THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

國家鋼結構工程技術研究中心香港分中心
Chinese National Engineering Research Centre For Steel Construction (Hong Kong Branch)

Address: Hong Kong Polytechnic University, Phase 8, Hung Hom, Kowloon, Hong Kong.
Telephone: (852) 3400 8451 Email: cnerc.steel@polyu.edu.hk Website: https://www.polyu.edu.hk/cnerc-steel/

Work Theme A: Sustainable Infrastructure Development

A2: Localized corrosion in galvanized steel reinforcements in reinforced concrete structures

Project Title:

a) "Corrosion Mechanisms and Prevention of High Performance Steel in Reinforced Concrete Structures"

Principal Investigator: Prof. C. S. POON (CEE)

Project Team Members:

Dr. W.J. Zhu; Dr. H.B. Zheng; Dr. Hu Xiang; Ms. Phoebe T.W. Wong; Ms. Y. M. Cai

Project Outline:

The sub-project will be conducted in the following four aspects:

1. Corrosion mechanisms

The corrosion mechanisms of high performance steel (galvanized, high strength, and stainless steel) in concrete structures exposed to chloride environment (marine environment) will be studied in this sub-project. Both microcell and macroscopic methods will be adopted to investigate the corrosion mechanisms, combined with electrochemical, physical and chemical knowledge.

2. Corrosion prevention of high performance steel

The effect of different cement binders, organic corrosion inhibitors will be studied based on a series of experimental tests. The effect of concrete coatings on the corrosion of high performance steel in concrete will also be studied.

3. Mechanical and bond behaviour of corroded high performance steel

The influence of corrosion on the mechanical properties and bond behaviour of the high performance steel will be investigated in this sub-project. The residual morphological appearance of the high performance steel induced by the chloride corrosion will be analyzed together with the residual mechanical performance of the steel. The residual mechanical properties will be identified carefully with the corrosion levels, corrosion patterns and corrosion distribution. Pull-out test and physical-chemical examination will also be conducted to the corroded samples in order to check the influence of corrosion on the bond behaviour.

4. Corrosion monitoring

The corrosion propagation of high performance steel will be monitored continually. The electrochemical polarization of the high performance steel in the concrete will be checked during different corrosion processes. All the four aspects are firmly about the corrosion of high performance steel in concrete structures, which is also considered as one of the most important fields for the durability of the high performance steel. With the contribution of this sub-project, the application of high performance steel will be improved significantly and will be of great help for the CNERC. The aim of this sub-project is to investigate the corrosion mechanisms and prevention of the high performance steel in concrete structures in marine environment.

The sub-project has the following specific objectives:

1. To investigate the corrosion mechanisms of the high performance steel embedded in concrete, the electrochemical propagation of the corrosion process in both the initiation period and the deteriorating period, including the corrosion art, corrosion patterns and the corrosion distribution.

2. To identify the effects of different cement binders, organic corrosion inhibitors and concrete coating on the corrosion of high performance steel in concrete.

3. To make clear the influence of corrosion on the mechanical properties of the residual reinforcement, the corrosion art on the mechanical performance of the steel; to identify the effect of corrosion on the bond of the high performance steel in both microcell way and mechanical way.

4. To monitor the corrosion process so as to identify the corrosion propagation of the high performance steel in the concrete.

Progress / Achievement:

1) <u>Comparative studies on passivation and depassivation behaviors of three types of steel bars in simulated concrete pore solution</u>

Passivation and depassivation processes of three common steel bars were compared after immersion in the simulated concrete pore solution using the open circuit potentials (OCP), electrochemical impedance spectroscopy (EIS) and linear polarization resistance (LPR) test methods. The electronic properties and chemical compositions of the passive films were further analysed by in-situ Mott-Schottky analysis and X-ray photoelectron spectroscopy (XPS) tests. This work would be useful to improve the understanding of the passivation and depassivation behaviors of the commonly used steel bars.

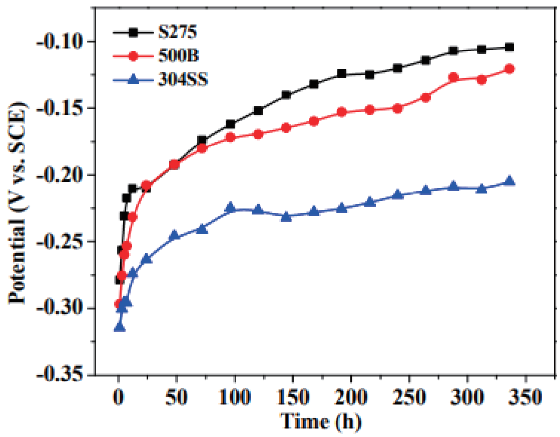

Fig. 1 Variations of open circuit potential for the steel specimens with immersion time in saturated calcium hydroxide solution

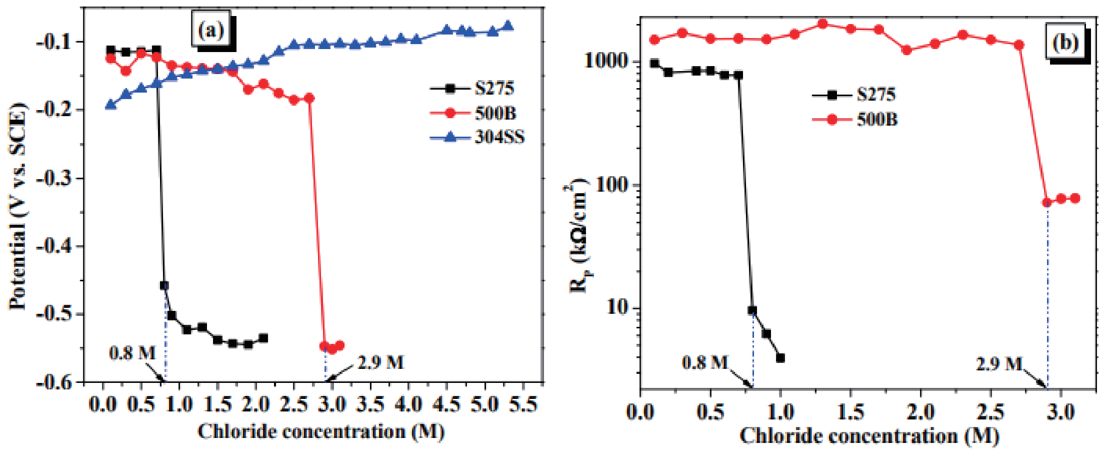

Fig. 4 Evolution of open circuit potential (a) and linear polarization resistance (b) for the steel specimens with the increase of chloride ion concentration in saturated calcium hydroxide solution

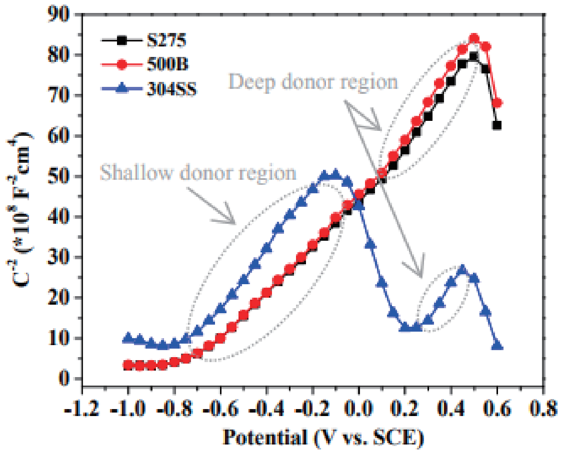

Fig. 6 Mott-Schottky curves of the passive films formed on the surface of the steel specimens immersed in saturated calcium hydroxide solution for 336 h

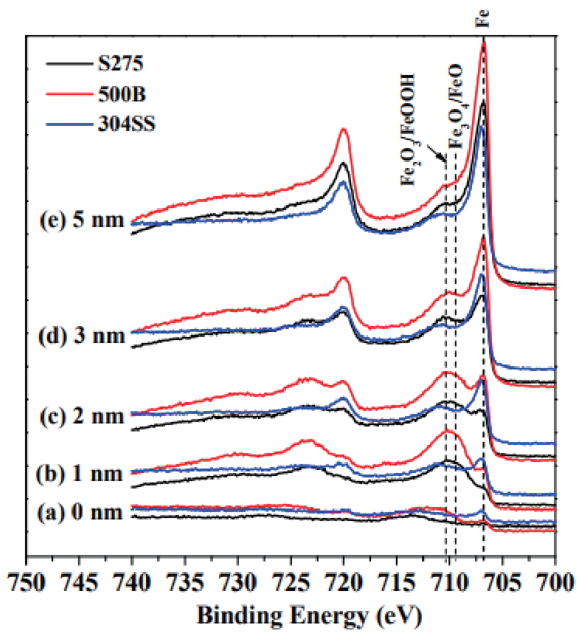

Fig. 7 Fe 2p spectra at different sputtered depths for the steel specimens

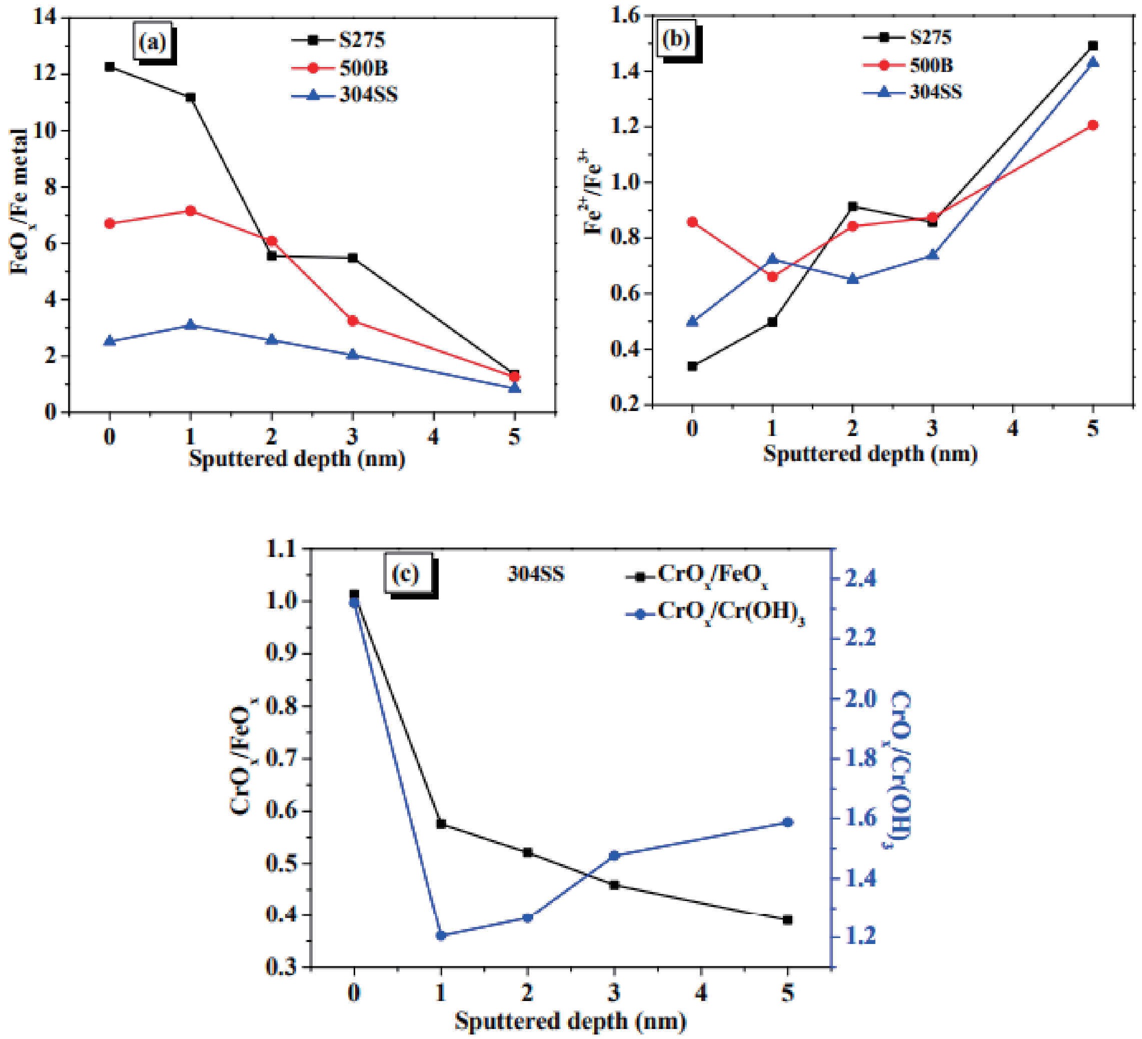

Fig. 8 Comparison of the Fe- and Cr-oxide/hydroxide for S275, 500B and 304SS at different passive film depths: (a) and (b) were the ratios of FeOx/Fe and Fe2+/Fe3+ for S275, 500B and 304SS; (c) was the ratios of CrOx/FeOx and CrOx/Cr(OH)3 for 304SS

In the passivation process, S275 had a relatively lower passivation rate in the first 24 h and a relatively poor passive state after 336 h in comparison with 500B and 304SS. For the 500B and 304SS, the passivation process mainly occurred in 72 h, and a rapid passive rate and better passive state were observed, especially for the 304SS.

In the depassivation process, the threshold value of Cl for the S275 and 500B in the saturated calcium hydroxide solution was found to be 0.8 M and 2.9 M. For the 304SS, the value was higher than 5.3 M. The results showed a relatively high anti-corrosion performance of 500B and 304SS.

Compared with S275, the lower donor density of the passive film formed on the 500B and 304SS in the Mott-Schottky analysis showed that a dense and coherent passive film was formed. These was attributed to the different chemical compositions of the passive films.

The higher Fe2+ oxides on the surface layer of the passive film for the 500B and 304SS were considered to provide a more stable passivation state and a better protection against corrosion. Moreover, the CrOx in the oxide film for the 304SS also played a key role on the self-repair and stability of the passive film. For the S275, the surface layer of the passive film was mainly composed of the less protective Fe3+ oxides, which led to a poor anti-corrosion performance of the passive film.

2) Simulation of experiment

Previously, accelerated electrochemical corrosion was applied on specially designed concrete specimen D1; another specimen D2 is designed to have an artificial wedge-shape air gap to simulate delamination in concrete, corrosion is not accelerated on the rebars. Since there are uncontrollable variables in real experiments, simulation of electromagnetic signals in concrete allows the study of different variables that cannot be observed in authentic results. By considering the observation made from experimental results, the rates of section loss and defect development are included to imitate a realistic simulation of the corroding concrete specimens. The simulation results are presented as follows.

Simulation of specimen D1 and D2 were performed to compare with experimental results. Such comparison allows the study of individual effect of defects on rebar reflection amplitude. A well-known simulation software among the GPR community, gprMax, was applied.

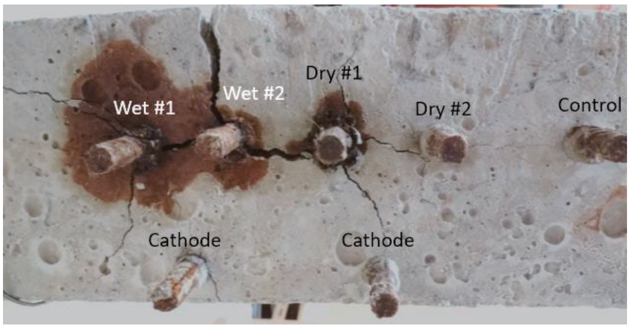

Figure 1: Extent of deterioration of specimen D1 at the end of the experiment.

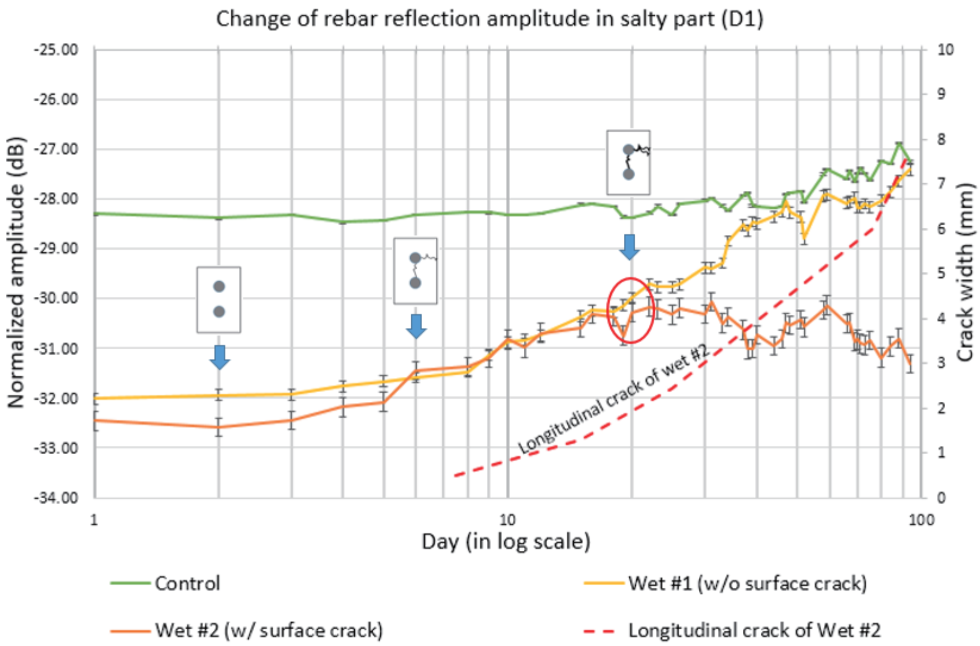

Figure 2: Experimental results of specimen D1.

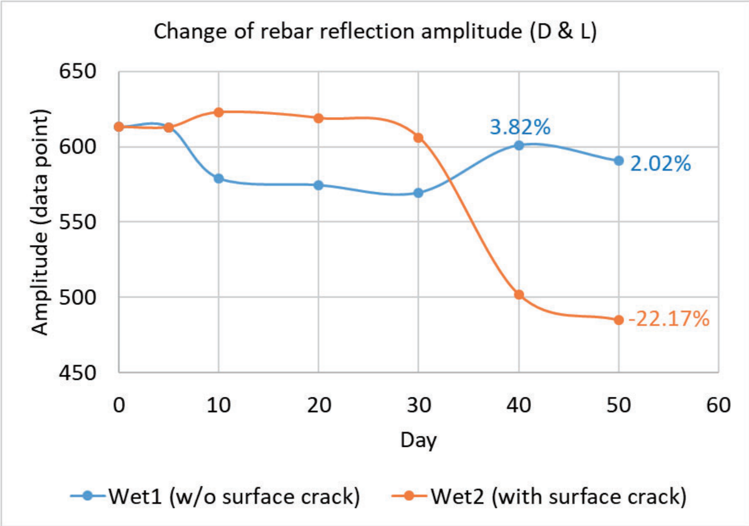

Figure 3: Simulation results of specimen D1.

Figure 4: Design of specimen D2. An artificial air gap in wedge shape is situated between rebar #2 and #3.

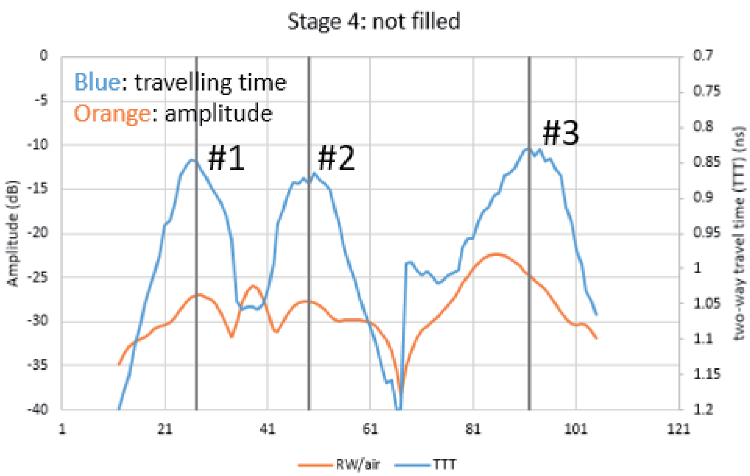

Figure 5: Experimental results of specimen D2. The rebar reflection amplitude of rebar #3 is significantly higher than the other 2 rebars.

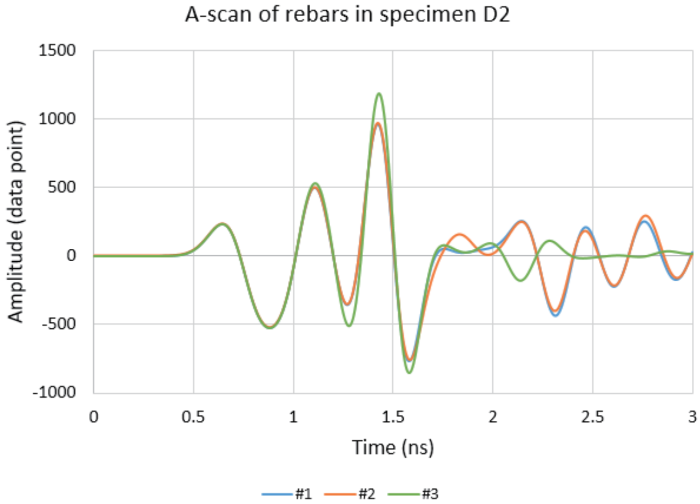

Figure 6: Simulation results of specimen D2. The results are compatible with experimental results.

The 2 sets of simulation results show that the presence of overhead surface crack has significant effect on decreasing the rebar reflection amplitude; in contrast, delamination leads to an increase in amplitude. In comparison, the scale of increase is less significant in simulation results; internal cracks at other angles may have contributed to the increase as well. Therefore, the degree of increase in experimental results is greater.

In general, the simulation results and experimental results are compatible with each other.

Research output:

[1] Zhu W, François R, Poon C S, et al. Influences of corrosion degree and corrosion morphology on the ductility of steel reinforcement[J]. Construction and Building Materials, 2017, 148: 297-306. **(Published)**

[2] 2)H. Zheng, J. G. Dai, C. S. Poon, W. Li. Influence of calcium ion in concrete pore solution on the passivation of galvanized steel bars[J]. Cement & Concrete Research, 2018, 108C: 46-58. **(Published)**

[3] Zhu W, Dai J G, Poon C S. Prediction of the bond strength between non-uniformly corroded steel reinforcement and deteriorated concrete[J]. Construction and Building Materials, 2018, 187: 1267-1276. **(Published)**

[4] H. Zheng, J. G. Dai, W. Li, C. S. Poon. Influence of chloride ion on depassivation of passive film on galvanized steel bars in concrete pore solution[J]. Construction & Building Materials, 2018, 166: 572-58 **(Published)**

[5] Wong P.T.W., Poon C.S., Lai W.L.W. Laboratory validation of corrosion-induced delamination in concrete by ground penetrating radar. Presented in the 17th International Conference on Ground Penetrating Radar, Rapperswil, Switzerland, 2018. **(Conference paper)**

[6] H. Zheng, C. S. Poon, et al. Influence of Nano silica on the corrosion behavior of steel bars in concrete. Sixth International Symposium on Nanotechnology in Construction. Hong Kong, 2018. **(Conference paper)**

[7] Wong P.T.W., Lai W.L.W., Sham F.C.J., et al. Establishment of a Health Model of Corrosion in Concrete via Ground Penetrating Radar (GPR) Imaging. Submitted to Construction and Building Materials (**Under revision**).

[8] 9) Y. Cai, H. Zheng, X. Hu, J. Lu, C. S. Poon. Comparative study on the passivation and depassivation of three types of steel bars in simulated concrete pore solution. Corrosion Science. **(Under review)**

[9] H. Zheng, J. G. Dai, C. S. Poon. Dynamic Passivation Process of Galvanized Steel bars in Cement Mortars Prepared with Nano-silica[J], Cement & Concrete Research. **(Under review)**

[10] Wong P.T.W., Lai W.L.W., Poon C.S. An experimental study on the dielectric property and microscopic examination of minor corrosion in steel and their effect on reflected GPR signals in corroding concrete. **(To be submitted)**

[11] H. Zheng, J. G. Dai, C. S. Poon. Dynamic Passivation Process of Galvanized Steel bars in Cement Mortars Prepared with fly ash [J], Construction & Building Materials. **(Drafting)**

[12] X. Hu, C. S. Poon et al. Studies on polarization and corrosion process of steel in simulated pore solution of cement paste[J]. ASCE. **(Preparing)**

[13] X. Hu, C. S. Poon et al. Relationship between chloride-related corrosion and chloride binding of cement-based materials[J]. Cement and concrete research. **(Preparing)**