

EFFECTS OF CORROSION

CONTECVET IN30902I. A validated user's manual for assessing the residual life of concrete structures. (2001). DG Enterprise, CEC.

** In the Lack of Measurement*

From **Corrosion rate** to maximum cross-section loss

$$P_{pit}(t) = p(t) = 0.0116 \alpha t_p I_{corr}$$

$P_{pit}(t)$: maximum pit depth at the time of analysis
α: pitting factor, set equal to 10
t_p : propagation period
I_{corr} : corrosion rate

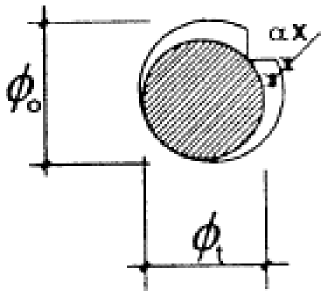


Table C3. Ranges of I_{corr} values suggested for exposure classes of EN206.

Exposure Classes		I_{CORR} [μA/cm²]	
0	No risk of corrosion	~ 0.01	
Carbonation		1.1.1.2 Partially carbonated	*Totally carbonated*
C1	Dry	~ 0.01	~ 0.01
C2	Wet – rarely – Dry	0.1 – 0.5	0.2 – 0.5
C3	Moderate humidity	0.05 – 0.1	0.1 – 0.2
C4	Cyclic wet – dry	0.01 – 0.2	0.2 – 0.5
Chloride initiated corrosion			
D1	Moderate humidity	0,1 – 0,2	
D2	Wet – rarely – dry	0,1 – 0,5	
D3	Cyclic wet – dry	0,5 – 5	
S1	Airborne sea water	0,5 – 5	
S2	Submerged	0,1 – 1,0	
S3	Tidal zone	1 – 10	

Input Parameter			
Exposure	**XS1**	**XS2**	**XS3**
I_{corr} [μA/cm²]	1.7	0.5	2.5

XS1						
Time [years]	**50**	**60**	**70**	**80**	**90**	**100**
$P_{pit}(t)$ [mm]	0.39	2.37	4.34	6.31	8.28	10.25

XS2						
Time [years]	**50**	**60**	**70**	**80**	**90**	**100**
$P_{pit}(t)$ [mm]	0.75	1.33	1.91	2.49	3.07	3.65

XS3						
Time [years]	**50**	**60**	**70**	**80**	**90**	**100**
$P_{pit}(t)$ [mm]	4.93	7.83	10.73	13.63	16.5	19.43

EFFECTS OF CORROSION

From corrosion rate to **maximum cross-section loss**

$$A_p(t)=\begin{cases} A_1+A_2 & p(t)\le \dfrac{D_0}{\sqrt{2}} \\ \dfrac{\pi D_0^2}{4}-A_1+A_2 & \dfrac{D_0}{\sqrt{2}}<p(t)\le D_0 \\ \dfrac{\pi D_0^2}{4} & p(t)>D_0 \end{cases}$$

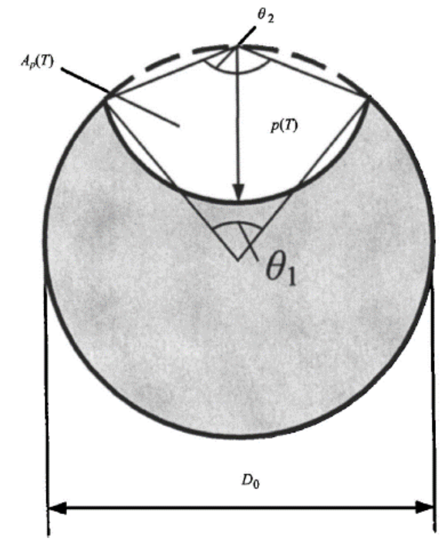
$$A_1=\frac{1}{2}\left[\vartheta_1\left(\frac{D_0}{2}\right)^2-a\left|\frac{D_0}{2}-\frac{p(t)^2}{D_0}\right|\right]$$

$$A_2=\frac{1}{2}\left[\vartheta_2\left(p(t)\right)^2-a\left(\frac{p(t)^2}{D_0}\right)\right]$$

$$\vartheta_2=2\arcsin\left(\frac{a}{2p(t)}\right)$$

$$a=2p(t)\sqrt{1-\left[\frac{p(t)}{D_0}\right]^2}$$

$$\vartheta_1=2\arcsin\left(\frac{a}{D_0}\right)$$



$$\eta_{\max}=\frac{A_{s0}-A_p(t)}{A_{s0}}$$

η_{max} : maximum cross-sectional loss of the corroded rebar
A_{s0} : un-corroded cross-sectional area of rebar
$A_p(t)$: residual cross-sectional area of rebar

Val Dimitri. Deterioration of RC Beams due to Corrosion and its influence on Beam Reliability. Journal of Structural Engineering, 133(9):1297-1306,(2007).

EFFECTS OF CORROSION

Chen E., Berrocal C., Fernandez I., Lofgren I., Lundgren K. Assessment of the mechanical behaviour of reinforcement bars with localised pitting corrosion by Digital Image Correlation. Engineering Structures, 219(2020).

- modify the mechanical response of the reinforcement

Equilibrium in proximity to the region of maximum pit

$$\varepsilon_u^{out} = \begin{cases} \varepsilon_{u0} - \left(\varepsilon_{u0} - \varepsilon_{sh0}\right)\left(\dfrac{f_{u0}}{f_{u0} - f_{y0}}\eta_{\max}\right)^P & \eta_{\max} < \eta_{crit} \\ \in \left[\varepsilon_{y0}, \varepsilon_{sh0}\right] & \eta_{\max} = \eta_{crit} \\ \dfrac{f_{y0}\varepsilon_{y0}}{f_{y0}}\left(1 - \eta_{\max}\right) & \eta_{\max} > \eta_{crit} \end{cases}$$

η_{crit} : critical load corrosion level

$$\eta_{crit} = 1 - \frac{f_{y0}}{f_{u0}}$$

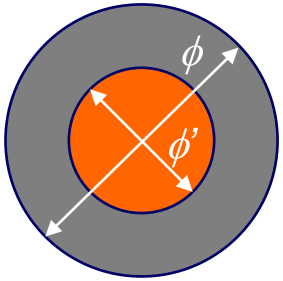
P : strain-hardening power

$$P = E_{sh0}\frac{\varepsilon_{u0} - \varepsilon_{sh0}}{f_{u0} - f_{y0}}$$

$$\sigma_u^{out} A_0 = f_{u0} A_{\min}$$

Example for T = 70 years				
Panel CA3				
Exposure Class	Uncor.	XS1	XS2	XS3
f_y [MPa]	425.4	425.4	425.4	282.1
f_u [MPa]	541.0	490.3	530.6	282.1
ε_y	0.002127	0.002127	0.002127	0.00141
ε_u	0.06	0.03457	0.05475	0.00141
ϕ [mm]	19			
η_{max}	0.0	0.09	0.02	0.48
f_c [MPa]	44.50	38.57	44.50	32.96

- reduce the resisting section of reinforcement (through the reduction of the reinforcement ratio)



EFFECTS OF CORROSION

Coronelli D. and Gambarova P., (2004). Structural Assessment of Corroded Reinforced Concrete Beams: Modeling Guidelines. Journal of Structural Engineering, 130(8):1214-1224.

- determine the cracking of the surrounding concrete

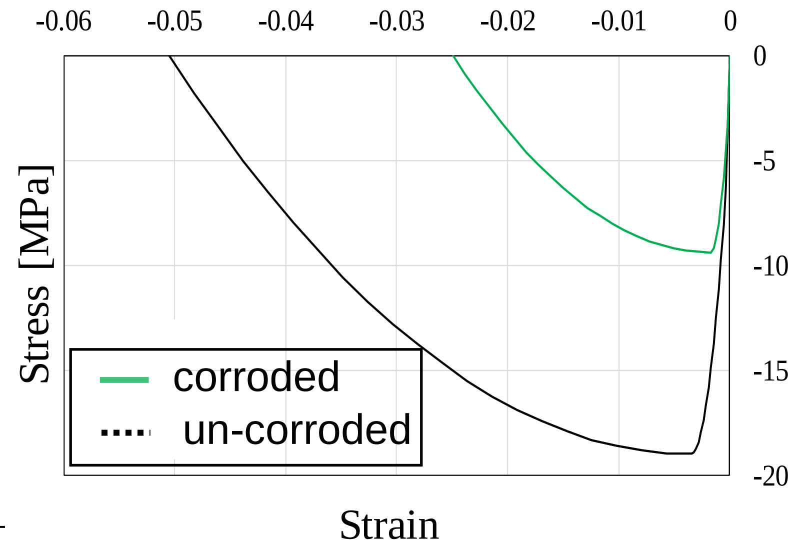
Coronelli and Gambarova (2004)

$$f_c' = \frac{f_c}{1 + k \, {\varepsilon_1}/{\varepsilon_{c0}}}$$

f_c : compressive strength of undamaged concrete
k : coefficient related to the bar roughness and diameter (0.1)
ε_1 : average strain in the cracked concrete at right angles to the direction of the applied compression
ε_{c0} : concrete strain at maximum compressive strength f_c

$$\varepsilon_1 = \frac{(b_f - b_0)}{b_0} = \frac{n_{bars} w_{cr}}{b_0}$$

w_{cr} : total crack width for a given corrosion level
b_0 : uncorroded section width



$$A_s = \left(1 - 2.1\eta_{average}\right) A_{s0} \Rightarrow \eta_{average} = \frac{A_{s0} - A_s}{2.1 A_{s0}} = \frac{\eta_{max}}{2.1}$$

$$w_{cr} = w_{c,\max} = K \ln \frac{\eta_{average}}{\eta_{cr}}$$

$$\eta_{cr} = 1 - \left[1 - \frac{\alpha}{d_0}\left(7.53 + 9.32 \frac{c}{d_0}\right) 10^{-3}\right]^2 \qquad \alpha = \frac{2\left(1 - \sqrt{1 - 2.1\eta_{average}}\right)}{1 - \sqrt{1 - \eta_{average}}}$$

$$K = 2\left(\frac{c}{d_0}\right) 10^3 + 0.22$$

A_s : minimum residual cross-section area of reinforcement
$\eta_{average}$: average cross-sectional loss of the corroded rebar
A_{s0} : initial uncorroded cross-section area of reinforcement
c : thickness of concrete cover
d_0 : uncorroded reinforcement diameter

Xia J., Jin W-L. (2014). "Prediction of corrosion-induced crack width of corroded reinforced concrete structures. 4th International Conference on the Durability of Concrete Structures 24-26 July 2014.

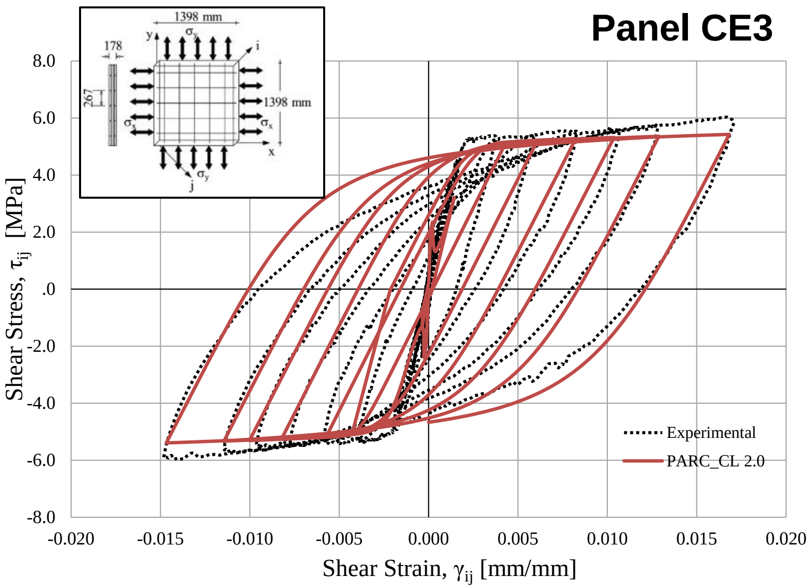
MODEL VALIDATION

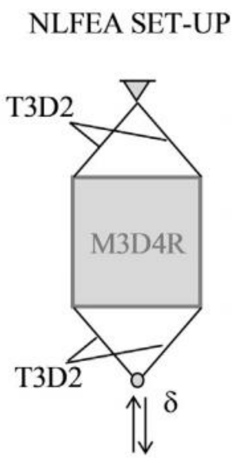
Mansour Mohamad and Hsu Thomas T. C (2005). Behaviour of Reinforced Concrete Elements under Cyclic Shear. I: Experiments. Journal of Structural Engineering, 131(19):44-53.

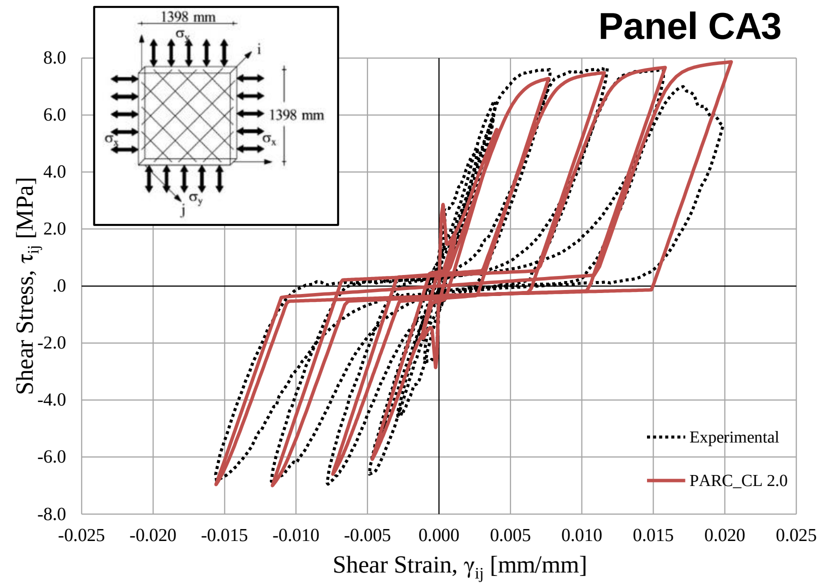
The materials used for the test:

▶ *Longitudinal and transversal reinforcement are the same*

Specimen	Concrete			Steel			
Panel	f_c [Mpa]	ε_{c0} [-]	E_c [Mpa]	f_y [Mpa]	f_u [Mpa]	E_s [Mpa]	E_h [Mpa]
CE3	50	0.0024	35909.49	425.4	541.1	200000	2000
CE4	47	0.0022	35176.44	453.4	569.0	200000	2000
CA3	44.5	0.0024	34541.35	425.4	541.1	200000	2000
CA4	45	0.0028	34670.24	453.4	569.0	200000	2000







Belletti B., Scolari M., Vecchi F. (2017). PARC_CL 2.0 crack model for NLFEA of reinforced concrete structures. Computers and Structures, 191:165-179.

MAIN RESULTS

Evaluation of corrosion deterioration

ULTIMATE POINT

$$M^{+} = f(\tau^{+}_{max}, \gamma^{+}_{max})$$

$$M^{-} = f(\tau^{-}_{max}, \gamma^{-}_{max})$$

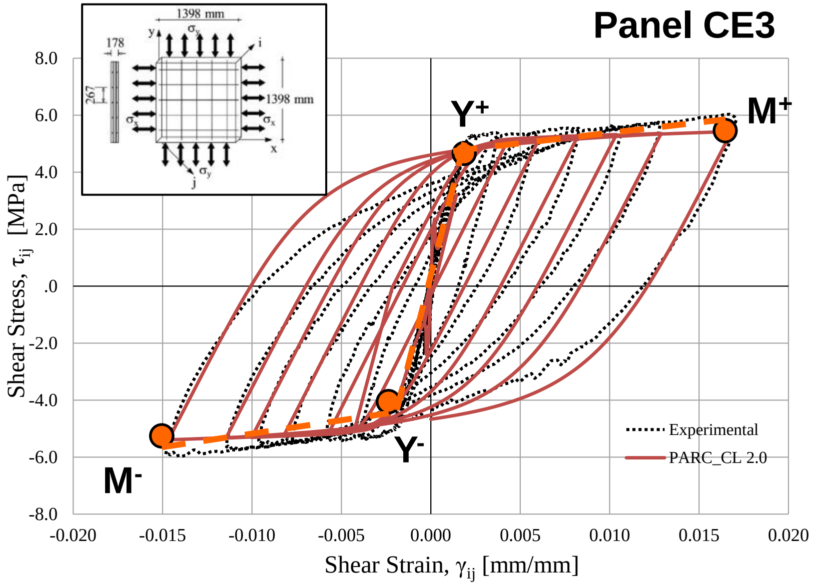
YIELDING POINT

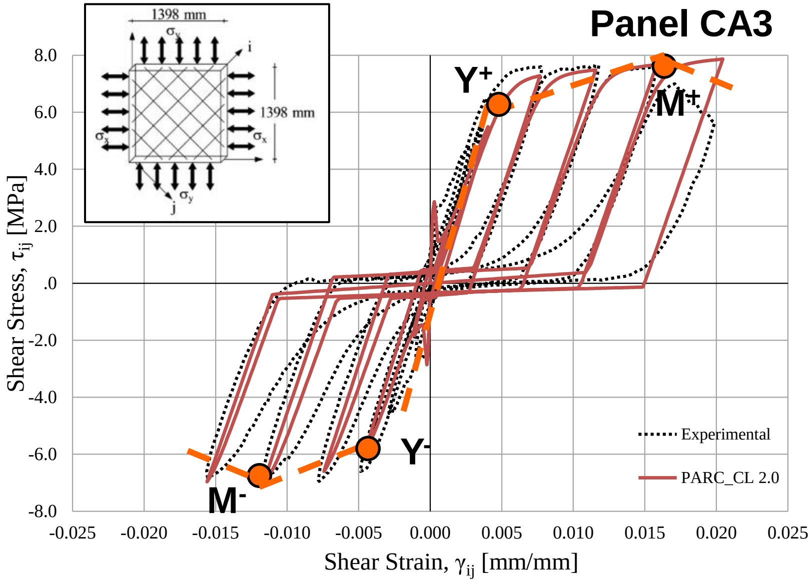
$$Y^{+} = f(\tau^{+}_{y}, \gamma^{+}_{y})$$

$$Y^{-} = f(\tau^{-}_{y}, \gamma^{-}_{y})$$

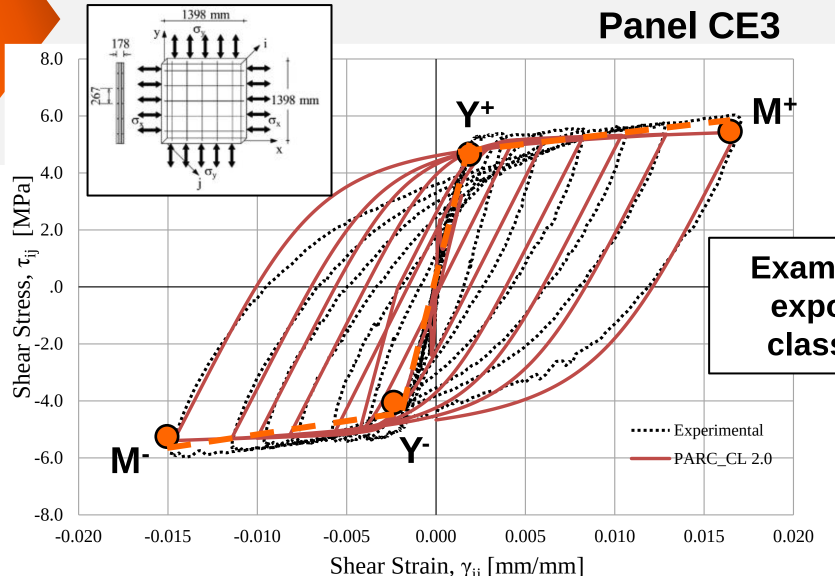
MAIN PARAMETERS

- Reduction in terms of maximum shear stress and maximum shear strain
- Preyield Shear Stiffness $K_{\gamma} = \frac{\tau_y}{\gamma_y}$

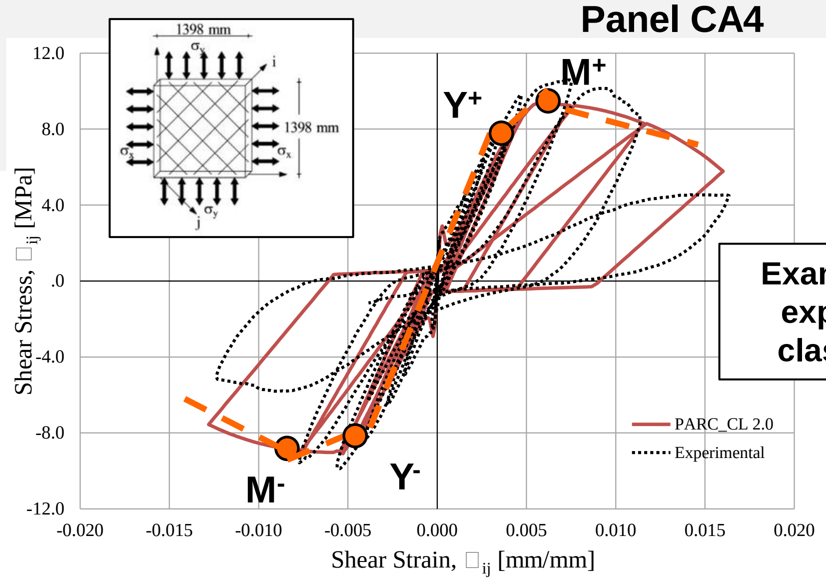




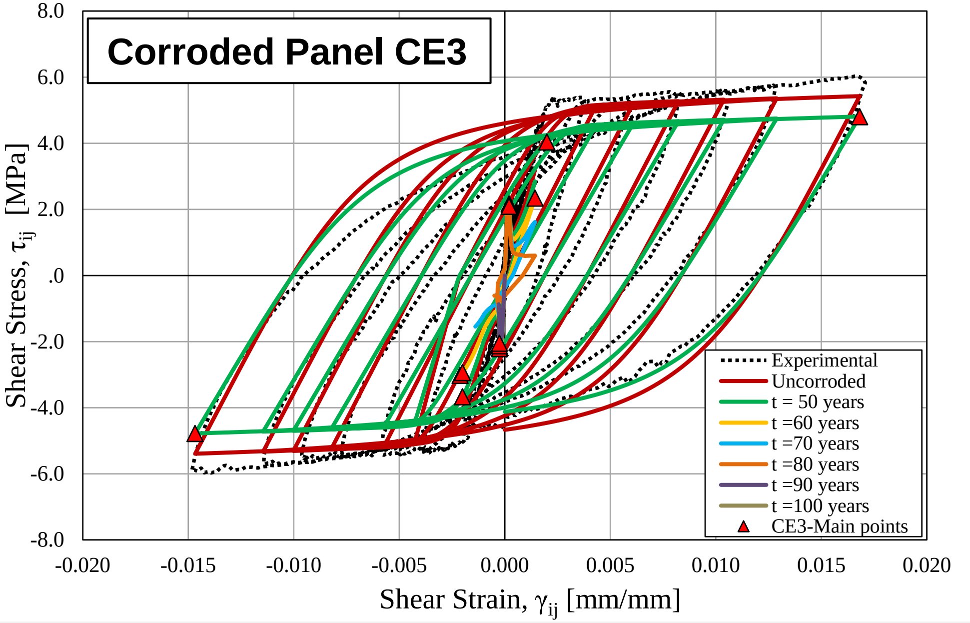
MAIN RESULTS

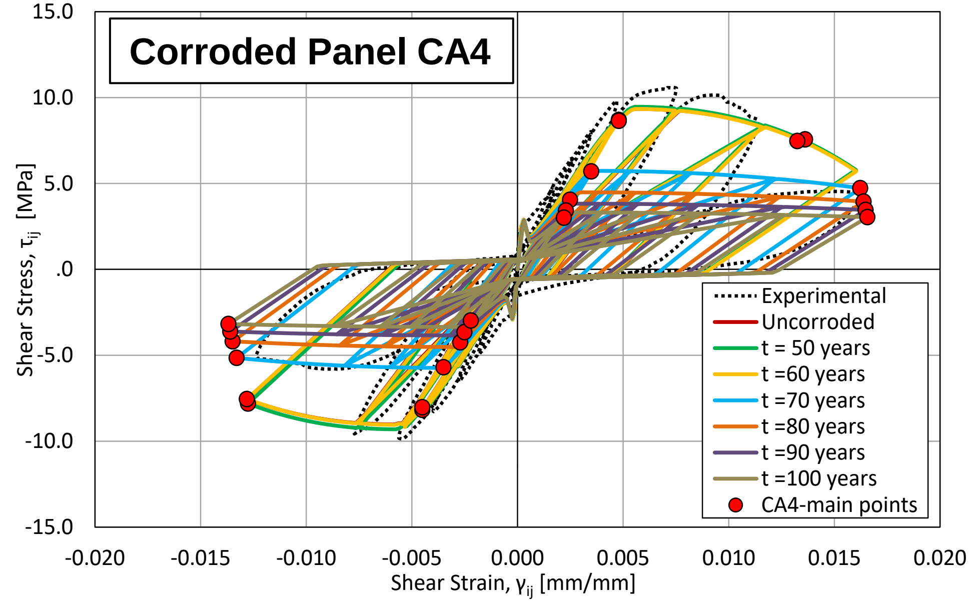


Example for exposure class XS3

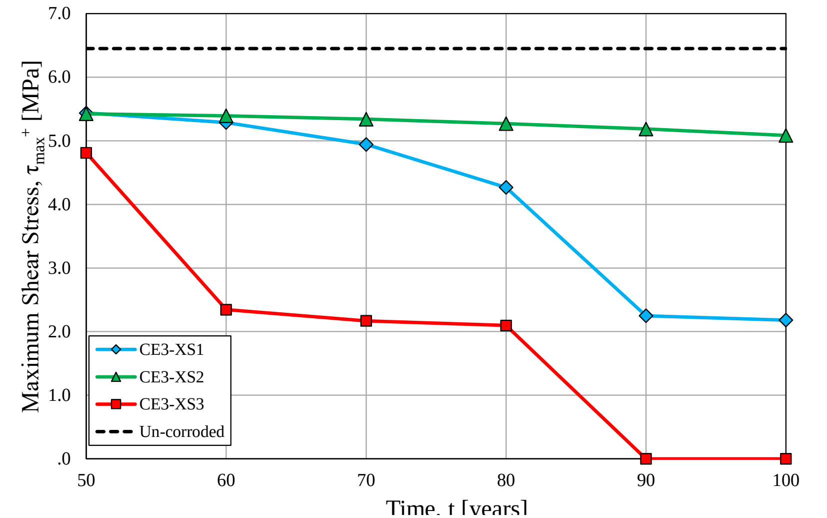


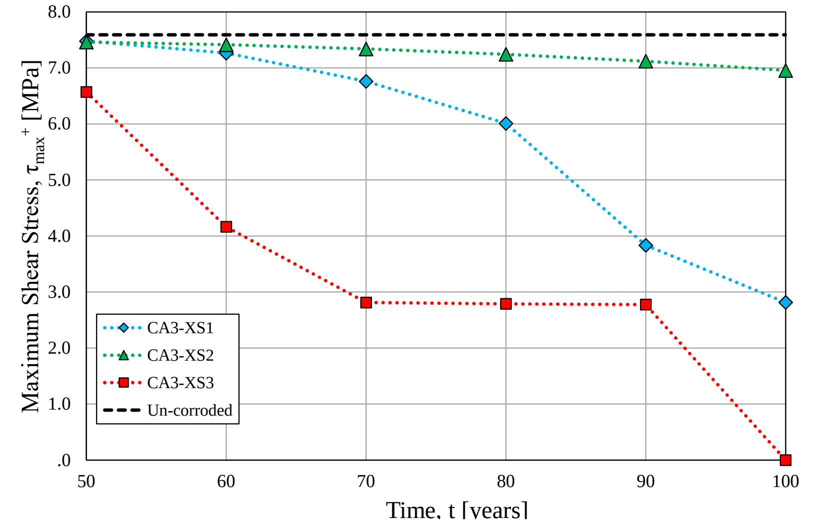
Example for exposure class XS1

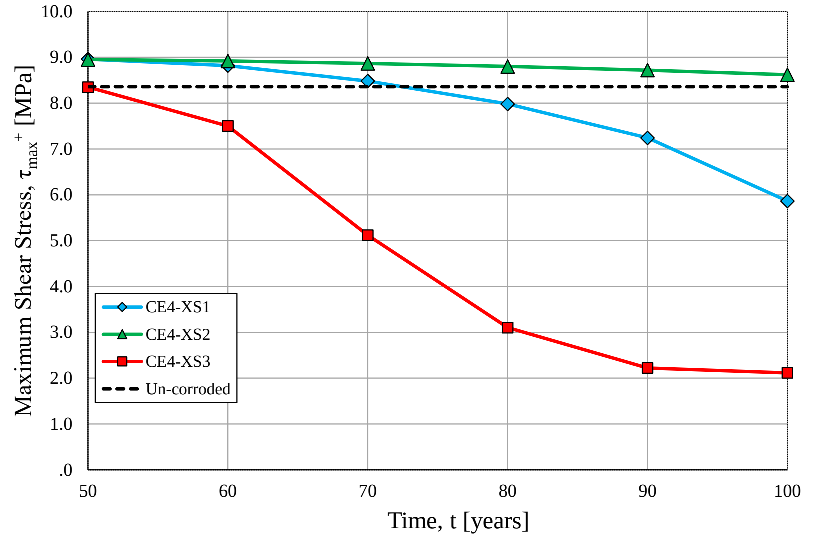


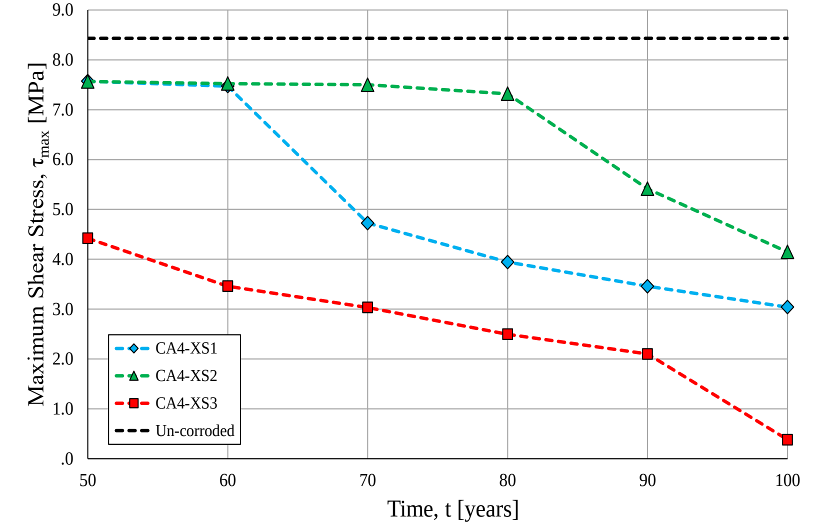


MAIN RESULTS
Maximum Shear Stress

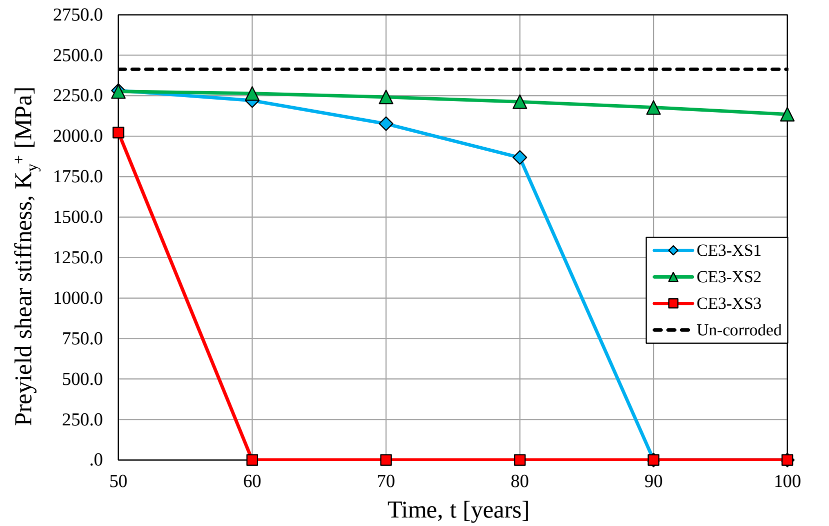


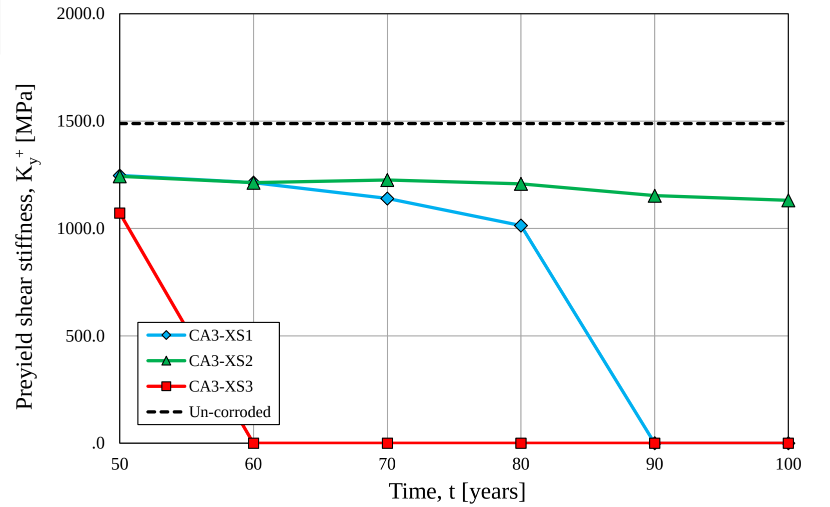


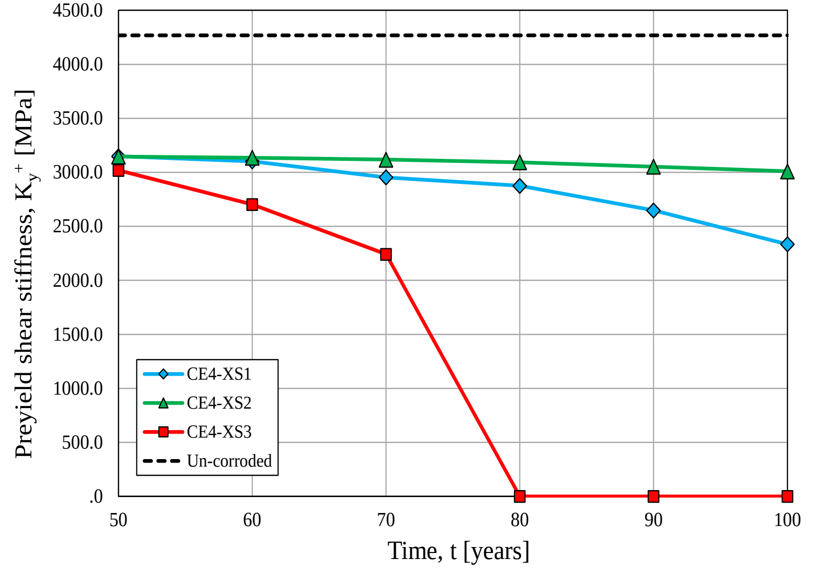


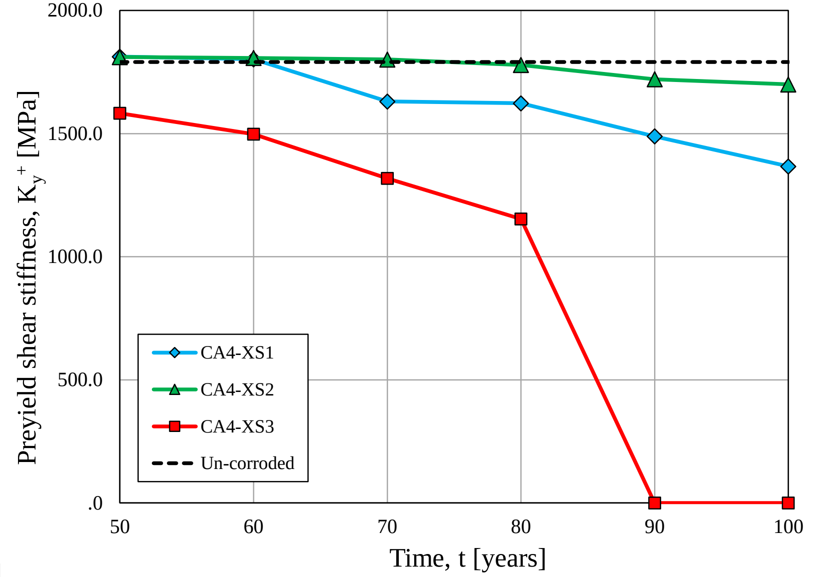


MAIN RESULTS
Preyield Shear Stiffness









Conclusions

1 NLFEA are useful tools for the prediction of seismic behaviour of existing concrete structures, that once validated can be used instead of more expensive experimental tests. In this work, the PARC_CL model is used.

2 The un-corroded panels show higher resistance and ductility under cyclic load than the corroded panels;

3 Referring to shear stress, the higher reduction over the time is recorded for the exposure class XS3 – wet and dry condition – while the lowest reduction in terms of shear stress is recorded for the exposure class XS2 – submerged condition.

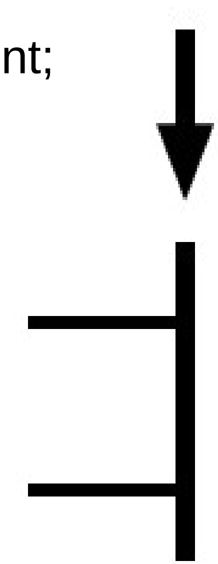
4 Over the time, a general reduction of preyield shear stiffness due to corrosion deterioration is observed.

Future research are now ongoing:

- to estimate the contribution provided by creep and shrinkage effect over the time;
- to evaluate the response of corroded RC panels with different longitudinal and transversal reinforcement ratio.
- to investigate the buckling phenomenon of compressed steel reinforcement;

Local effect produces **global consequences**

It significantly modifies the **seismic response** **reducing the capacity** both in terms of **strength** and **ductility**



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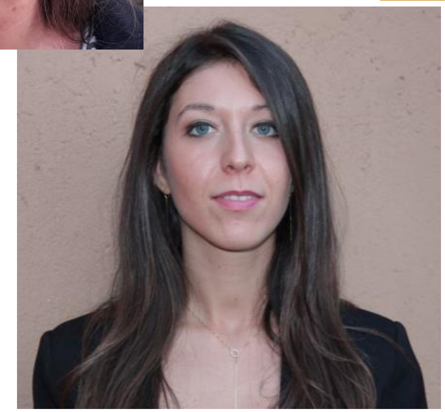

THANK YOU FOR YOUR ATTENTION!

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