An overview of corrosion protection provided by carbon fibre reinforced polymer bonded on reinforced concrete

AN OVERVIEW OF CORROSION PROTECTION PROVIDED BY CARBON FIBRE REINFORCED POLYMER BONDED ON REINFORCED CONCRETE

A Wei[1], R Al-Ameri[1], M Tan[1] & Y.C. Koay[2]
[1]School of Engineering, Deakin University, Geelong, Australia,
[2]VicRoads Asset Services (Structures), Melbourne, Australia

SUMMARY: Reinforced concrete (RC) has been widely used in the construction for many years because of its stability, economy, and resiliently in extreme conditions. However, steel corrosion is regarded as one of the most important issues affecting the durability and stiffness/strength of RC structures. Carbon fibre reinforced polymer (CFRP) has been used as repairing and strengthening method via bonding onto RC. CFRP is now widely used due to its high corrosion resistance, high mechanical strength and ease of application on site. Meanwhile, CFRP has also been investigated recently as an anode material in the impressed current cathodic protection (ICCP) system due to its electrically conductive properties.

This paper presents an overview of steel corrosion affected by parameters of CFRP bonded on RC surface and the ICCP system using CFRP as anode. Different parameters such as epoxy types, CFRP layers, exposed environment and corrosion measurements are discussed and evaluated. The possibility of CFRP using as the dual function of both anode material in ICCP system and strengthening material on RC against corrosion is examined.

The current results indicate that CFRP has advantages of strengthening RC structures suffering from corrosion and improving corrosion resistivity. However, limited literature could be found with regard to steel corrosion investigation of RC structures with bonded CFRP under sustained loading. Further working on steel corrosion affected by CFRP simulated in the actual RC structures are expected and will be studied in a PhD project using electrochemical methods such as: Half-cell potential, Linear polarised resistance (LPR), and electrochemical impedance spectroscopy (EIS). The ICCP system using CFRP as the anode material is also investigated using simulations of a marine environment subject to wet-dry cycle, sustained loading, and high temperatures.

Keywords: Steel corrosion, Carbon fibre reinforced polymers, Reinforced concrete, Impressed current cathodic protection.

1. INTRODUCTION

Reinforced concrete (RC) has been widely used in the construction field because of its stability, economy, and resilience in extreme conditions [1, 2]. As concrete has high compressive strength but low tensile strength, steel bars are embedded in concrete so as to improve the tensile capacity of RC structures. However, corrosion of steel bars is regarded as one of the most important issue for the durability of the structures, especially for bridges and buildings [3, 4]. The features of failures induced by corrosion in RC structures are usually considered as the reduction of the cross section in steel bars, the decrease of bonding between steel bars and concrete, the degradation of steel properties and concrete cover cracking and ultimately spalling [5]. In order to prevent structures failure and destruction induced by steel corrosion, a huge cost of repairing and maintenance is spent worldwide [6]. Therefore, corrosion of steel bars should be understood and managed for the durability of RC structures.

Methods of corrosion repair and prevention have been used to delay and increase corrosion resistance in the RC. A typical technique for repairing is concrete patching and enlarge the cross section to improve the strength, in which deteriorated concrete is removed corroded steel bars cleaned and areas reinstated with more steel bars and patching mortar. However, this method may add further dead load to the structure that was not initially designed and lead to the structures being in the unsafe state when adding more steel bars and concrete on the existing structures [7]. Additionally, corrosion rate could be increased after concrete patching due to the electrochemical reaction between the newly repaired areas and surrounding areas. Surface coatings are another preventive method in creating a barrier to stop corrosion activity by restricting moisture, oxygen and chloride contamination, an example of such coatings is epoxy-coated reinforcement and galvanised reinforcement [8]. However, the coating of steel bars is costly, and the protection will be reduced when the epoxy layer is damaged during the process of transport or installation. . Corrosion inhibitors added to RC can also slow or prevent chloride ion diffusion and increase corrosion resistance [9]. Additionally, adequate cover of RC surface is another pathway in the long-term durability protection from steel corrosion.

An innovative technique to the traditional repair method is the application of carbon fibre reinforced polymers (CFRP), as seen in Figure 1. CFRP has been applied in RC structures for strengthening and also has advantages in terms of high chemical resistance, minimal impact of structures, high strength to weight ratio, high tensile strength [1, 10] and convenient installation [11, 12]. CFRP has been used for shear, flexural or axial loading enhancement in columns, slabs and walls for many types of structures. Strengthening, bonding between CFRP and concrete, stiffness, and ductility, mechanical and electrical performance for CFRP on RC structures has been studied by others [13]. Heffernan and Erki [14] and Bonfiglioli et al. [15] investigated the fatigue life of RC beams and indicated that CFRP could enhance the structures through the externally bonding strength. Ye et al. [16] studied the shear strength of RC columns strengthened by CFRP and concluded that shear strength of RC columns was significantly increased with external strengthening. White et al. [17] performed experimental and modelling study in strain rate of RC beams after CFRP strengthening, and the results indicated that CFRP could increase capacity, stiffness and energy absorption by approximately 5% in. Ye et al. [18] indicated that the ductility of RC columns could be substantially improved with CFRP strengthening according to study the seismic performance of RC columns under constant axial load and lateral cyclic load. Therefore, CFRP strengthens the mechanical performance and loading capacities of RC structures.

Figure 1 Structural strengthening using CFRP

(Available at: http://truesdellcorp.com/index.php/northeast-wisconsin-tech-structural-failure-repair)

Due to the property of high resistance, CFRP has also been studied for the delay of aggressive ions diffusion and whether it can decrease corrosion rate in RC structures. Different parameters of fibres such as types, number of layers and application directions have been studied [19, 20]. Corrosion induced by chloride ions is considered as the most destructive mechanism of corrosion in RC structures, as chloride diffusion results in the breakdown of passive layers and then leads to pitting corrosion occurring in the electrochemical reactions [21]. CFRP with epoxy has been successfully proved in improving the strength and stiffness of RC structures exposed to various environment based on limiting the solution absorption in RC structures [22]. Additionally, CFRP is used by asset owners due to its desirable properties for repair strategies due to its corrosion resistance. In recent times, efforts have been made to use CFRP as an anode in an impressed current cathodic protection (ICCP) system. In an ICCP system, a cathodic current is applied to the steel reinforcement, and then the steel potential is shifted towards the lower corrosion rate material [23]. The potential dual function of CFRP to provide both strengthening and to act as the ICCP anode has significant practical benefits for structure repairs.

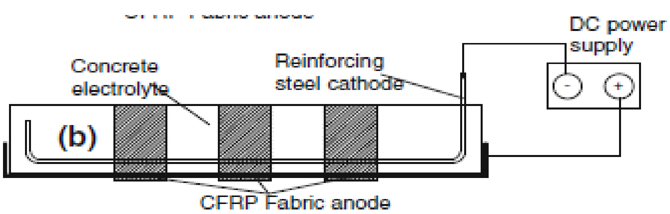

Figure 2 Schematic ICCP application to corroded reinforced concrete beams [24]

On the basis of these perceived benefits, a number of studies were commenced to investigate the use of CFRP as both anode material and strengthening material in ICCP system [25-27]. Literature about steel corrosion behaviour affected by CFRP strengthening on actual RC structures is unclear. Therefore, in order to promote the research of CFRP for dual function, this paper will develop an overview of steel corrosion performance affected by CFRP bonded on RC and the CFRP anode using in the ICCP system.

2. CORROSION OF STEEL REINFORCEMENT EMBEDDED IN CONCRETE STRUCTURES ADHERED BY CFRP

Limited studies have been carried out on the effect of corrosion using external CFRP adhered on RC structures. Studies have begun to investigate corrosion of steel reinforcement embedded in concrete structures with CFRP adhered. Subhani et al. [28] investigated the bond strength using different kinds of epoxy between CFRP and concrete in retrofitted beams in the marine environment. A proposed long-term model in predicting the bond strength during flexural tests was developed in a wet – dry cycle environment. El-Hacha et al. [29] also studied the effect of severe environmental conditions on CFRP wrapped RC columns. Thirty-six plain concrete cylinders (150 x 300mm) were cast and tested, in which nine of them were unstrengthened as the reference and the rest of the cylinders were strengthened by two layers of CFRP. Specimens were exposed to high temperatures (45 °C), or heating–cooling cycles (23 to 45°C). The results indicated that the concrete strength increased by 43% and 74% in unconfined and heating-cooling cycles, respectively using two layers CFRP wrapping. The axial strain performance in confining specimens was improved by up to 4 times. Additionally, corrosion behaviours have been investigated on various parameters, such as CFRP wrapping materials, numbers of layers, exposure environment, bonding behaviour between CFRP and concrete, and corrosion measurement techniques have been compared, as seen in Table 1.

2.1 The functions of CFRP in corrosion of RC

The authors could find very little literature on the CFRP corrosion behaviour in RC structures. Badawi and Soudki [25] studied the effect of CFRP confinement on cracking induced by corrosion in RC beams. Uniform and shear span corrosion was demonstrated at three different degrees of corrosion. In this case, impressed current was applied to accelerate the corrosion process. The results indicated that CFRP could reduce corrosion expansion by up to 70% and slow down the corrosion rate by up to 35% based on the calculation of the corrosion mass loss.

Gadve et al. [30] studied the corrosion rate of reinforcement on corroded cylinders in salt water. Pull out strength, mass loss, half-cell potential of steel bars, and cell voltage were measured. The conclusions indicated that CFRP could delay the corrosion rate and improve corrosion resistance in RC structures.

Zhuang et al. [31] investigated the effectiveness of CFRP against steel corrosion on RC piles. Twelve RC piles strengthened or unstrengthened by CFRP were studied in a simulated tidal marine environment for 6 hours from 25^{o}C to 40^{o}C. The impressed current technique was performed to accelerate the corrosion process. Half-cell potential measurement, steel weight loss and strains of piles were measured at various corrosion degrees. The results illustrated that CFRP could reduce corrosion activity by up to 45% compared to 52% of unstrengthened piles using the half-cell potential measurement, and reduce by 20% the corrosion rate from mass loss test.

Masoud et al. [32] studied the structural behaviour of RC beams strengthened by CFRP in the marine environment under monotonic and fatigue loading. Unstrengthening, wrapping using CFRP and flexural strengthening were investigated. The experimental results indicated that CFRP application on RC was effective in repairing damages and protecting structures against corrosion. Ultimate monotonic strength was increased by about 37% - 87%, and the fatigue of strengthened samples was increased by from 2.5 and 6.0 times compared to the unstrengthened similarly corroded specimens.

In summary, RC specimens in the above literature were generally studied using one layer CFRP for strengthening and exposed to a simulated marine environment where chloride ions can lead to localised corrosion due to passive film destruction. Most of the research studie corrosion behaviour using impressed currents to accelerate corrosion processes for pre-corroded RC specimens. The methods of half-cell potential and mass loss were widely used for corrosion measurement. Chloride ion diffusion and penetration can be slowed and oxygen in the corrosion process can be restricted due to the external CFRP and epoxy [33] acting as a barrier. It can be concluded that CFRP could improve corrosion resistance and reduce the corrosion rate by up to 45% when strengthened on RC structures.

Table 1. Corrosion protection using CFRP adhered on RC structures

Reference	CFRP adhered types	CFRP layers	Pre-corroded	Exposed environment	Long Term Sustained Loading	Duration	Corrosion measurement methods	Key conclusions
Badawi and Soudki [25]	U shape wrap	One	Yes	Salted concrete	NA	145 days	Crack width; Strain; Mass loss	CFRP reduce corrosion rate by 35%.
Gadve et al. [30]	Wrapping cylinders	One	Yes	3.5% NaCl solution;	NA	25 days	Half-cell potential; Pull-out strength test; Mass loss; Cell voltage	CFRP slow down corrosion rate.
Zhuang et al. [31]	Wrapping piles	One	Yes/NA	Marine; Wet-dry cycle; 25-40^{o}C temperature	NA	45 days	Half-cell potential; Mass loss; Strains test	CFRP reduce corrosion rate by 20% - 45%.
Masoud et al. [32]	U-shape on beams	One	Yes	3% NaCl in concrete mixture	NA	44 days	Monotonic and fatigue loading test	CFRP is efficient in reducing steel corrosion.
Wootton et al. [6]	Wrapping cylinders	One to three	Yes	Saltwater	NA	50 days	Mass loss	CFRP increase corrosion resistance.
Debaiky et al. [7]	Wrapping Columns	One/Two	Yes/NA	Total chloride solution	NA	100/200 /300 days	Half-cell potential; LPR (Current density I_{corr}); Crack mapping; Mass loss; Strain/stress test	CFRP significantly decrease corrosion rate.
Suh et al. [34]	Wrapping pre-stressed piles	One to Four	NA	Wet-dry cycle; marine environment	NA	1200 days	Half-cell potential; LPR (Corrosion rate); Mass loss; Bond test	CFRP with epoxy against cracks; slow down corrosion rate.
Soudki et al. [35]	Strips/U shape on beams	One/Four	NA	Wet- dry cycle; 3% NaCl	NA	600 days	Half-cell potential; LPR (Corrosion resistance & Current density I_{corr}); Mass loss; Failure test	CFRP enhance loading capacity by 11 to 28 % and reduce corrosion rate.

2.2 Corrosion affected by different various external factors in RC with CFRP

Different parameters can influence the corrosion process for RC structures with CFRP applied, such as epoxy types, CFRP wrapping layers, exposed environment and sustained loadings. Wootton et al. [6] investigated the corrosion performance of steel bars embedded in concrete cylinders with CFRP external wrapping. An impressed current was applied to accelerate the corrosion process. Measurement of corrosion potentials, impressed current flow levels and mass loss were performed. The results indicated that CFRP could decrease steel mass loss, reduce chloride content of concrete and slow down cracking and spalling. However, the results were different dependant on the various parameters of wrapping fibres orientation and wrap layer numbers. The epoxy type used to bond the CFRP also significantly affects the corrosion resistance in the RC.

Debaiky et al. [7] discussed the corrosion activities at initiation and propagation stages when using CFRP as a wrapped repair material corroded RC columns. CFRP wrapping patterns of one layer or two layers, fully or partially were compared during the experiment. Results were analysed by using the methods of half-cell potential, LPR, crack mapping and the weight loss of steels. The experimental results indicated that CFRP wrapping delayed corrosion occurring before corrosion propagation, and significantly decreased the corrosion rate especially when RC columns were fully covered.

Suh et al. [34] investigated the effectiveness of repairing techniques for corrosion control using CFRP over three years' of experiments under marine environment wet-dry cycle conditions. Two types of prewrapped substrate were prepared: full repair types where the delaminated concrete was removed and reformed, and another type was sealed with epoxy where cracks were performed and then wrapped by CFRP. The experimental results concluded that CFRP with epoxy sealing cracks was effective and the corrosion rate was dramatically decreased even under severe corrosion damage conditions.

The behaviours of CFRP strengthened RC beams in a corrosive environment were examined by Soudki et al. [35]. Eight beams were pre - cracked and then repaired using CFRP and subject to a wet-dry cycle environment. Three uncracked beams were prepared as the reference specimens at room temperature. Two types of fabrics and strips were compared. A failure test and an electrochemical corrosion rate test were practiced. The results indicated that CFRP and resin system could enhance the loading capacity by 11% to 28%, reduce the corrosion rate, and decrease the chloride diffusion. The stiffness and yield load of the RC beams were not significantly impacted when exposed to this harsh environment.

In conclusion, although CFRP could significantly reduce steel corrosion rate and improve corrosion resistance in RC structures, the various external factors in RC with CFRP could also play an important role in affecting corrosion, such as epoxy types, CFRP wrapping layers, exposed environment and sustained loadings. The increasing wrapping layers can increase corrosion resistance from one to two layers, however, three wrapping layers will not significantly effect on corrosion resistance when compared to two layers [6]. The marine environment and associated wet-dry cycle conditions were well studied in the above literature. Corrosion measurement via Half-cell potential, LPR and mass loss were widely used to assess the corrosion process conditions. However, a larger number of specimens are expected to further simulate structures conditions so as to identify the detailed influence results. As the corrosion process is an electrochemical reaction process, it is reasonable to detect the corrosion process of reinforcement in concrete using electrochemical methods.

2.3 Corrosion measurements in RC with external CFRP adhered

In order to determine corrosion rates and patterns in RC structures, non-destructive methods have been necessarily applied in assessing the corrosion conditions without destroying the current service structures. There are no direct methods available for corrosion rate measurement during the whole progress, therefore, the parameters that indirectly measure the corrosion process have to be studied [30]. Electrochemical monitoring methods have advantages of non-destructive and fast testing of RC structures [36]. Therefore, the corrosion process of reinforcement in concrete is generally detected using electrochemical methods as the corrosion process is an electrochemical reaction. Existing monitoring methods for steel corrosion in RC structures have been reviewed in Table 1, which mainly includes the half-cell potential measurement; concrete resistivity measurement; linear polarised resistance (LPR); mass loss, and bond strength test method. Among of these methods, half-cell potential, LPR and mass loss measurements are the predominantly used test methods in these studies. Half – cell potential method is broadly used in RC structures and is standardized by ASTM C876-15 (1999) [37, 38]. LPR method has been successfully evaluated for steel corrosion testing and monitoring in highly – resistive concrete structures [39, 40].

3. CFRP AS ANODE IN IMPRESSED CURRENT CATHODIC PROTECTION SYSTEMS

Some researchers have studied CFRP as the anode in impressed current cathodic protection (ICCP) system in recent times. The dual function of CFRP for both strengthening and an ICCP anode due to the CFRP being electrical conductive [24, 41].

3.1 CFRP sheet applications for ICCP system on RC cylinders

Research has mainly focused on the use of CFRP as an ICCP on simple cylinders with one steel bar as the cathode or a single piece of CFRP in simulated corrosion solutions. Zhu et al. [42] studied the mechanical and electrochemical performance of CFRP in oxygen evolution environment by conducting accelerated polarization. Different amounts of current density were applied under various test durations. The driving voltage, potential and tensile strength testsfair were carried out. The experimental results concluded that CFRP could be used as both an anode in ICCP system and the passive material for strengthening RC structures.

Gadve et al. [41] studied the corrosion protection provided to steel bars embedded in concrete using CFRP adhesively wrapped outside the surface of cylinders. CFRP was used as the conductive anode without using any external anode, while the steel bars were the cathodes in the pre-corroded specimens. External DC power supply was applied to impress the constant current of 50 mA (current density 870 mA/cm^2) between CFRP and the steel bar. The specimens were exposed to the 3.5% NaCl solution at 50^{o}C temperature environment. The specimens were tested for pull-out strength, mass loss, potentiodynamic scans and the half-cell potential of steel. The experimental results indicated that CFRP could be active in protecting steel bars from corrosion for the CP function.

Zhu et al. [43] studied the deterioration of RC with CFRP anode after polarization. The steel bars were accelerated corrosion at first, and then the polarization test was performed between the anode of CFRP and the cathode of steel bar. Conductive carbon paste and carbon fibre reinforced mortar were used to connect between CFRP and concrete. The current density of 1244 mA/m^2 and 2488 mA/m^2 was applied for 25 days. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) techniques were used to study the deterioration mechanism on the CFRP interface with concrete. The feeding voltage was applied during the polarization period. The experimental results illustrated the deterioration of the interface between the CFRP and the contact material may occur due to the chemical changes.

Electrical and mechanical behaviour testing of CFRP were carried out by Zhu et al. [13] in a different solution environments. Behaviour of CFRP as an anode in the ICCP system was investigated in RC structures. The results indicated that the corrosion potential was acceptable according to the "instant off" potential tests and met requirements [44]. The mechanical and electrical performance of CFRP was not adversely affected with a current density up to 2 A/m^2.

CFRP has been also applied as a novel external anode to study the electrochemical chloride extraction in RC specimens by Zhu et al. [45]. Three different specimens with a water-cement (w/c) ratio of 0.32, 0.4, and 0.5 and three different constant current densities of 1, 2, and 3 A/m^2 were applied. The results concluded that the bond loss decreased when the current density increased and with lower of w/c ratio's. There was no significant degradation of CFRP anode during the treatment system.

The literature above mainly studies the CFRP as anode using very simple cylinders with one steel bar. The possibility of CFRP used as the active anode in ICCP systems was investigated. Different impressed current densities from the power source and different concrete properties have been investigated. Up to 2488mA/m^2 could be applied in the ICCP system. However, real RC structures should be further studied with CFRP stirrups connected with the longitudinal steel bars for ICCP system.

3.2 CFRP applications on RC in ICCP system

Traditional CP and CFRP anode for ICCP have been compared by Lambert et al. [24]. The dual function of CFRP for both strengthening and acting as the ICCP anode in RC structures have been discussed. U-shaped wrapping of CFRP was applied and strips on the tensile side of RC beams were extended. Different current densities impressed for ICCP and potential decays were measured. Meanwhile, load-deflection was tested and the relationship of load-deflection was developed. The experimental results illustrated that CFRP could increase the stiffness and reduce the ultimate deflection of beams. U-shape wrapping of CFRP was 13.5% larger than the without U-shape wrapping. The current density could be applied up to 128 mA/m^2 for ICCP, and CFRP was suitable for the dual function of strengthening and ICCP in RC structures.

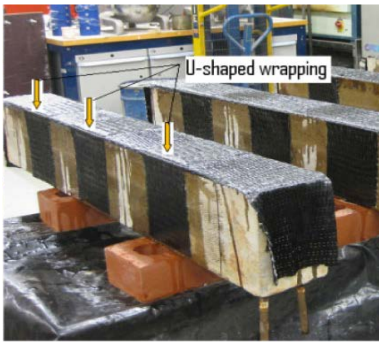

Figure 3 Schematic ICCP application to corroded reinforced concrete beams [24]

Van Nguyen et al. [46] investigated the performance of CFRP as ICCP anode in RC beams for up to 1100 hours. CFRP anode has been assessed in both concrete and calcium hydroxide solution. A maximum current density of 128 mA/m^2 of steel area was recommended in this experiment. The current was checked and the "on" and "instant-off'' potential values of steel were recorded daily. The results concluded that CFRP can be employed effectively as the anode for ICCP system. However, CFRP was extended out of the edge of both RC beams, which is not suitable in real structures.

Gadve et al. [47] also investigated both the passive and active protection of steel corrosion using CFRP adhered to the concrete surface under highly corrosive environment. About 2 to 20% of conductive particulates by weight of epoxy were mixed into the epoxy for uniform conductivity of CFRP. An external DC power supplier was applied to impress the constant current of 150 mA for 1500 hours. Four parameters of flexure strength, mass loss, half-cell potential and cell voltages were studied. The corrosion potential measurement was obtained from the potentiodynamic scan on cylindrical specimens daily. The experimental results indicated the effective performance of CFRP as the strengthening material and ICCP anode material.

In summary, CFRP in ICCP system could act as anodes adhered on RC and no other external anode is needed, which is cost saving opportunity. However, graphite particles were widely used in the conductive epoxy mixture, which is only suitable for the new CFRP application on RC. Normal structures with CFRP for strengthening used the non-conductive epoxy resin for bonding. Therefore, new connection technique could be a challenge for removing the current cured epoxy with CFRP, and then be connected with an electrical wire for impressing current supply.

4. SUMMARY

CFRP could significantly decrease the corrosion rate of RC structures. Current investigations mainly focused on steel corrosion under marine or wet-dry cycle environment without sustained loading. Limited literature could be found in steel corrosion investigation of RC structures external bonded by CFRP under sustained loading. Further working on steel corrosion affected by CFRP simulated in the actual RC structures are expected to be deeply and comprehensively studied.

Active protection using CFRP as an anode has been started to research for the dual function of both strengthening and ICCP anode system. The dual function of CFRP application could provide cost savings and easier maintenance. However, current investigations mainly focus on experiments using simple specimens, which are questionable. New connection techniques are a challenge for removing the current dry epoxy in CFRP, in which CFRP conductively connected with an electrical wire for impressing current supply.

A number of techniques have been applied to allow for steel corrosion measurement. Non-destructive methods are recommended in order to assess the corrosion activity without destroying existing service structures. As there is no single method can be analysed in the whole corrosion process, several methods could be applied in RC structures with CFRP. Corrosion measurements of half-cell potential, LPR, and mass loss were the major used techniques in RC with CFRP.

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6. AUTHOR DETAILS

Aifang Wei, also known as Amy, is a PhD student in the School of Civil Engineering at Deakin University. She is working on improving corrosion resistance using advanced material of Carbon Fibres in reinforced concrete structures. Her PhD project mainly focuses on electrochemical methods for steel corrosion testing, monitoring and protecting embedded in concrete using CFRP adhered and epoxy treated chopped carbon fibre reinforced concrete.

Dr Riyadh Al-Ameri is a senior lecturer in Structural Engineering at the School of Engineering, Deakin University since 2010. He received his MSc & PhD in Structural Engineering from Cardiff University (UK, 1990). He has more than 25 years of mixed industrial and academic experience. Before joining Deakin, took a senior role with the construction industry in design and consultation space. Visiting Academic and Honorary Associate at Monash University (2005). Received awards for Excellence in Industry Collaborations, Endeavour Research Fellowship, and Teaching Excellence. Published more than sixty papers. Keynote speaker and member of the International Scientific committee of several international conferences and current reviewer for many international journals in his field. Al-Ameri is a Fellow of the Institution of Engineers Australia, chartered Structural Engineer, and on the National Engineering register in Civil and Structural colleges. Member of the National Executive Committee of the Australian Association of Steel Concrete Composite Structures (AASCCS), the International Association for Bridge Maintenance and Safety (IABMS), the International Institute for FRP in Construction (IIFC), and the American Society of Civil Engineers (ASCE).

Mike Yongjun Tan is a Professor in Applied Electrochemistry and Corrosion Technologies at Deakin University in Australia. He is also a Research Program Leader of the Energy Pipelines Cooperative Research Centre. Dr Tan's principal teaching and research interests are in corrosion science and engineering and their applications for enhancing the reliability and durability of civil and industrial infrastructures. He contributed to electrochemical methods for corrosion testing, monitoring and prediction and corrosion inhibitor and anti-corrosion coating research. He is the author of some 150 publications and a book entitled 'Heterogeneous Electrode Processes and Localised Corrosion' (2012 John Wiley & Sons).

Dr. Yew-Chin Koay is a Team Leader Structural Technology and Assets at VicRoads. He completed his PhD degree from RMIT University and has almost 20 years experience as civil, structural and infrastructure engineer; postdoctoral fellow and lecturer in Australia, China, Malaysia and South Korea. Dr. Koay received several prestigious fellowships such as Endeavour Research Fellowship, Korea Sceince and Engineering Foundation, VicRoads Kerry Burke Memorial Scholarship, etc. He is a founding member of Young Researcher and Graduate Symposium (YRGS), an advisory board member of Australian Network of Structural Health Monitoring (ANSHM) and committee member of Standards Australia. He was a Chair Scientific Committee of Austraods Bridge Conference (ABC) 2017.