


南京工业大学土木工程学院2022年度科学报告会

基于抗震韧性的近海腐蚀桥梁FRP复合加固方法研究

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Nanjing, China (Online)

OUTLINE

1. Introduction

➢ **Objective:** resilient bridge/transportation network

San Diego Bridge 1969

Seven Mile Bridge 1982

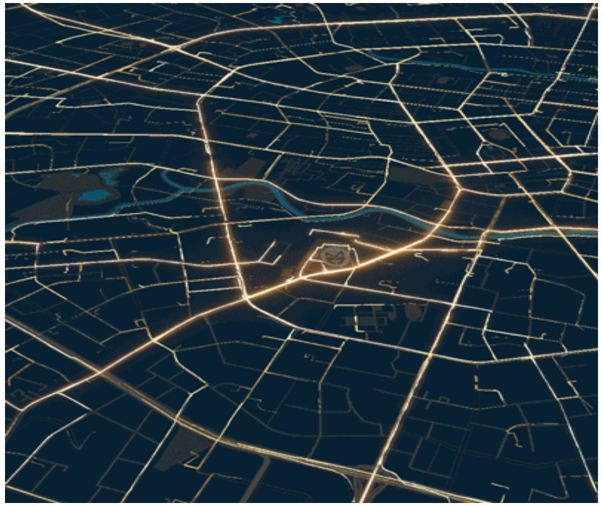
Sea Cliff Bridge 2005

Shantou Bay Bridge 1995

East Sea Bridge 2005

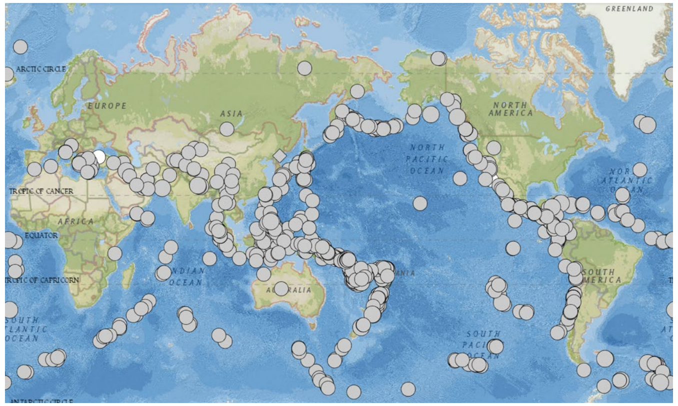
Xinghai Bay Bridge 2011

Coastal and off-shore bridges



Bridge/transportation network

- Since 2012 Dec. 10th: 10 years
- Magnitude > 6.0
- Earthquake's Depth < 20km
- Event number = 711



- Maintain adequate functionality
- Evacuation of affected people
- Transportation of emergency goods
- Operation of social facilities
- Restore pre-event functionality with limited time and cost

Seismic resilience

1. Introduction

➢ **Problem statement:** chloride-induced corrosion + earthquakes

Corrosion + Earthquakes

Resilience?

Load Capacity

Durability

Self-centering

Seismic retrofitting

2. Determination of corrosion damages

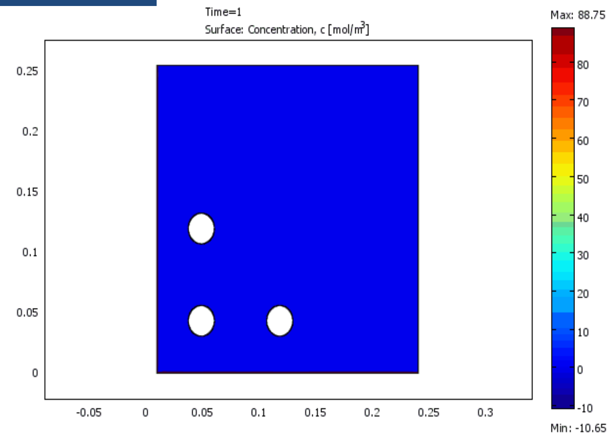
➢ Two key issues

Initial corrosion time

$$\frac{\partial C_f}{\partial t} = \frac{\partial}{\partial x}\left(D_{Cl}^* \frac{\partial C_f}{\partial x}\right) \qquad D_{cl}^* = \frac{D_{cl}}{1 + \frac{1}{\omega_e}\frac{\partial C_b}{\partial C_f}}$$

$$\partial C_b / \partial C_f = 0.378 C_f^{-0.64}$$

$$D_{cl} = D_{cl,ref} f_1(h) f_2(T) f_3(t) f_4(C_f)$$



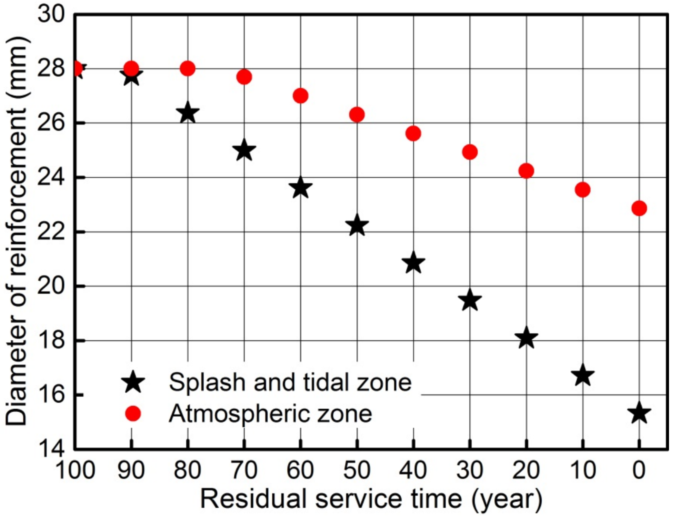
No	Function	Parameter
1	$D_{Cl.ref} = 10^{aw/c-b}$	a=2.4; b=12.06
2	$f_1(h) = 1/\{1+[(1-h)/(1-h_c)]^4\}$	h_c =0.75
3	$f_2(T) = \exp[U/R(1/T_{ref} - 1/T)]$	R=8.314 (J/mol. K); T_{ref} =293 (K)
4	$f_3(t) = (t_{ref}/t)^m$	t_{ref} =28 (day)
5	$f_4(C_f) = 1 - k_{ion}(C_f)^n$	k_{ion} =8.366; n=0.5

Structural degradation

$$D(t) = \begin{cases} D_0 & t \le T_i \\ D_0 - 0.023 i_{corr}(t - T_i) & T_i < t \le T_f \\ 0 & T_f < t \end{cases}$$

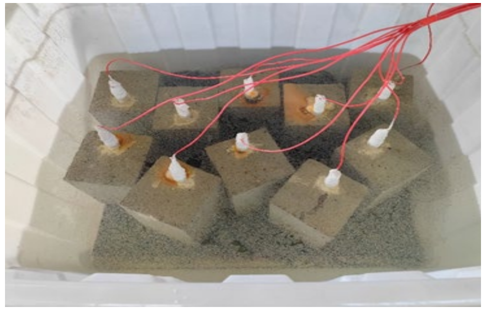
$$Q_{corr} = 1 - \left(D(t)/D_0\right)^2$$

$$f_y(t) = \left[1 - 0.005 Q_{corr}(t)\right] f_{y0}$$



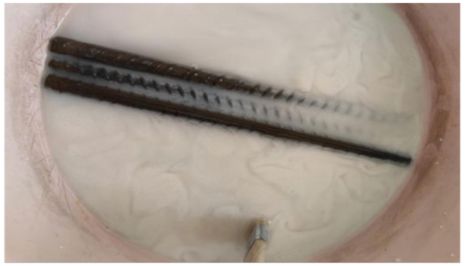
2. Determination of corrosion damages

➢ Accuracy of accelerated corrosion


4% NaCl，300μA/cm²


Corroded sample


20% Diluted hydrochloric acid


3% Lime water


Corroded steel bars


Measure mass loss rates

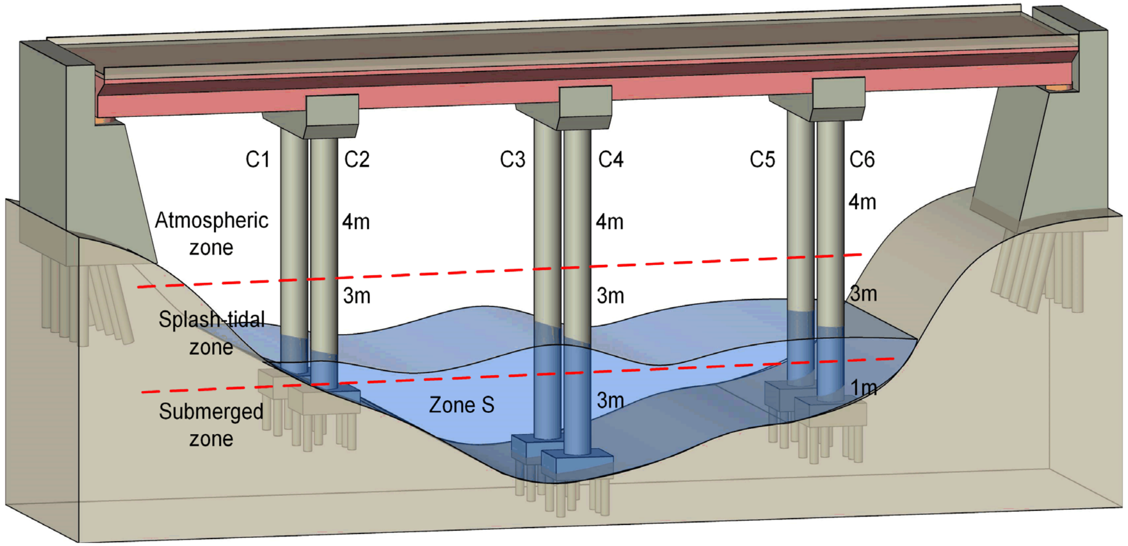
$$D(t) = D_0 - 0.023 i_{corr} (t - T_i)$$

$$Q_{\mathrm{corr}} = 1 - \left(D(t) / D_0 \right)^2$$

Time (days)	No.	Mass (g)	Average mass loss rate（%）	Theoretical result（%）
19	1	424.9	7.40	7.36
	2	426.1		
	3	419.9		
47	1	388.6	16.4	17.9
	2	377.9		
	3	381.1		
56	1	319.9	29.6	21.2
	2	328.7		
	3	318.0		

2. Determination of corrosion damages

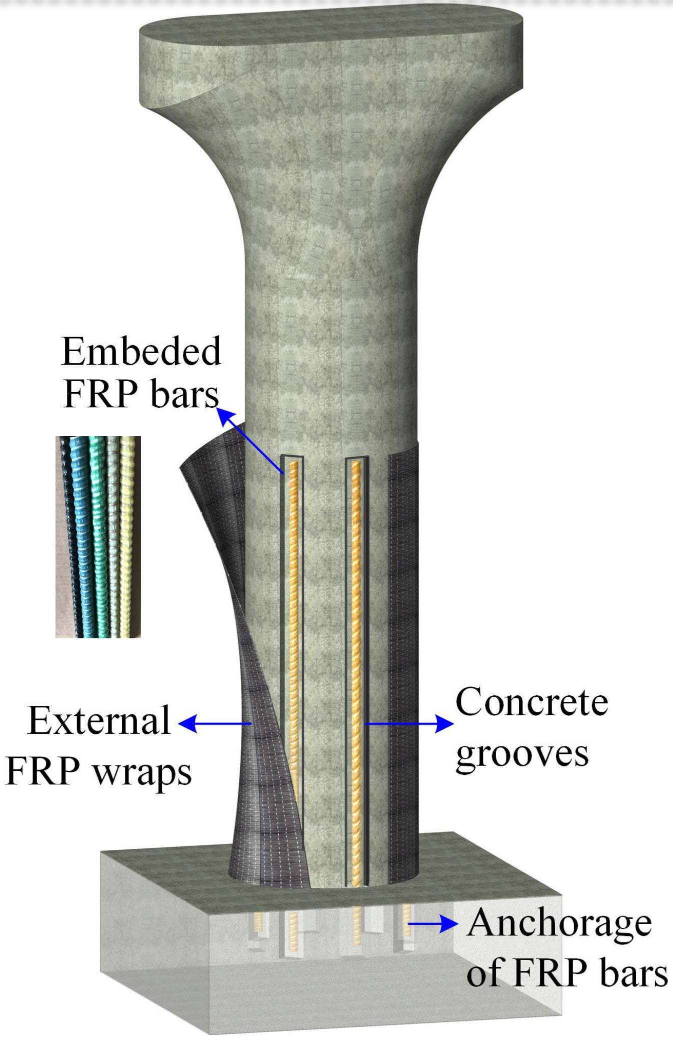
➢ Non-uniform corrosion damages



OUTLINE

3. Description of the retrofitting strategy

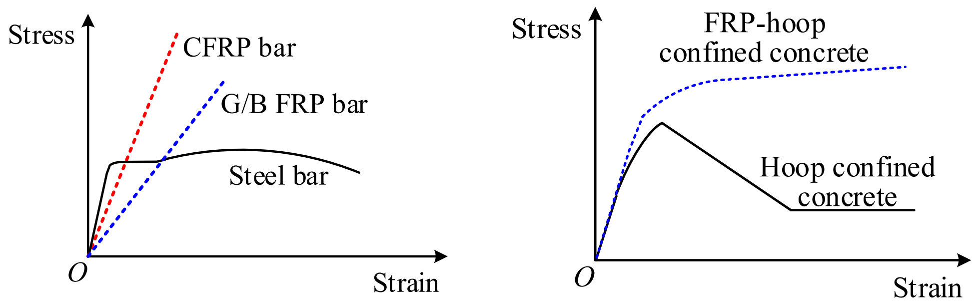
➢ Procedures and mechanism

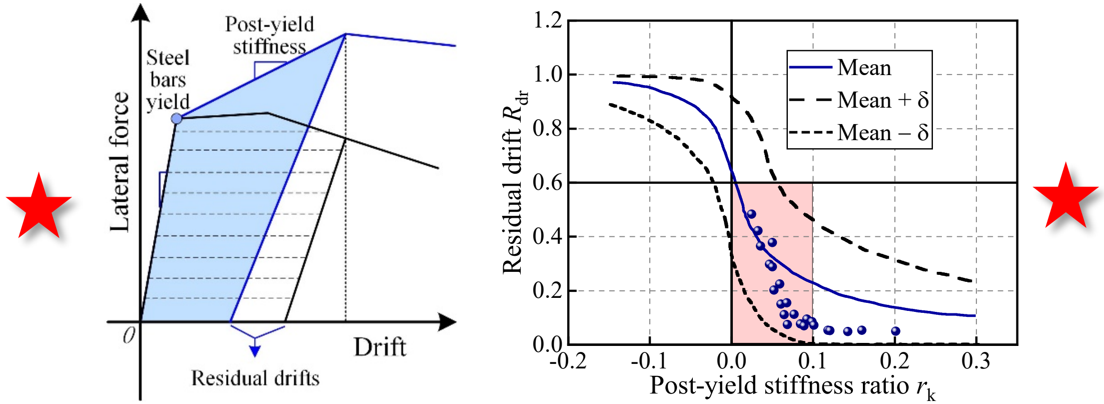


Retrofitting procedures

Load Capacity | **Durability** | **Self-centering**

- **Combination:** FRP wraps + NSM with FRP bars
- **External FRP wraps:** confinement, shear capacity
- **Internal FRP bars:** flexural capacity, self-centering

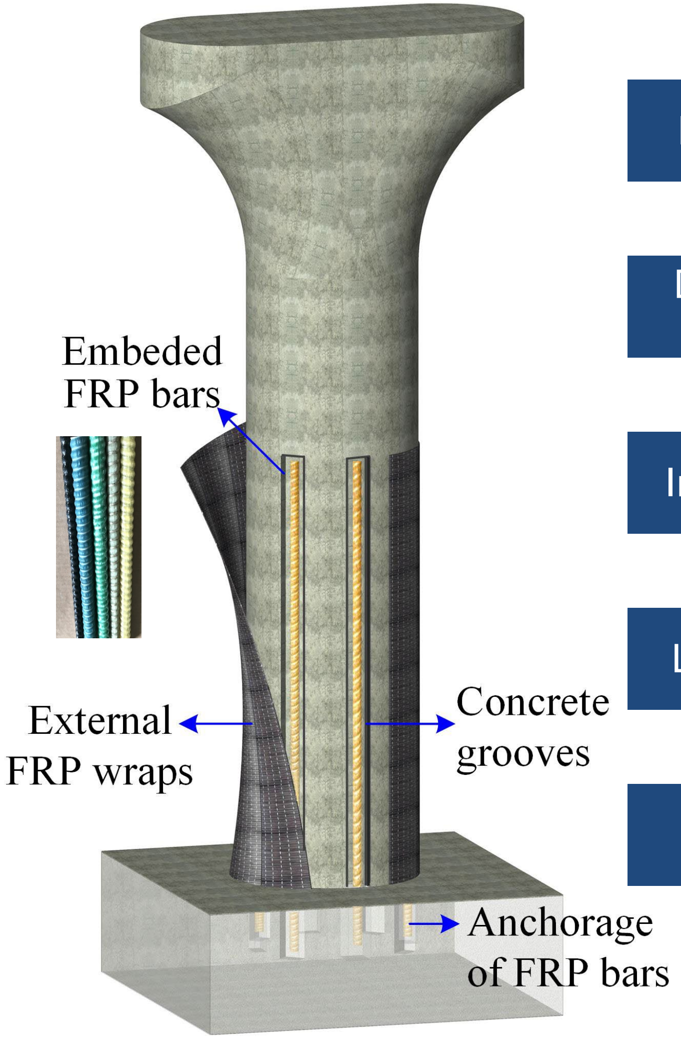




Mechanism: two key issues of resilience

3. Description of the retrofitting strategy

➢ Retrofitting design



Retrofitting procedures

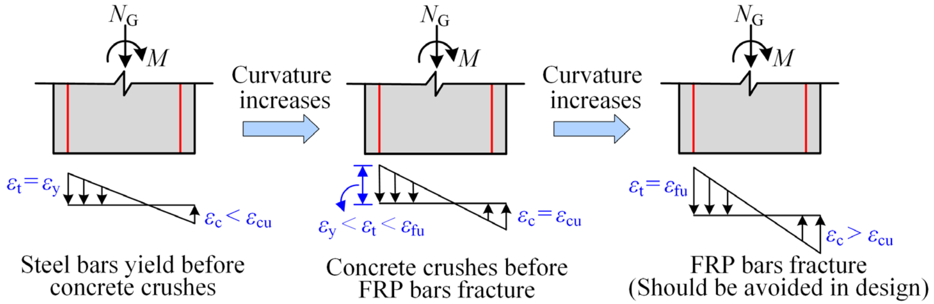
Failure mode

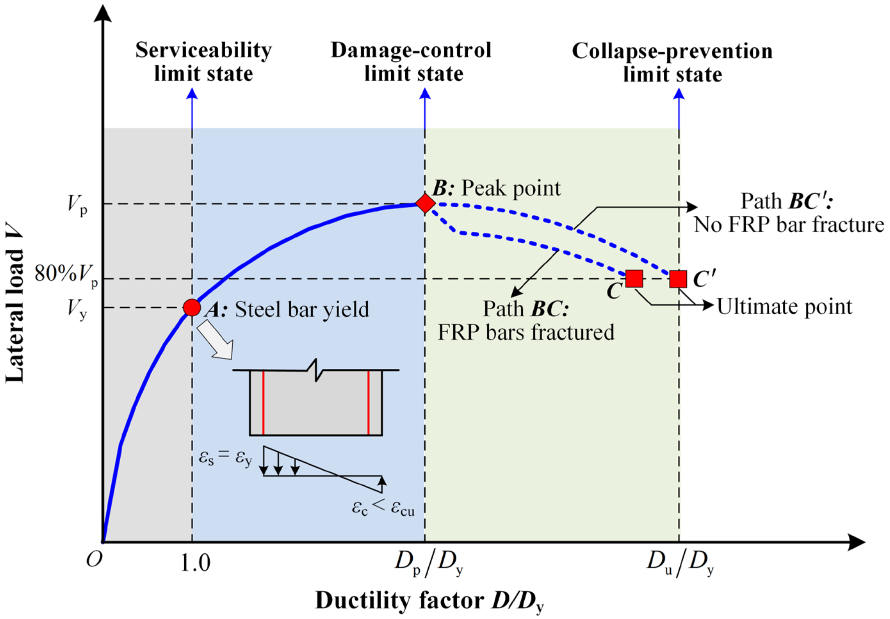
Damage limit state

Initial stiffness

Load capacity

r_k - R_{DR}



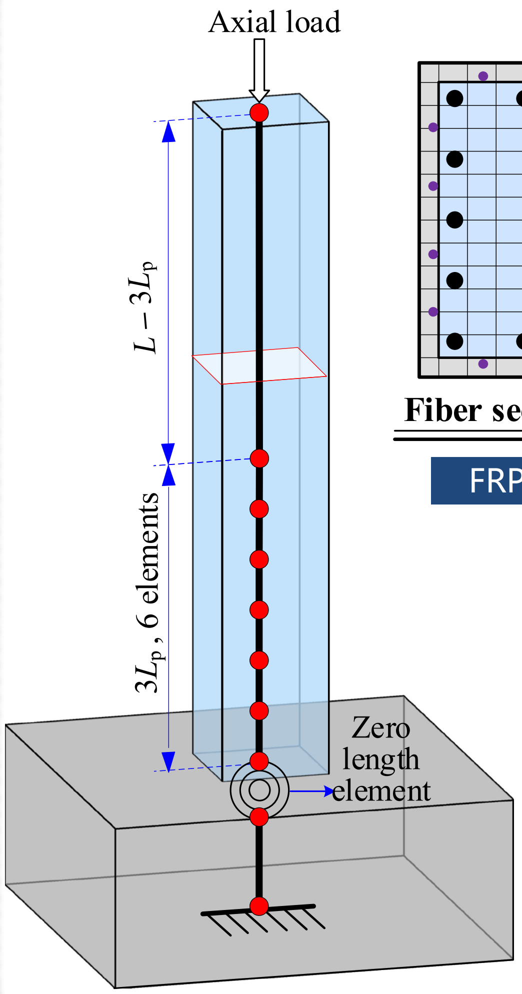


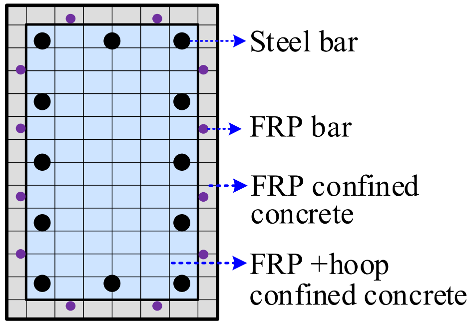
Design	Index
Design Stage 1	k_y
	V_y
	Δ_u
Design Stage 2	r_k
	Δ_r

Retrofitting design

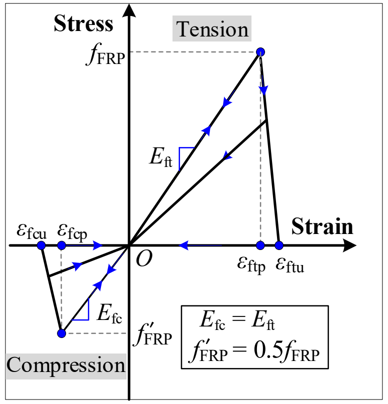
4. FE analysis of retrofitting effects

➢ FE modeling method





Fiber section of column



FRP+hoop confined concrete model (Wang 2012)

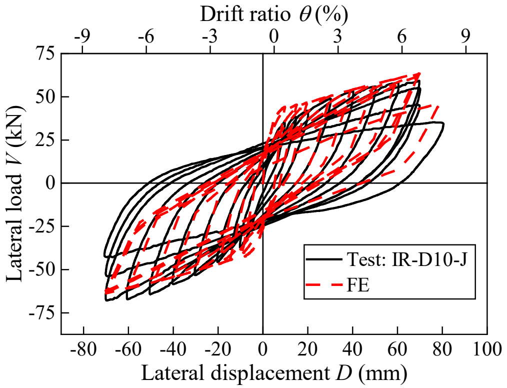
$$f_{cc}=f'_c\left(1+0.35\lambda_f+0.50\lambda_h+0.85\lambda_l\right)$$

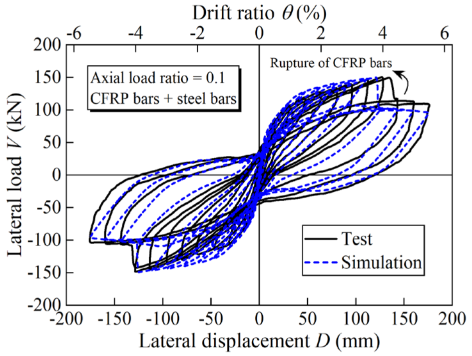
$$\varepsilon_{cc}=\varepsilon_{c0}\left(1+2.0\lambda_f+2.5\lambda_h\right)$$

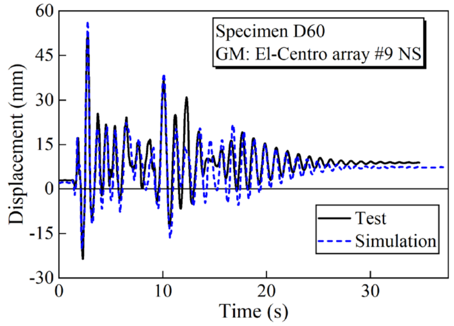
$$\frac{f_{cu}}{f'_c}=0.2+0.59\left(\frac{f_{ls}}{f'_c}\right)^{0.20}+3.47\left(\frac{f_{lf}}{f'_c}\right)^{0.64}$$

$$\frac{\varepsilon_{cu}}{\varepsilon_{c0}}=2+5.06\left(\frac{f_{ls}}{f'_c}\right)^{0.03}+73.31\left(\frac{f_{lf}}{f'_c}\right)^{1.07}$$

2D Fiber element model



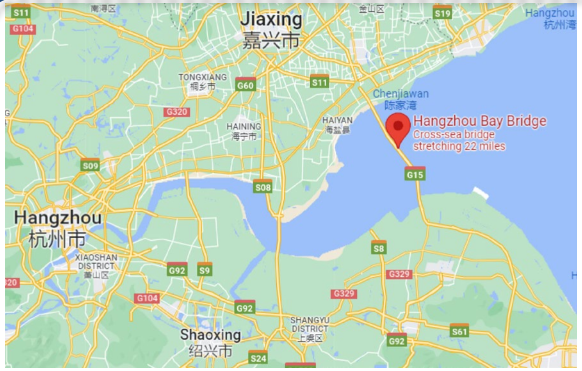


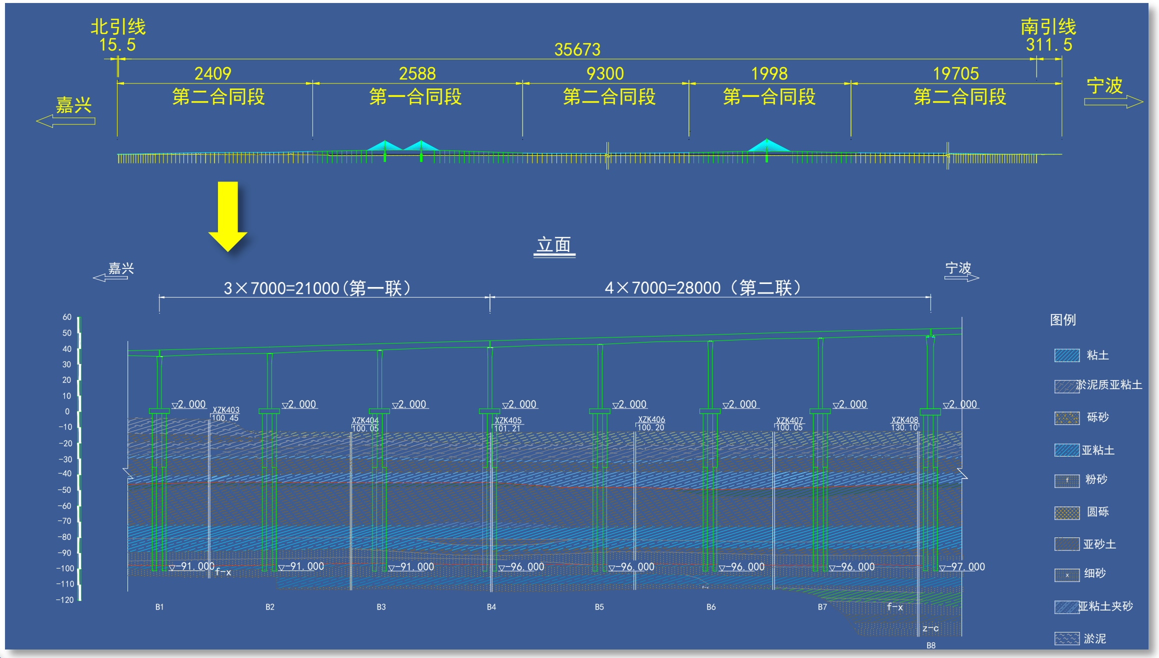


Model verification

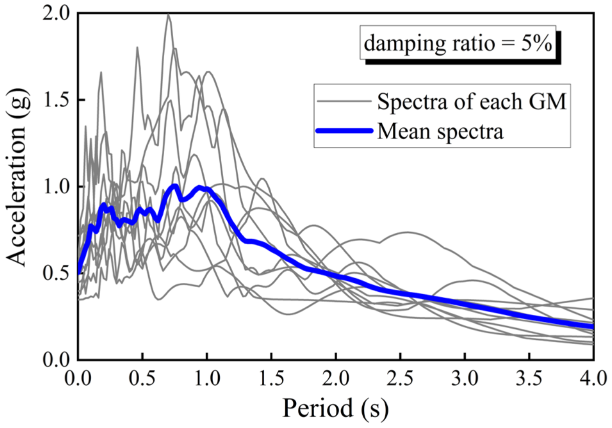
4. FE analysis of retrofitting effects

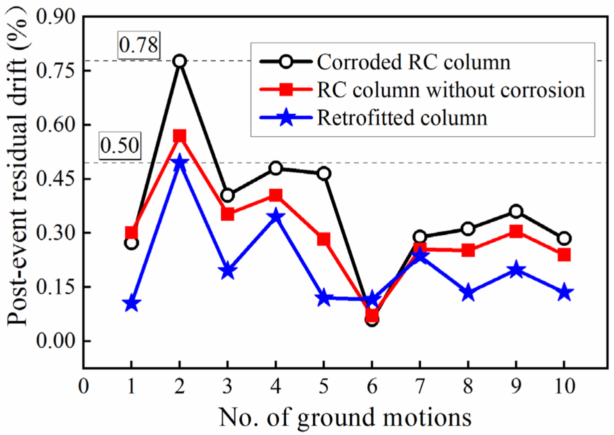
➢ Analysis results





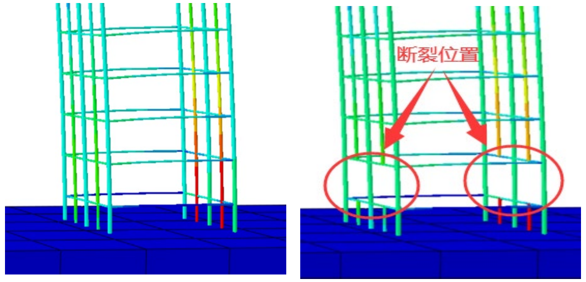
North approach bridge, Hangzhou Bay Bridge 2008





36%

43%



Local damage:
Hashin damage model

$$E_1 = E_f V_f + E_m V_m \qquad \frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m}$$

$$Y_t = \sigma_{mtu}\left[1-(\sqrt{V_f}-V_f)(1-\frac{E_m}{E_f})\right]$$

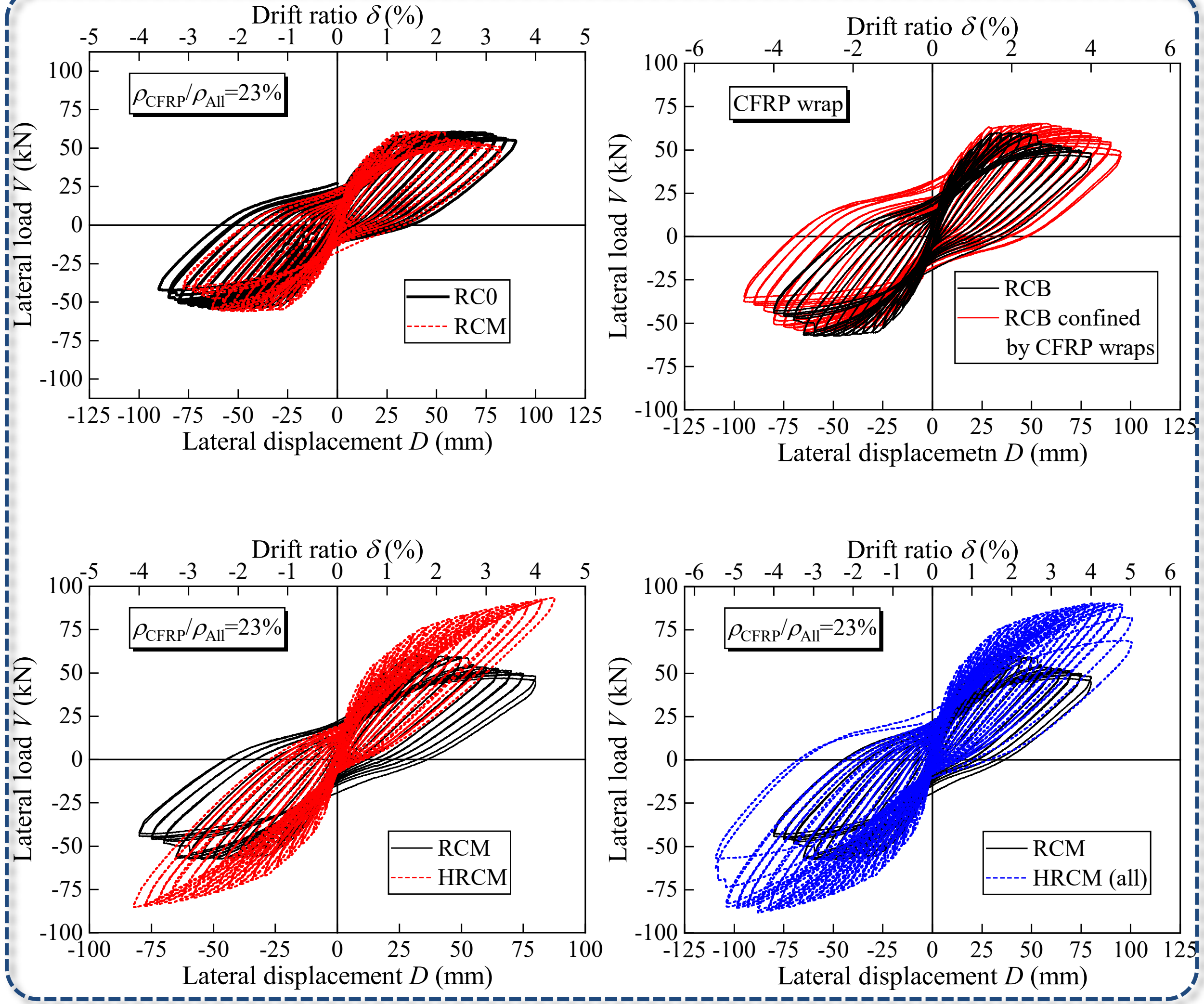
$$Y_c = \sigma_{mcu}\left[1-(\sqrt{V_f}-V_f)(1-\frac{E_m}{E_f})\right]$$

$$S = \tau_m\left[1-(\sqrt{V_f}-V_f)(1-\frac{G_m}{G_f})\right]$$

5. Experimental verification

➢ Quasi-static test

Specimen failure model



Hysteretic curves

CONCLUSIONS

(1) Monitoring the accelerated corrosion process is necessary to the determination of the chloride-induced damage in experimental studies, and is important to the retrofitting design;

(2) Two key issues of the hybrid retrofitting method:

① bilinear load-displacement curves；

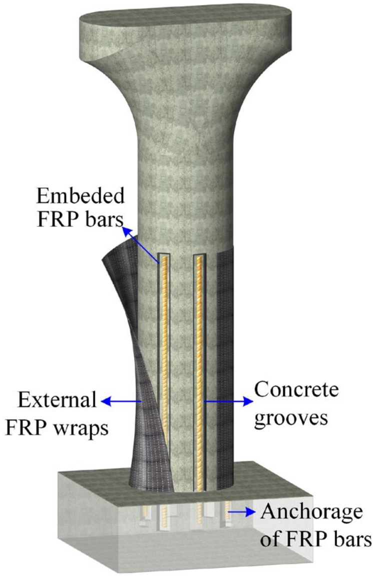
② post-earthquake residual displacement prediction method.

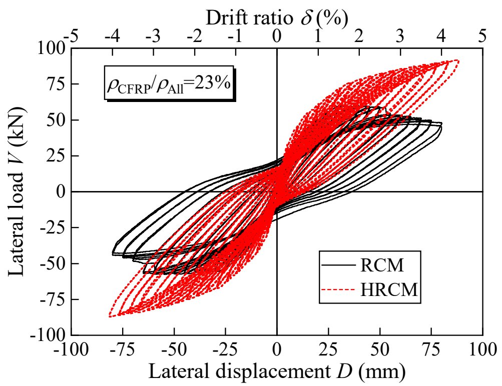
(3) As compared to RC precast bridge columns:

① The largest post-earthquake residual drift ratios decreased by 36% ↘ ;

②The average post-earthquake residual drift ratios decreased by 43% ↘.

(4) Quasi-static test results indicate that the retrofitted corroded RC columns shows evident post-yield stiffness ratio.





感谢各位老师
敬请批评指正

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