Sixth International Conference on Durability of Concrete Structures **Paper Number MID08**
18 - 20 July 2018
University of Leeds, Leeds, West Yorkshire, LS2 9JT, United Kingdom

Experimental Investigation on the ICCP-SS Technique for Sea-sand RC Beams

H-S. Liang, J-H. Zhu, F. Xing, Z-W. Zeng
Faculty of Engineering, Shenzhen University, Shenzhen, China

M-N. Su
School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, UK

T. Ueda and L-L. Wei
Laboratory of Engineering for Maintenance System, Faculty of Engineering,
Hokkaido University, Sapporo, Japan

ABSTRACT

Impressed current cathodic protection (ICCP) is an efficient method to prevent further corrosion of the re-bars, while strengthening structures (SS) by using carbon fibre mesh can help improve the loading capacity of the degraded sea-sand reinforced concrete (RC) structures. This study proposes a new dual-functional method, ICCP-SS, to retrofit the sea-sand RC structures by using the carbon - fibre reinforced cementitious matrix (C-FRCM). The C-FRCM composite, comprised of carbon fibre mesh and inorganic cementitious material, is both the anodic material in the ICCP process as well as the structural strengthening material. This paper presents an experimental program consisting of 11 simply supported beams, 10 of them casted by simulated sea-sand and subjected to accelerated corrosion process for 130 days. The specimens casted by sea-sand were afterwards bonded with C-FRCM composite, treated by ICCP for 130 days, and finally tested. In this study, the flexure strength of the beams, the deflection and curvature of the specimens, as well as the strain and the open circuit potential of re-bars are obtained and used to assess the performance of the repaired specimens In addition, this paper also compares the experimental results with the capacity predictions set out in the American Concrete Institute's guideline ACI 440.2R-08 for FRP strengthening system. The proposed technique has been shown to be effective in retarding the corrosion of re-bars and recovering the loading capacity of the corroded specimens, which should be beneficial for the durability of sea-sand RC structures.

Keywords: C-FRCM; impressed current cathodic protection (ICCP); reinforced concrete; sea sand; simply supported beams; structural strengthening

1.0 INTRODUCTION

The use of reinforced concrete (RC) dates back over a century. RC structures are widely popular in the construction industry. However, the huge demand of concrete is resulting in the resource shortages, such as fresh water and river sand. Nowadays, sea sand has to be used to replace river sand in many countries. However, sea sand normally contains high percentage of chlorides, which could be up to 2% (i.e. the known Cl^- concentration in sea water) (Dias *et al.*, 2008). In order to avoid the corrosion of steel re-bars caused by sea-sand, it should be thoroughly washed before being used. ACI 201-2001 (2001) gives limitations of 0.06% and 0.08% (by mass of cement, similarly hereinafter) for reinforced concrete in moist environments with and without exposure to external chlorides, respectively. BS EN 206-1:2000 (2000) specifies the limits of 0.1% and 0.4% in concrete containing pre-stressing steel reinforcement and steel reinforcement or other embedded metal, respectively. In China, the figures are limited to 0.06% and 0.10% for sea sand concrete in moist environments with and without exposure to external chlorides, respectively (JCJ 206, 2010). However, it is not easy to guarantee the chloride contents in the sea-sand, and if the target chloride content is satisfied, sea sand concrete might cause the corrosion of re-bars and the degradation of RC structures. What is worse, washing sea sand will cost a great amount of fresh water, electricity and human resources.

Impressed current cathodic protection (ICCP) is a technique for reducing the corrosion of metals. It has been used to protect the re-bars in structures that use RC since the 1970s (Koleva *et al.*, 2009). In the process of cathodic protection, an impressed current is applied to the steel reinforcement in order to charge the steel negatively. As a result of the cathodic polarization, the steel becomes cathode and corrosion is impossible (Christodoulou *et al.*, 2010). Many studies have investigated the effects of ICCP systems on steel protection. These studies have focused on interrupted ICCP (Broomfield and Tinnea, 1993), criteria and important parameters of ICCP (Pedeferri, 1996), RC structures in a marine environment (Presuel-Moreno, 2005), and persistent protective effects of field structures (Christodoulou *et al.*, 2010). The sound effect of ICCP technique has been proven in the literature.

A widely-used method of strengthening a degraded RC structure is to externally bond it with strengthening materials such as steel plates, or FRP (fibre reinforced polymer) plates/sheet/meshes. Comprehensive experimental (Bonacci and Maalej, 2000, 2001; Teng *et al.*, 2003; Toutanji *et al.*, 2006) and numerical investigations (Ascione and Feo, 2000; Chen *et al.*, 2015; Teng, 2016) have been conducted in past decades to investigate the optimum design method, the practical construction procedure, and the key factors of the strengthening method using bonded FRP. To date, the development of FRP strengthening technique and design methods for RC structures are rather mature.

On one hand, using the ICCP system can efficiently impede the ongoing corrosion of re-bars in sea-sand RC structures, but it cannot recover the strength loss due to the corrosion at an early stage. On the other hand, externally bonded FRP is a widely used retrofitting method to improve the loading capacity of degraded RC structures, but it cannot impede the further corrosion of re-bars. Therefore, this study proposed a novel retrofitting method by taking advantage of the both techniques, termed as ICCP-SS (impressed current cathodic protection – structural strengthening) method. In this new retrofitting method, a dual-functional carbon-fiber reinforced cementitious matrix (C-FRCM) was used as both the anode in the ICCP system and the strengthening material in the SS system (Zhu *et al.*, 2017). The C-FRCM was comprised of carbon fabric mesh and inorganic cement-based cementitious adhesive material (see Fig. 1). Though there are numerous studies on both the ICCP and SS techniques, the ICCP-SS technique is relatively new, and only limited investigations are found in literature (Zhu *et al.*, in press). The effects of ICCP on the C-FRCM and the bonding behaviour, which might cause a negative effect on the SS system, need further careful investigation.

This paper presents an experimental program on simulated sea-sand simply supported beams, which experienced 130-day accelerated corrosion process and 130-day cathodic protection. To measure the diverse corrosive effects, a total of 11 concrete specimens were cast, 9 of them with an amount of NaCl to simulate the sea-sand concrete. Test results were recorded and compared to assess the effects of the ICCP system, the SS system and the ICCP-SS system on the corroded specimens.

Fig. 1. Carbon-fibric reinforced cementitious matrix (C-FRCM) manufactured in the laboratory

2.0 TEST PREPARATION

An experimental program that included testing on 11 large-scale simulated sea-sand reinforced concrete beams was conducted in the structural laboratory of Shenzhen University.

2.1 Specimens

In order to investigate effect of the impressed current cathodic protection - structural strengthening (ICCP-SS) technique, the control specimens were designed to be repaired by ICCP, SS or ICCP-SS techniques. All the control specimens experienced an accelerated process before bonding the C-FRCM composite onto the soffit. Afterwards, different constant currents are applied to the specimens which are designed to be repaired by ICCP and ICCP-SS techniques, whereas it is not needed for specimens repaired by SS technique. For ICCP specimens, the C-FRCM composite is removed after the ICCP treatment before testing.

Following the abovementioned process, eleven test specimens were divided into five groups: (1) two specimens without NaCl (i.e. reference specimens); (2) one specimen contained NaCl without any treatment (i.e. reference specimen); (3) one specimen contained NaCl and was repaired by SS technique; (4) four specimens contained NaCl and were repaired by ICCP technique; (5) three specimens contained NaCl and were repaired by ICCP-SS technique. The mass of NaCl was 3% of the cement, and was contained in the mix of concrete. After the curing period, the specimens were exposed to accelerated corrosion, followed by the ICCP. The labelling system used for the specimens is given in Table 1. If a test is repeated, a letter “R” is added in the label of the specimen.

The average compressive strength of the concrete cubes in 150 mm that were tested was found to be 53 MPa (Grade C40). The diameter of re-bars used in the specimens was 10-mm. The material properties of re-bars, carbon fibre mesh, cementitious material, and C-FRCM composite were

Table 1. List of beam specimens

Specimens	NaCl (by mass of cement, %)	Repaired method	
		SS (layer of carbon meshes)	ICCP (mA/m^2)
SB	0	0	0
SB-R	0	0	0
SB-C	3	0	0
SB-C-F1	3	1	0
SB-C-IS	3	0	26
SB-C-IS-R	3	0	26
SB-C-IL	3	0	80
SB-C-IL-R	3	0	80
SB-C-F1-IS	3	1	26
SB-C-F1-IS-R	3	1	26
SB-C-F1-IL	3	1	80

obtained through tests according to the ASTM E8/E8M (2016), the ASTM D4018 (1999), the BS EN 196-1(2005), and AC434 (2016).

2.2 Accelerated corrosion procedure

An accelerated corrosion technique was adopted to induce corrosion damage in the test specimens within a reasonable time period. An amount of salt about 3% by the mass of cement was added to the concrete mixture to simulate the sea-sand concrete. This amount of chloride, which was greater than any chloride threshold value for corrosion onset reported in the literature (Ascione and Feo, 2000), de-passivated the re-bars and induced corrosion. No salt was included in the concrete mixture that was used to produce the control specimens. After the concrete had set, the specimens were placed in an open air space and were subjected to two wet–dry cycles per week (2.5 days wet followed by 1 day dry) continuing 130 days (Fig. 2).

2.3 Installation of C-FRCM to the soffit of RC beams

The C-FRCM composite was installed on the soffit of corroded RC beams after accelerated corrosion period. Firstly, the weak segment at the soffit surface of beams was polished away to make the harder coarse aggregate exposure so that it kept a good bond performance between strengthening material and substrate concrete. The treated soffit of beams should be kept saturated dry condition before bonding the C-FRCM. The first layer of cementitious matrix with a nominal thickness of 5 mm was applied

Fig. 2. Specimens under accelerated corrosion process in the open air space

on the treated soffit surface of the beam. Then, the pre-cut carbon fabric mesh was laid on the first layer of cementitious matrix and was impregnated into the matrix slightly, as shown in Fig. 3. Finally, the second layer of cementitious matrix with the samethickness of 5 mm was applied to cover the carbon fabric mesh. The nominal thickness of C-FRCM installed as above processing was around 10 mm. The bond sizes were the same with beam specimen at 100 mm in width and 1300 mm in length.

2.4 ICCP treatment

The ICCP treatment was performed after installing the C-FRCM composites and curing for 28 days. The re-bar was connected to the negative terminal and

Fig.3. Installation of C-FRCM to the soffit of RC beams

the carbon fabric mesh anode embedded into the C-FRCM to the positive terminal of a multi-channel DC power supply in order to apply protective current to the corroded steel re-bars. The ICCP system was operated in a laboratory for 130 days. The applied current densities were 26 mA/m^2 (small current density) and 80 mA/m^2 (large current density) of the re-bars' surface area. The currents were checked and the open circuit potential values of the embedded steel were recorded daily.

The test specimens were monitored for corrosion activity with internal reference electrode (RE) and external instrumentation. Before the concrete was cast, a RE was placed in the mid-span of each beam during assembly of the steel cage. The embedded REs were calomel RE saturated by KCl solution, placed vertically on the upper side of the mid-span of the beams. The saturated KCl solution was kept inside the probe by a rubber cap. The measurements were conducted in light of the requirements of ASTM C876-09 (2009).

3.0 BENDING TESTS

A four-point loading system with a hydraulic jack was used to test the specimens (Fig. 4). The loading capacity was recorded by a load cell placed between the hydraulic jack and spreader beam. Deflection at the midspan of specimen was measured by the LVDT. The loading speed was under displacement control at a loading rate of 0.5 mm/min. A computer-based data acquisition system recorded the data at a frequency of 1Hz that were obtained.

4.0 RESULTS

4.1 Results on the ICCP performance

During the 130-day operation of the ICCP, the open circuit potential values of the re-bars of seven specimens were recorded. In accordance with the recommendations of ASTM C876 (2009) if the open circuit potential value is greater than -126 mV, it demonstrates that the embedded steel has only 10% chance of being corroded; if the open circuit potential value is less than -275 mV, it demonstrates that the embedded steel has 90% chance being corroded; if the open circuit potential value is between these two values, it means the status of the re-bars is uncertain. The potential of the re-bars in the reference beam without NaCl (specimen SB) is above the -126 mV level during the whole monitoring period. The specimens with NaCl were generally below the line of -275 mV. When the ICCP starts to operate, the potential increases and gets closer to the margin of -126 mV as the time goes by. As for the specimens that contained NaCl but hadn't been protected by ICCP, they stayed around the line of -275 mV. If greater current densities had been applied to the specimens, the protection effects may be more obvious. However, it should be noted that too great a current density would also result in the premature deterioration of the bond interface. In some investigations (Lambert *et al.*, 2015), higher applied current densities were adopted; from 125 to 200 mA/m^2 of steel surface area. The electrochemical parameters measured in this study also indicated that the embedded steel has been successfully protected. However, an amount of gaseous yellow liquid appeared on the surface of the CFRP fabric anode after 474 hours of ICCP treatment, which may cause the separation of the CFRP anode from the concrete interface (Lambert *et al.*, 2015). Therefore, smaller values of applied current densities (26 and 80 mA/m^2) were chosen in this study.

Fig. 4. Four-point bending test set-up

Table 2. Summary of test results

Specimens	Ultimate loads (kN)	Deflection (mm)	Decrease in strength compared to control beams (SB and SB-R) (average load = 54.5 kN)	Increase in strength compared to corroded beam (SB-C) (load = 42 kN)
SB	56	10.7	---	33.3%
SB-R	53	15.4	---	26.2%
SB-C	37	11.6	-22.9%	---
SB-C-F1	49	19.3	-10.1%	16.7%
SB-C-IS	47	22.4	-13.8%	11.9%
SB-C-IS-R	51	21.8	-10.1%	16.7%
SB-C-IL	47	18.2	-13.8%	11.9%
SB-C-IL-R	49	13.2	-10.1%	16.7%
SB-C-F1-IS	46	24.4	-8.3%	19.1%
SB-C-F1-IS-R	46	12.6	-8.3%	19.1%
SB-C-F1-IL	51	21.3	-2.8%	26.2%

4.2 Results on the bending tests

The results of loading capacity evaluation in bending test are shown in Table 2. For the reference beams (SB and SB-R), the loading capacities are 56 kN and 53 kN (average load = 54.5 kN). For the corroded specimen without ICCP (SB-C), the load capacity is 37 kN, which is 32.1% lower than the average load capacity of the reference beams. This might be attributed to the reduction in the effective area of re-bars. The ultimate capacity of the beam strengthened with carbon fabric mesh without ICCP (SB-C-F1) is 49 kN, which is 32.4% higher than the average ultimate capacity of the unstrengthened beam (SB-C). This demonstrates that bonded carbon fabric mesh can effectively improve the flexural capacity of corroded beams. However, it is still lower than the flexural capacity of the reference beams (SB and SB-R), possibly due to the insufficient strengthening material.

A total of 4 beams were protected by only ICCP after accelerated corrosion. The flexural capacities of these beams were found to be 47 kN, 51 kN, 47 kN and 49 kN for SB-C-IS, SB-C-IS-R, SB-C-IL, and SB-C-IL-R, respectively, which are 27.1%-37.8% higher than the unstrengthened beam (SB-C), but 6.4% - 13.8% lower than the reference beams (SB and SB-R). On the one hand, this demonstrates that the operation of ICCP technique can effectively impede the further corrosion of re-bars, so that the specimens repaired by ICCP have higher loading capacities than the specimens without the operation of ICCP due to the differences in effective cross-section of re-bars and bonding performance. On the other hand, it shows that ICCP treatment cannot help to recover the loading capacities due to the existed corrosion of re-bars.

The ultimate capacity of the beams retrofitted by ICCP-SS method (SB-C-F1-IS, SB-C-F1-IS-R and SB-C-F1-IL) were found to be 46 kN, 46 kN, and 51 kN, respectively. The increase in loading capacity compared to the unstrengthened beam (SB-C) is up to 37.8%. The flexural resistance of specimen SB-C-F1-IL has been recovered to the reference beam specimen SB-R. In comparison with the simulated sea-sand beams repaired by only SS, it is found that the ICCP-SS technique slightly showed its superior advantage (with up to 5.4% increase regarding to the flexural capacity). The reason for this is because the ICCP-SS technique impedes further corrosion of re-bars, and also recovers the strength loss of the corroded specimens; while for the specimens repaired by SS technique, corrosion of re-bars still continues.

It can be found from comparison with beams repaired by only ICCP or SS that the ICCP-SS technique has shown advantage. The ICCP technique can help deter the further corrosion of re-bars, but ICCP cannot help recovering the strength loss of the beams, while the SS technique can help recover strength loss, but the corrosion of re-bars will continue as time goes by. However, the effect of small and large current densities is not clear on the specimens. More importantly, the beams repaired by ICCP-SS technique showed similar loading capacities as the uncorroded beams. The test results proved the effectiveness of the ICCP-SS technique. However, it is found that the differences between the specimens repaired by ICCP, SS and ICCP-SS techniques are not sufficiently distinct. The reasons might be largely related to a short ICCP operation period and an insufficient account of carbon fabric mesh. On the one hand, both the accelerated corrosion procedure and the ICCP procedure are only operated for 130 days, which are rather short compared to the usual accelerated exposure test. The ICCP-SS technique is a retrofitting method to ensure the durability performance of RC structures, therefore its superiority will become more evident over a longer time period. In the next series of tests, this issue will be fully considered to improve the experimental design.

All beams were tested to failure and the failure modes were monitored. The typical failure modes of the tested beams are shown in Fig. 5. During testing, the first major crack occurs in the constant moment region, followed by some minor shear cracks as the load increases. All the tested beams had the re-bars yielding, and finally failed when the cementitious material in the mid-span region fractured and the compression concrete crushed. No delamination between C-FRCM composite and concrete was observed.

Fig. 5. Failure mode of tested beams

4.3 Results comparison with ACI440(2008)

In this section, we compare the ultimate bending capacities obtained from the testing (M_{exp}) — the observed material properties and geometries — with the nominal flexural design strengths given in ACI 440.2R-08 (M_{ACI}) (see Fig. 6). The calculation of the bending moment capacity is the combination of the flexural strength provided by the steel re-bars and bonded carbon fibre mesh. In order to obtain the nominal capacities, all the properties of materials and geometric information were obtained from tests and measurement, and all safety factors were set to be unity. Please be noted that the material properties were obtained in the un-corroded condition.

In the present study, both the ACI prediction and the experiments show that all the strengthened specimens failed by concrete crushing. The values given in ACI 440.2R-08 are generally approximately 10% less than the experimental resistance of the simply supported beams (mean M_{exp}/M_{ACI} = 1.12), with a small coefficient of variation (COV) equal to 0.085. From the comparison shown in Fig.6, all the specimens except for the reference specimens show the less ratio of tested strength to predicted strength than that of the reference specimen. The less ratio of the reference specimen (SB-C) could be partly due to the degraded material properties subjected to corrosion. We need to develop the prediction method for SS and ICCP repair with better accuracy.

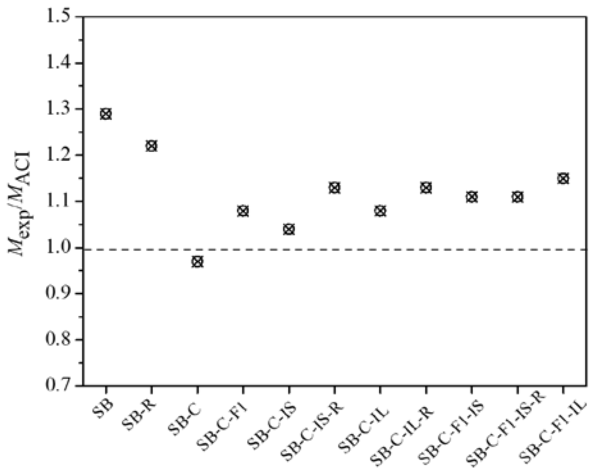

Fig. 6. Comparison between experimental results and the predictions by ACI 440

5.0 CONCLUSIONS

This study has investigated a dual-functional retrofitting method for sea-sand reinforced concrete beams. This method combines the merits of impressed current cathodic protection (ICCP) and structural strengthening (SS) techniques. The carbon fibre mesh that is used in the ICCP-SS retrofitting method is both the anode in the ICCP system and the strengthening material in the SS system. This paper presents the experimental program and discusses on the test results. The experimental program includes an accelerated corrosion procedure, the ICCP period, and the bending tests. From the test results, it is found that the carbon fibre mesh and the cementitious adhesive material is capable of being exposed to high current densities up to 80 mA/m2 without mechanical bonding. The C-FRCM composite can be used to strengthen sea-sand RC beams, maintaining the structural integrity and increasing the ultimate strength of damaged beams. The impact of the applied currents is not yet distinct from the experimental findings. The ICCP-SS technique works effectively, but its superior merit has not been fully explored in this study; this might be largely attributed to the insufficient corrosion level and the limited ICCP period. This paper also compares the experimental results with the capacity predictions set out in the American Concrete Institute's guideline ACI 440.2R-08 for FRP strengthening system. In future, more efforts are needed to optimize the applied current density and the amount of strengthening material. Longer operation periods for the corrosion and ICCP procedures, as well as the effects of different current densities in ICCP should be considered to determine the durability performance of sea-sand RC structures.

Acknowledgement

The research work described in this paper was supported by the National Natural Science Foundation China (Project No.: 51508336, 51538007, 51478269).

References

ACI 201.2R-01. Guide to Durable Concrete. American Concrete Institute 38800 Country Club Drive Farmington Hills, MI 48331, U.S.A.2001.

ACI 440.2R. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. American Concrete Institute 38800 Country Club Drive Farmington Hills, MI 48331, U.S.A.2008.

ASTM E8/E8M. Standard test methods for tension testing of metallic materials. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.2016.

ASTM C876. Standard test method for corrosion potential of uncoated reinforcing steel in concrete. West Conshohocken, PA 19428-2959, United States.2009.

ASTM D4018. Standard test methods for properties of continuous filament carbon and graphite fiber tows. ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, United States.1999.

Ascione L, Feo L. Modeling of composite/concrete interface of RC beams strengthened with composite laminates. Composites Part B: Engineering. 2000;31(6):535-40.

Bonacci JF, Maalej M. Externally bonded fiber-reinforced polymer for rehabilitation of corrosion damaged concrete beams. Structural Journal. 2000;97(5):703-11.

Bonacci J, Maalej M. Behavioral trends of RC beams strengthened with externally bonded FRP. Journal of Composites for Construction. 2001;5(2):102-13.

Broomfield JP, Tinnea JS. Cathodic protection of reinforced concrete bridge components. 1993.

BS EN 206-1:2000. Concrete — Part 1: Specification, performance, production and conformity. 2000

BS EN 196-1. Methods of testing cement-Part 1: Determination of strength. 2005.

Chen G, Teng J, Chen J, Xiao Q. 2015, Finite element modeling of debonding failures in FRP-strengthened RC beams: A dynamic approach. Computers & Structures,158:167-83.

Christodoulou C, Glass G, Webb J, Austin S, Goodier C. Assessing the long term benefits of Impressed Current Cathodic Protection. Corrosion Science. 2010;52(8):2671-9.

Dias W, Seneviratne G, Nanayakkara S. Offshore sand for reinforced concrete. Construction and Building Materials. 2008;22(7):1377-84.

International Code Council (ICC), 2016. Masonry and Concrete Strengthening Using Fabric-reinforced Cementitious Matrix (FRCM) and Steel Reinforced Grout (SRG) Composite Systems, AC434.

JGJ 206-2010. Technical Code for Application of Sea Sand Concrete. China, 2010.

Koleva D, Guo Z, Van Breugel K, De Wit J. Conventional and pulse cathodic protection of reinforced concrete: electrochemical behavior of the steel reinforcement after corrosion and protection. Materials and corrosion. 2009;60(5):344-54.

Lambert P, Van Nguyen C, Mangat PS, O'Flaherty FJ, Jones G. Dual function carbon fibre fabric strengthening and impressed current cathodic protection (ICCP) anode for reinforced concrete structures. Materials and structures. 2015;48(7):2157-67.

Pedeferri P. Cathodic protection and cathodic prevention. Construction and Building Materials. 1996;10(5):391-402.

Presuel-Moreno F, Sagues A, Kranc S. Steel activation in concrete following interruption of long-term cathodic polarization. Corrosion. 2005;61(5):428-36.

Teng J, Smith ST, Yao J, Chen JF. Intermediate crack-induced debonding in RC beams and slabs. Construction and building materials. 2003;17(6):447-62.

Teng JG, Zhang SS, Chen J. Strength model for end cover separation failure in RC beams strengthened with near-surface mounted (NSM) FRP strips. Engineering Structures. 2016;110:222-32.

Toutanji H, Zhao L, Zhang Y. Flexural behavior of reinforced concrete beams externally strengthened with CFRP sheets bonded with an inorganic matrix. Engineering Structures. 2006;28(4):557-66.

Zhu, J. H., Wei, L., Moahmoud, H., Redaelli, E., Bertolini, L. (2017). "Investigation on CFRP as dual-functional material in chloride-contaminated solutions." Construction and Building Materials, 151, 127-137.

Zhu,J.H., Su, M.N., Huang, Ueda, T., Xing, F., (2018), The ICCP-SS Technique for Retrofitting Reinforced Concrete Compressive Members subjected to Corrosion. Constructional & Building Materials, 167: 669-679..