Proceedings of the Third International Workshop on Seawater Sea-Sand Concrete (SSC) Structures Reinforced with FRP Composites

Editors:

J.G. Teng
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Organised by:

Research Institute for Sustainable Urban Development &
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Department of Ocean Science and Engineering
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11-12 January 2020

ISBN: 978-988-14480-8-8

Published by:
Research Institute for Sustainable Urban Development & Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China.
Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen, China.

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Preface

The use of fibre-reinforced polymer (FRP) as a reinforcing material for structures constructed of seawater sea-sand concrete (SSC) was first proposed by the Chair of the present Workshop in 2011 and has since caught the attention of an increasing number of researchers. Seawater and sea-sand are not allowed in conventional steel-reinforced concrete structures due to the steel corrosion concern. In FRP-reinforced concrete structures, as the steel corrosion concern is no longer relevant and FRP is expected to be little affected by the rich chloride content in seawater/sea-sand, seawater and sea-sand can be directly used in making the concrete. The resulting structures, referred to as FRP-SSC structures, are particularly attractive for use in marine infrastructure projects as they eliminate the steel corrosion problem and allow locally available materials to be used in such projects.

Since the idea of FRP-SSC structures was first proposed in 2011, a significant number of research projects have been funded around the world, including a major multi-disciplinary research project which was funded by the Research Grants Council (RGC) of the Hong Kong Special Administrative Region in 2018 with a grant value of over HK$52 million (including over HK$ 5 million as matching funding from the local participating universities) through its Theme-based Research Scheme (TRS).

It is obvious that for FRP-SSC structures to be widely used, a great deal of research is needed to optimise their structural forms, to understand their short- and long-term behaviour, and to develop safe and economical design methods. This Workshop series was initiated in 2016 to provide an international forum for in-depth exchanges on FRP-SSC structures and closely related topics, to examine the current status and to discuss the future directions of the area. The second of this Workshop series was held in 2018, which included a launching ceremony of the five-year (2019-2023) TRS project on its first day.

The 3rd FRP-SSC Workshop was held on 11-12 January 2020. The programme of the two-day Workshop included 14 Invited Presentations and 11 other presentations on FRP-SSC structures or related topics. Each presentation was followed by discussions to achieve the objectives of the Workshop. The Workshop was attended by over 150 participants (including the invited speakers). In addition, a closed-door meeting of the research team and the external advisory board members of the TRS project was held on the morning of the second day of the Workshop.

Many people have contributed to the organization of the Workshop. On behalf of the Organizing Committee, we would like to thank all invited speakers for sharing their work and insight at the Workshop, and all participants for their participation. Our special thanks go to Dr. Cheng JIANG and Dr. Chao HOU, as well as the other members of the Organizing Committee, who provided the much needed secretarial support, covering technical, logistics and all other necessary aspects.

Jin-Guang TENG (Workshop Chair),

Jian-Fei CHEN (Workshop Co-Chair) & Tao YU (Workshop Co-Chair)

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11:00 - 11:30	**Speaker:** Prof. Urs Meier, EMPA **Title:** Latest Application of CFRP Tendons
11:30 - 12:00	**Speaker:** Prof. Yu-Fei Wu, Shenzhen University **Title:** New Technologies Applicable to SSC and Its Structures
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10:30 - 11:00	**Speaker:** Prof. Xiao-Ling Zhao, University of New South Wales **Title:** Hybrid Columns Made of Seawater Sea Sand Concrete, FRP and Stainless Steel
11:00 - 11:30	**Speaker:** Mr. Sheng-Nian Wang (Chief Engineer), China Communications Construction Company **Title:** Field Exposure Test Study on Civil Engineering Materials in Marine Environment
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SUSTech Campus Map

Applications of Basalt Fibre Reinforced Polymer in Marine Environment

Z.S. Wu[1,2,*], X. Wang[1,2] and J.Z. Shi[1,2]
[1] National and Local Unified Engineering Research Centre for Basalt Fibre Production and Application Technology, Southeast University, Nanjing 211189, China
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Basalt fibre-reinforced polymer (BFRP) is an environment-friendly material with high cost performance for infrastructures. To realize high performance and longevity of marine structures, methods are proposed to improve the fatigue and creep behaviours of BFRP (Figure 1 and 2). In addition, BFRPs have a strong resistance to alkaline, acid and salt environment (Figure 3). Thus, the adoption of BFRP can increase the life of marine structures from 10-30 years to 100-300 years.

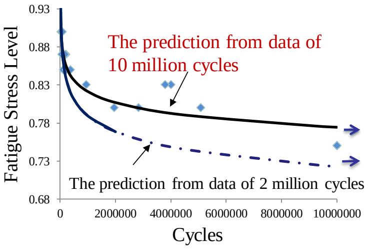

Figure 1 Fatigue prediction

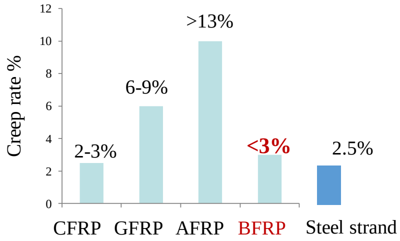

Figure 2 Creep rates

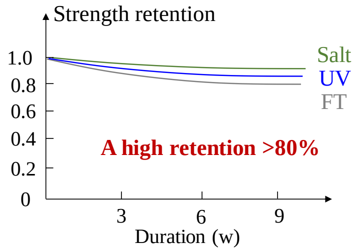

Figure 3 Durability

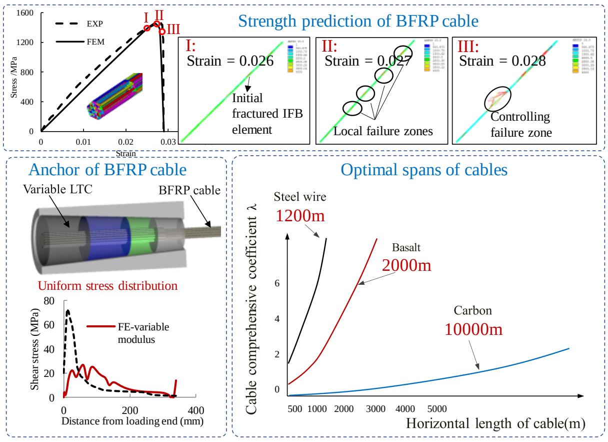

Figure 4 BFRP cables for long-span bridges

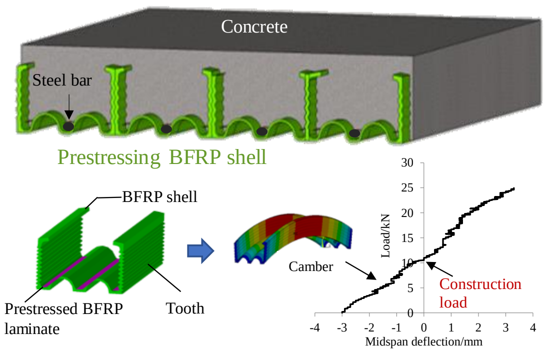

Figure 5 Bridge deck with BFRP profiles

With the aforementioned advanced BFRP composites, several main applications in marine infrastructures were proposed.

(1) Lightweight and longevity of long-span bridges with BFRP cables and profiles
High-performance BFRP cables are developed to replace the traditional steel cables. A shear-lag model assumes impregnated fibre bundle and matrix as the basic elements is proposed, by which the failure mechanism of BFRP cable can be revealed. Effective large-tonnage anchor systems for BFRP cables based on variable-stiffness LTC are proposed to fully develop the strength of cable. BFRP cables can realize a substantial increase in span up to 2000 m for cable stayed bridge (Figure 4). BFRP profiles with corrugated teeth are proposed, to realize high durability and lightweight of FRP-concrete composite bridge deck. Prestress technique is adopted in the profiles to enhance stiffness and reduce deflection under construction load (Figure 5).

(2) Durable and resilient concrete structures with hybrid design of BFRP bars/grids

To improve the durability, resilience, and workability of RC structures, two types of structures are developed, i.e. BFRP-steel hybrid reinforcement, and steel reinforcement with BFRP stirrup. Study results demonstrate crack resistance of the above structures under service status and superior durability under marine environment. Furthermore, resilience and damage-controllability can be realized by the new types of structures. The structures have a higher ductility and lower residual deformation at earthquake (Figure 6).

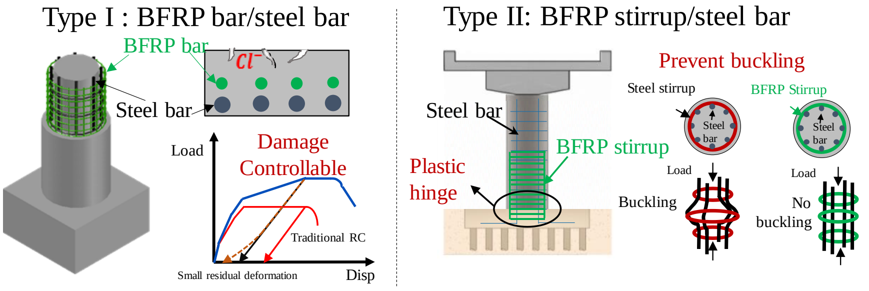

Figure 6 Durable and resilient concrete structures with hybrid design of BFRP bars/grids

(3) Long-span truss structures with BFRP profiles

By replacing steel with BFRP, the service life of long-span truss structures is significantly increased. A high joint efficiency is realized, based on material-joint integrated design concept. For large scale wind turbine structure, the wind turbine blade length is limited due to low modulus, strength of glass FRP. Commonly used glass FRP blade can only reach a length of 40 meters. The developed high-modulus basalt FRP wind turbine blade, which realises a significant larger length of 40-100 meters (Figure 7).

Figure 7 Long-span BFRP truss structures and ultra-large-radius wind turbine blade

KEYWORDS

Basalt fibre reinforced polymer (BFRP); marine environment; high performance; longevity; BFRP-steel RC structures; long-span bridge; long-span truss structures

Latest Application of CFRP Tendons

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A network arch bridge is a tied-arch bridge with hangers crossing several times. Through the arrangement of the hanger network, the bending moments and shear forces in arch and girder are reduced. The use of welded steel sections for hangers of network arches combined with hanger layouts that were tuned for minimum fatigue stress range and for avoidance of hangers getting slack, leads to technical challenges that could not always be solved entirely satisfactory in the near past. Especially long hangers at small inclination lead to difficulties related to the dead load deflections, variation of sag resulting from changing normal force and additional stress resulting from wind-induced vibrations. The use of hanger cables made from carbon fibre reinforced polymers (CFRP) changes the boundary conditions for the selection of a hanger layout. Therefore, it influences the load bearing system of the network arch. Due to the excellent fatigue behaviour, the layout of CFRP hangers can be tuned ignoring any criteria to limit fatigue stress ranges, but purely following the criteria of utilization in tension. As a result, the required hanger section drops to about 20% of what would be needed in steel. This leads together with the compared to steel lower young's modulus of CFRP to significantly larger elongations of the hangers. Subsequently the problem of hangers getting slack is being resolved as a side effect. Furthermore, the Eigen frequencies of the CFRP hangers increase significantly due to the relatively high pre-stress and the small dead load. Using CFRP tendons for hangers of network arches, highly efficient and still aesthetically pleasing hanger layouts may be created based on comparably steeply inclined hangers, avoiding hangers getting slack and without reduced service life resulting from wind induced vibrations. The field of efficient application for network arches thus may be extended beyond 300m span (Haspel 2019).

How to anchor such CFRP tendons was an important question. Empa researchers have very good long-term experience with a gradient anchorage system for CFRP parallel wire bundles as termination of stay and post-tensioning cables (Meier 2012). However, such cables are in comparison to hangers very long. Therefore, the cost for the anchorage is not of high importance. In contrast, hanger cables are relatively short, so the expenses for the terminations of the hangers are decisive to be able to compete against steel. Empa researchers were very early aware of this problem and developed a loop anchoring system (Figure 1). The production of such terminations with highly automated equipment is economic.

Figure 1. CFRP tendon of 2730 mm length and 33 mm diameter with titanium thimble (cable eye)

Network arch bridges have in Germany especially as railroad bridges a tradition of sixty years. Therefore, it was not surprising that the City Public Transport Operator Stuttgarter Straßenbahnen (SSB) decided to select the network arch bridge to cross with two train tracks eight lanes of the highway A8. To get an approval in this individual case a large experimental program was conducted by a team of Empa engineers (Meier 2017). One of the important criteria was the comparison of the elastic properties of the CFRP tendons before and after 12 million load cycles corresponding to hundred years of train operation. Figure 2 shows the results of the loading curves before and after fatigue testing. The curves are nearly congruent.

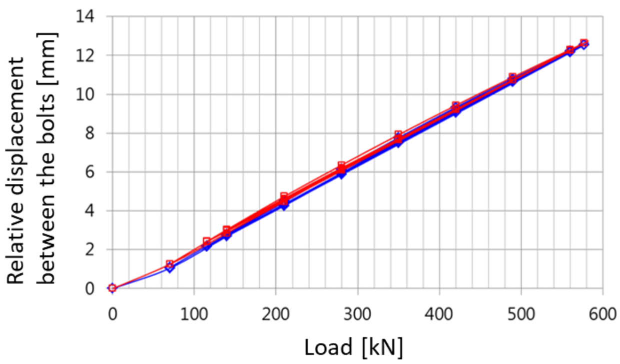

Figure 2. Relative displacement between the bolt axis before (blue line) and after 12 million load cycles (red line)

The reason for the scarcely remarkable softening of the CFRP hanger might be caused by some fretting fatigue due to the high testing frequency of 4.2 Hz (Baschnagel et al. 2016, Meier 2017, Terrasi et al. 2016).

In April 2018, the regional authority in Baden-Württemberg allowed the use of the CFRP hangers for the bridge shown in Figure 3. It will be completed in May 2020.

Figure 3. Network arch bridge designed by Schlaich Bergermann Partner for the City Public Transport Operator Stuttgarter Straßenbahnen (SSB) fully suspended on CFRP hangers. Length of the network arch: 80 metre. Source of rendering: Stuttgarter Straßenbahnen AG.

KEYWORDS
CFRP, network arch bridge, anchorage, termination, fatigue

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New Technologies Applicable to SSC and Its Structures

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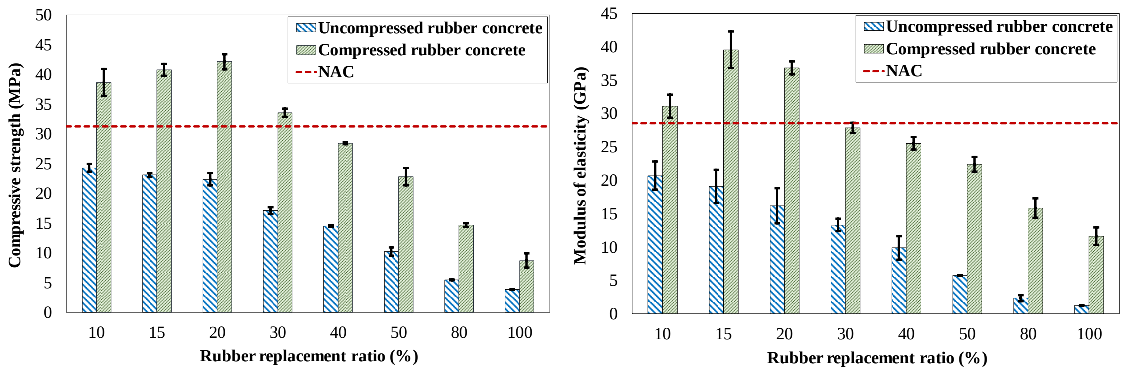
Seawater sea-sand concrete (SSC) could be different or inferior to normal concrete due to the difference in the mix. The consequences are two folds: (1) design and construction guidelines developed from normal FRP reinforced concrete structures may not be applicable, and (2) FRP reinforced SSC members may be inferior compared with relevant FRP reinforced normal concrete members. It is necessary to carry out a new round of research works for FRP-SSC structures similar to that having been carried out by the FRP research community for normal FRP reinforced concrete structures. However, the extent of research works can be significantly reduced if existing knowledge/technologies for normal concrete, normal steel reinforced concrete, and normal FRP reinforced concrete are applied appropriately. This presentation introduces a few technologies/theories that have not been applied so far to FRP-SSC structures.

1. A technology originally developed for rubber concrete

Rubber concrete where part of coarse or fine aggregates is replaced by rubber particles is much weaker/softer than normal concrete. A new technology has been proposed by the speaker and tested by his team recently that can significantly improve its mechanical properties (Figure 1). Application of the technology to SSC can also significantly increase its strength and elastic modulus.



a) Compressive strength (b) Modulus of elasticity

Figure 1. Mechanical properties of treated rubber concrete

2. A technology originally developed for recycled aggregate concrete (RAC)

Due to significant variation in physical properties of recycled aggregate (RA) from different sources, current models for predicting the behaviour of RAC are RA source dependent. No model is available in the literature to predict the stress-strain behaviour of (confined) RAC considering RA sources. A new factor related to physical properties of RA is introduced, and a general model using this factor as a variable of the model, hence applicable to all RA sources, is proposed. This approach could also be applicable to SSC, considering the large variation of sea-sand from different sources.

3. Application of RC flexural theorems to SSC structures

Stress-strain curve of SSC, including coral agg. conc. (CAC), can be significantly different from that of normal aggregate concrete (NAC) (Wang et al. 2017, Huang et al. 2018). According to the flexural theorem (Wu 2016), rectangular stress block parameters (ε_u, α_1, β_1) for flexural design of reinforced concrete members are only determined by the shape of concrete stress-strain curve (for under-reinforced members). Therefore, flexural design for SSC structures may be significantly different from that of normal RC structures. This part introduces the approach to flexural design of SSC structures using the theorem, without doing flexural tests of reinforced SSC members.

4. Identification of material properties for confined SSC

Dilation properties of SSC can be significantly different from that of normal concrete; hence the behaviour of confined SSC may require new models (Wang et al. 2017). Plasticity-based modelling (FEM) and design-oriented modelling of confined SSC structures can be made through a standard testing scheme for concrete materials only and subsequent calculations of model parameters from the material test results using the theoretical framework developed by the author’s team in the past (Jiang and Wu 2014, Jiang et al. 2017&2018, Mohsen and Wu 2017&2019).

5. Application of structural fuse for design of SSC structures

Safety margin and construction costs are two conflicting goals in conventional structural designs. However, the safety level and costs are generally not related in electrical/electronic circuit design due to the use of fuse. The triggering of a fuse stops “over-loading”, hence, costs allowing for overloading of components and wires can be saved, leading to more economic designs. Application of fuse to structural design not only increases safety of structures but also reduces the costs. A new structural fuse and reliability-based design of fused structures are introduced (Wu et al. 2019). Application of the technology will allow for higher design loads for structures constructed with inferior materials, such as SSC.

KEYWORDS
Seawater sea-sand concrete (SSC), FRP, RC members

ACKNOWLEDGEMENTS
The author gratefully acknowledges the significant contributions and supports by his students, collaborators, colleagues and funding bodies involved in the development of the relevant technologies.

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Constitutive Models of FRP Reinforced Seawater Coral Rock Aggregate Concrete

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* Corresponding Author

Seawater coral rock aggregates concrete (SCAC) is a typical marine aggregate concrete utilizing the local raw materials. The rock debris of the dead solidified coral reefs are one of the most significant sources of rock on remote islands and thus is inevitably utilized in the process of island construction. Using local coral rock aggregates (CAs) in marine construction can substantially reduce costs, decrease land utilization and shorten construction. Moreover, using lightweight, non-corrosion fibre-reinforced polymer (FRP) to reinforce concrete structure instead of steel can effectively counteract the greatest shortcomings of the chloride-containing ions in SCAC. To make better use of SCAC, the models of SCAC for two loading conditions and those of two FRP reinforced SCAC are developed, including uniaxial compression for SCAC, triaxial loading for SCAC, uniaxial compression of FRP confined SCAC, FRP bars pullout from SCAC.

The compression behaviours of SCAC under uniaxial loading were investigated comparing with lightweight aggregate concrete (LAC) and ordinary aggregate concrete (OAC). The results indicated that the compression behaviours of SCAC were different from those of OAC but similar to those of LAC because CAs are porous and have lower strength than ordinary aggregates. Based on the test in this paper and literatures, a stress-strain model was presented for SCAC under uniaxial compression (Figure 1).

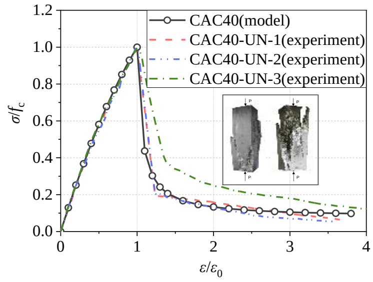

Figure 1. Comparisons between the test results and the uniaxial model predictions

The axial compressive behaviour of SCAC-filled FRP tube (SCFFT) was experimentally investigated and compared with OAC-filled FRP tube (OCFFT). The porous nature and low strength of CAs result in SCAC experiencing a compacting behaviour before the development of its rapid expansion and the activation of confinement in SCFFT. As a consequence, the axial loading of SCFFT displayed a slight drop in the transition zone. The non-homogeneity and brittleness of SCAC led to a non-uniform hoop strain distribution in SCFFT under compression and thus discounted the effect of confinement. The model developed originally for FRP-confined LAC was extended to for FRP-confined SCAC, and the extended model was confirmed to be capable of producing reliable predictions.

The true triaxial tests were performed to study the mechanical behaviour of SCAC under triaxial compression. The investigated variables include concrete type, concrete strength, lateral pressure and principal stress ratios. Under triaxial compression, the internal damage of the concrete is the crushing of aggregates instead of damage at the cement-aggregate interface. The crushing of aggregates results in macroscopic defects inside the concrete, which further leads to the premature destruction of cement stones. Comparisons with test results of the present study demonstrated that a failure criterion proposed for LAC (Wang et al. 2015) is applicable to CAC under active confinement or passive confinement (Figure 2).

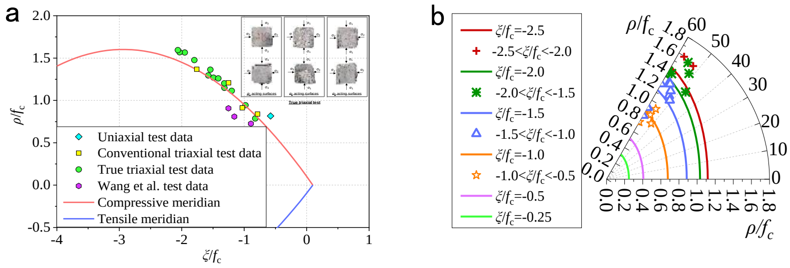

Figure 2. Comparisons between the test results and the triaxial failure model predictions: (a) Compressive and tensile meridians in the meridian plane; (b) Elliptic curve envelope within 0° ≤ θ ≤60° in the deviatoric plane

To understand the interaction between FRP bars and SCAC, pull-out tests were conducted to investigate the bond-slip behaviour. Three typical failure modes of specimens were presented: concrete cover splitting, pull-out with damage in concrete, layer of rebar peeling off. Various failures can be attributed to different concrete strength, cover thickness, rebar geometry and surface treatment. A two-branch model is developed to describe the bond stress-slip curves (Figure 3), in which the form of CMR model is adopted for the ascending stage.

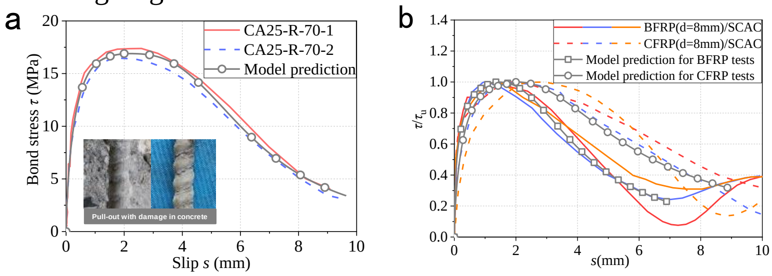

Figure 3. Comparisons between the model predictions and (a) test results in pull-out tests; (b) test results by Yang et al. (2018)

KEYWORDS

Seawater coral aggregate concrete; FRP; constitutive model; triaxial; bond

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by the National Natural Science Foundation of China (No. 51478246), the National Key Research and Development Program of China (No. 2017YFC0703001) and Southern Marine Science and Engineering Guangdong Laboratory Project (No. GML2019ZD0503).

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Electromechanical Impedance Testing Damage Detection of Submerged Civil Structures

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Electromechanical (E/M) impedance testing using piezoceramic (PZT) patches adhered to the surface of a substrate structure is regarded as a promising structural health monitoring (SHM) technique due to its ability to detect local and incipient damage in diverse types of structures. E/M impedance testing utilizes the direct/inverse piezoelectric effect, and the PZT patch acts as both sensor and actuator. Any damage done to the substrate structure will change its mechanical impedance, thus further changing the coupled electromechanical impedance of the patch-structure system, which can be measured using impedance analysers. Research in this field so far has largely been laboratory-based in ideal environmental conditions with impedance measurements taken using bulky and expensive commercial impedance analysers. Moreover, little has been done for structures submerged in water. This paper investigates the potential for using low-cost electromechanical impedance analysers for damage detection in submerged civil structures. The goal is to close the critical gap between laboratory development of the E/M impedance testing method and its deployment in the field. A single-board computer (SBC), called Red Pitaya (RP), is used to make high-fidelity impedance measurements and wirelessly communicate with a PC. Damage detection tests are established on steel beams to test RP's efficacy as a SHM tool. Damage detection tests on beams are conducted on submerged specimens and the results demonstrate the potential of using RP for detecting damage in submerged civil structures using low-cost impedance testing.

DAMAGE DETECTION UNDERWATER

To expand the range of environmental conditions in which the E/M impedance technique is employed, damage detection tests are conducted for specimens both in air and submerged under water. In addition to a silicone layer used to waterproof the beam surface, heat shrink tubes were used to waterproof the wires. Underwater signatures were taken with the beam suspended in two slings made of fishing line in a full 5-gallon bucket. The beams were suspended 6 inches under the surface of the water. Impedance signatures were taken using a Red Pitaya impedance analyser before submersion, submerged, and after drying out to see the effect of putting the specimen in water. As shown in Figure 1, the signatures before submersion and dry on foam match well with neglectable difference. However, the signature in submerged condition has many smoothed peaks due to increased damping. Underwater impedance signatures were taken before and after the cuts being introduced, and the corresponding RMSD metrics were calculated. As shown in Figures 2-4 and Figure 5, even with the loss in definition of the submerged signatures, the impedance testing technique can still detect incipient damage and different extents of damage introduced to steel beams. The RMSD values for underwater tests are smaller than in-air tests, because the peaks are smoothed over and RMSD has shortcoming of reflecting more on vertical shifting.

CONCLUSIONS

In this work, a low-cost commercially-available single-board computer and data-acquisition system called Red Pitaya was used for impedance measurements. Damage detection experiments were conducted on small steel beams with different number of wire cuts to simulate increasing extent of damage, and the ability of E/M impedance testing using Red Pitaya to detect incipient damage in dry and submerged conditions were demonstrated. Underwater impedance testing shows the potential to perform structural health monitoring and damage detection of underwater structures such as mitre gates. However, due to the high sensitivity of impedance testing method, effects of environmental conditions such as temperature, boundary conditions, and submersion depth need to be further investigated before field deployment.

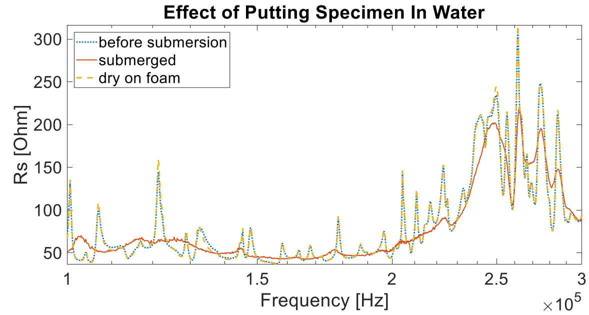

Figure 1. Comparison between signatures of specimen before submersion, submerged, and dry on foam.

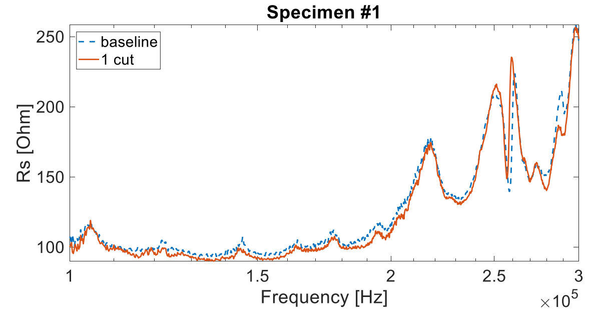

Figure 2. Underwater damage detection results by Red Pitaya: One cut.

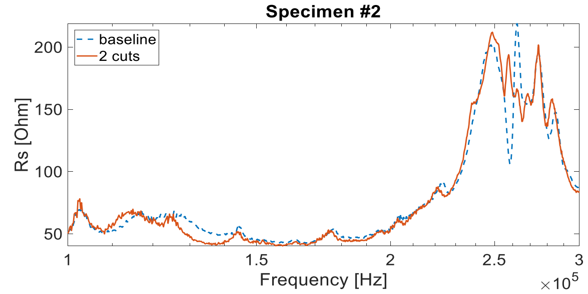

Figure 3. Underwater damage detection results by Red Pitaya: Two cuts.

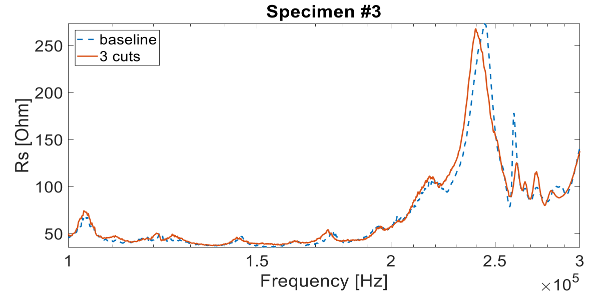

Figure 4. Underwater damage detection results by Red Pitaya: Three cuts.

KEYWORDS
Electromechanical impedance testing; piezoceramic patches; impedance analysers; Red Pitaya, submerged civil structures

ACKNOWLEDGEMENTS
The research described herein was sponsored by the US Army Corps of Engineers Navigation Systems Research Program. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the US Army.

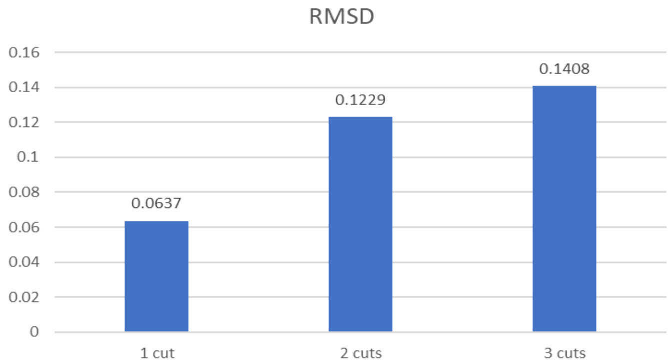

Figure 5. RMSD values for 3 damage cases of underwater damage detection experiment

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Development of Optical Fibre-Based Humidity Sensors for Monitoring the Moisture Content Inside FRP-SSC Structures

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This study presents a novel optical fibre relative humidity (RH) sensor design, based on fibre Bragg grating (FBG) technology, but specifically designed for monitoring the moisture content inside Seawater Sea-Sand Concrete (SSC) and Fibre-Reinforced Polymer Composites (FRP).

Humidity sensors were manufactured by coating a thin layer of polyimide polymer on the surface of optical fibre Bragg gratings (FBGs), exploiting the strain effect induced in a FBG through the swelling of the applied polymer coating due to the absorption of moisture, thus resulting in the FBG Bragg wavelength shift. Due to the cross-sensitivity of any FBG to strain, e.g. RH-induced strain, and temperature, temperature compensation was considered in the relative humidity (RH) sensor packaging, where a bare FBG is used for temperature measurement thus for temperature compensation.

A critical aspect of the work has been to tailor the design of the sensor system to meet the requirements of the measurement ‘in-the-field’: this involving developing a specific design of its protection and packaging for use in the harsh environments experienced. In this project, two types of packaging materials, i.e. perforated PEEK (polyether ether ketone) tubing and stainless tubing, have been considered, as they both offer excellent mechanical and chemical resistance, characteristics that are desirable for FRP-SSC structures. The sensor package consists of both inner and outer layers and in-between a membrane, preventing particles from the harsh test enviornment entering the probe to potentially damage the key sensor element, yet encouraging the interaction between the sensing element and the micro-environment that the sensor is exposed to. The sensors are required to be both accurate and sufficiently robust to survive the use by both non-specialists and to operate in the harsh environments experienced.

After the construction of the sensor probe, an effective humidity sensing system can thus be created using a commercial FBG interrogation system to capture the wavelength shifts when the probe is subjected to RH/temperature changes. Prior to the use of the sensor for temperature and RH measurement for field tests, the sensors are required to be calibrated, for example, in a humidity chamber. The coefficients obtained from the data sets are required to be included in the software that is designed to enable the real-time calculation of RH and temperature. Both the RH and temperature sensivities of the sensor are related to its coating thickness, for exmaple, ~5.6pm/%RH and ~12.9pm/°C for a sensor with 42μm coating and ~1.4pm/%RH, ~9.5pm/°C for 10μm coating.

The sensors packaged and calibrated will subsequently be cast inside FRP-SSC structures both for accelerated and for long-term condition monitoring. The sensor data obtained will also support the theoretical model validation in this joint programme.

KEYWORDS
FRP; SSC; relative-humidity (RH)/temperature measurement; optical fibre sensor; structural condition monitoring

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the financial support provided by the Research Grants Council of Hong Kong (Project No: PolyU 5151/03E).

Multiscale Approach of Damage Evolution in Cement-Based Materials

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During their service life, concrete structures undergo complex, time dependent and multiscale interactions with the surrounding environment. Weathering forces, such as water and salts from marine environments, promote internal chemical changes and evolution of the pore structure of the reinforced concrete, including at the reinforcement-concrete interfaces, which cause internal mechanical stresses that lead to degradation of the macroscopic performance of reinforced concrete structures. Key challenges to describing the time-dependent behaviour and deterioration of the macroscopic performance of reinforced concrete structures include appropriate description of the material microstructure evolution and of the bond behaviour between the reinforcements and the cementitious material.

Microstructure informed models coupled with multi-phase homogenisation techniques provide an alternative to traditional physico-chemical and mechanical models. These data-driven models are informed by experimental data and take into account the underlying microstructure and the presence of inclusions to evaluate the constitutive response of the composite. Grid nanoindentation coupled with phase elemental composition and homogenisation techniques has recently been proposed for quantitative characterisation of the intrinsic mechanical properties of the material constitutive phases as a function of chemical changes. This approach was applied to predict the macroscopic response of a non-uniformly degraded cement paste from leaching-induced decalcification and is discussed in Brown et al. (2018); Brown and Sanchez (2015).

The reinforcement-matrix interface plays a significant role in the overall material mechanical response and degradation mechanisms of the macroscopic performance of reinforced concrete structures. Current models of interfacial debonding are based on frictional shear stress, however relationships between interfacial chemistry, strength of the interface, and resulting bulk material strength and their evolution in response to weathering forces are lacking. Interactions at the reinforcement-matrix interface are dependent on local molecular structure and bonding. Investigations into the behaviour of the interface at the nanometer length scale are therefore needed to better understand interfacial bonding characteristics and underlying mechanisms and provide the building blocks for macroscopic constitutive models. Examples of such investigations employing molecular dynamics simulations as a basis to fundamentally study the reinforcing and bonding mechanisms in graphene reinforced cement-based materials can be found in Al-Muhit (2019); Al-Muhit and Sanchez (2020).

The presentation will discuss recent work performed in the Multiscale Materials Performance Laboratory at Vanderbilt University that is directed at developing a fundamental understanding of the relationship between microstructure evolution, interface bonding, and mechanical response of cement-based materials subjected to aggressive environments. In particular, recent work on nanoindentation based micro–macro upscaling methods and molecular dynamics simulations of interfacial responses in cementitious materials will be discussed.

KEYWORDS
Concrete, reinforcement-matrix interface, microstructure, grid nanoindentation, molecular dynamics

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the financial support provided by NSF 0547024 and NSF 1462575. The computational resources provided by the U.S Department of Energy funded Consortium for Risk

Evaluation with Stakeholder Participation III (CRESP, Cooperative Agreement Number DE-FC01 06EW07053; PI: David Kosson) is also acknowledged. F. Sanchez gratefully acknowledges the travel support from the Theme-based Research Scheme 2018/19 of the Research Grants Council (Hong Kong).

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Multi-Ion Equilibrium and Migration Model in Pore Solution of Sea Water Concrete

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The interaction and equilibrium of ions produced by the hydration of cement and those from the sea water (Na^+, Cl^-, Mg^{2+}, SO_4^{2-}, etc) are installed in the framework of the multi-scale analysis, and the verification of coupled ion kinetics and the electric potential field is reported. Some risk analysis is made possible so that we might prepare for the high concentration of alkalinity which can cause the ASR expansion of concrete in view of the long-term performances of the sea water concrete structures (Gong and Maekawa 2019). Since the pore solution of sea water concrete may behave as an electrolyte, electric potential of ground with concrete facilities can be different from conventional ones. Thus, the corrosion of other infrastructures might be accelerated similar to railway and subway facilities through stray current. In considering these, the multi-ion migration, equilibrium (Elakneswaran and Ishida 2014) and electric potential fields are installed into the multi-scale modelling (Maekawa et al. 2008) as:

$$\frac{\partial(\phi S C_{ion})}{\partial t} + \nabla \cdot \overrightarrow{J_{ion}} - Q_{ion} = 0 \tag{1}$$

$$\overrightarrow{J_{ion}} = -\phi S\left(\frac{D_{ion}}{\Omega}\delta\right)\left[\frac{\partial \ln(r_{ion})}{\partial \ln(C_{ion})} + 1\right] \cdot \nabla C_{ion} - \phi S\left(\frac{D_{ion}}{\Omega}\delta\right)\frac{F z_{ion} C_{ion}}{RT} \cdot \nabla\psi \tag{2}$$

$$D_{ion} = RT\,\frac{\lambda_{ion}}{z_{ion}^2 F^2} \tag{3}$$

$$\nabla \cdot \overrightarrow{J_e} + \frac{d\rho}{dt} = 0,\ \overrightarrow{J_e} = \sum_{ion} F z_{ion} \cdot \overrightarrow{J_{ion}} \tag{4}$$

where, ϕ is porosity of concrete, S is saturation degree, C_{ion} is ion concentration, D_{ion} is diffusion coefficient, Ω is tortuosity, δ is constrictivity, γ_{ion} is activity coefficient, F is Faraday's constant, z_{ion} is ion balance, ψ is electric potential, R is gas constant, T is temperature and λ_{ion} is ion conductivity.

Q_{int} is the mass sink associated with the multi-ion interaction and the products by electro-chemical reactions of anode and cathode poles, and ρ is the electric sink term of oxidation and reduction. For the multi-ion equilibrium and condensation/solution of soluble salts, the geochemical multispecies code PHREEQC was linked with the multi-scale platform of DuCOM, where calcium silicate hydrate (CSH) [$3(CaO)(Al_2O_3)3CaSO_4$: $32H_2O$], Portlandite [$Ca(OH)_2$], Ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12}$:$26H_2O$], Mono-sulfo-aluminate [$Ca_4Al_2(OH)_{12}\cdot SO_4$:$6H_2O$], Calcite [$CaCO_3$], Gypsum [$CaSO_4$], Thaumasite [$Ca_3Si(OH)_6(CO_3)(SO_4)$:$12H_2O$], Brucite [$Mg(OH)_2$], Hydro-talcite [$Mg_6Al_2CO_3(OH)_{16}$:$4(H_2O)$], Friedel salt [$Ca_2Al(OH)_6Cl_2$:$2H_2O$], Mono-carbo-aluminate [$3CaO\cdot Al_2O_3\cdot CaCO_3$:$11H_2O$], Hemi-carbo-aluminate [$Ca_8Al_4CO_{16}$:$24H_2O$], Halite [NaCl] and Bischofite [$MgCl_2$:$6H_2O$] are installed. Thus, the computed ions are OH^-, Na^+, K^+, Ca^{2+}, Cl^-, SO_4^{2-}, Al^{3+}, SiO_4^{4-}, Mg^{2+} and HCO_3^-. The full coupling of the electric potential field is also conducted in order to deal with the global actions of concrete, soil foundation and urban facilities.

For verification of the system by accelerated experiments, visualized testing with non-uniform electric field was proposed as shown in Figure 1 (Maekawa et al. 2019). The sodium poly-acrylate superabsorbent polymer is applied for the electrolyte which is equivalent to the pore solution of concrete composites. The solution of Portlandite [$Ca(OH)_2$] is mixed with the superabsorbent polymer in order to make the transparent material electrolyte with pH=12~13. Here, the polymer with iron is externally charged so as to introduce the electro-chemical reactions. The cathodic pole produces hydrogen gas which is firmly captured inside the transparent polymer by naked-eye observation, and the anodic position indicates black rusts to be easily detected as well. The concentration of hydroxide ion is easily measured by means of the PH censor. Here, it must be noted that the iron bars are used as an indicator of polarisation. At the same time, the influence of the sea water concrete on the neighbors (e.g. boundaries of the specimen) can be discussed in this project.

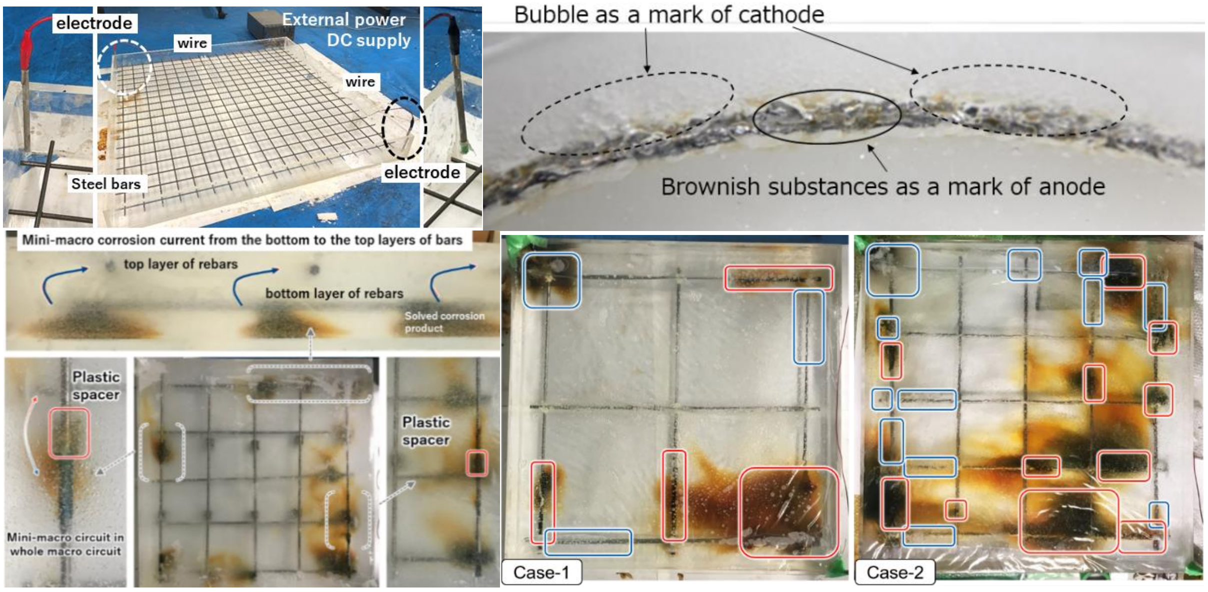

Figure 1. The sodium poly-acrylate superabsorbent polymer experiment (as a model of electrode of concrete pore solution by Maekawa et al. 2019) where iron bars are used for driving multi-ion transport and non-uniform ion concentration

KEYWORDS
Multi-ion equilibrium; ion transport; sea water; geochemistry; Nernst-Plank-Poisson equation

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Hybrid Columns Made of Seawater Sea Sand Concrete, FRP and Stainless Steel

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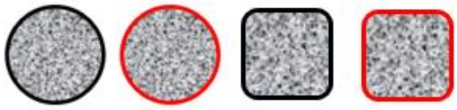
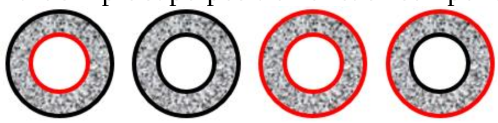
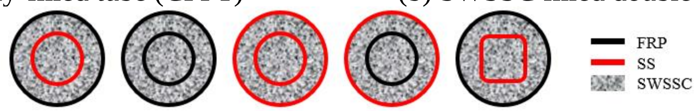
With the increase of population, huge demand on ordinary Portland cement concrete is exacerbating the resource shortage (e.g., fresh water, river sand) and causing serious environment impacts (e.g., emission of CO_2 during the production of Portland cement). Fibre reinforced polymer (FRP) and stainless steel (SS) were adopted to replace carbon steel in the hybrid sections due to their greater corrosion resistance. This research focused on the behaviour of hybrid tubular sections utilising seawater sea sand concrete (SWSSC), glass/carbon/basalt -FRP and stainless steel. Both the short-term structural behaviour and durability performance were investigated by the means of experimental study and theoretical analysis.

Alkali activated slag concrete with seawater and sea sand was developed, which could reach a target 28-day strength of about 40 MPa and desirable workability. It is found that the sodium chloride in seawater, sea sand and curing water is beneficial to the strength increase of concrete. The response of SWSSC subjected to elevated temperatures is similar to that of ordinary concrete, in which the incompatibility of thermal expansion between paste and aggregate is the main reason for the residual strength decrease (Li et al. 2018b).

FRP tube had fibres oriented in multiple directions (i.e., 15°/±40°/±75°) so that it offered comparable strength and stiffness in both hoop and longitudinal directions. SS tubes were 316 grade austenitic stainless steel whose stress-strain relationship exhibited a significant strain hardening. This research investigated the compressive behaviour of SWSSC-filled FRP and/or SS tubular stub columns whose cross-sections are illustrated in Figure 1 (Li et al. 2016a, b, 2018c, 2019c, d). Generally, the hybrid columns displayed an improved strength and ductility than the simple superposition of each components.


(a) SWSSC fully-filled tube (CFFT)


(b) SWSSC filled double-skin tube (CFDST)



(c) Double tube SWSSC column (DTCC)

Figure 1. Cross-sections of hybrid columns made of SWSSC, FRP and stainless steel

Theoretical models (Li et al. 2018a, 2019a, b) were proposed for the hybrid columns shown in Figure 1. The proposed analysis-oriented load-axial strain models could properly account for the influence of Poisson's effect, dilation properties, biaxial stress state of FRP/SS tube, buckling of FRP/SS tube, void ratio, non-uniform confinement (in CFDSTs) and the interaction between the inner FRP/SS tube with its surrounded concrete (in DTCCs).

Besides the short-term structure behaviours, the long-term performance of the hybrid columns was investigated by the accelerated degradation test. If adopting the residual hoop strength as an indicator of the long-term performance of FRP, CFRP behaved better than GFRP and BFRP (Figure 2). The capacity reduction of the hybrid columns was mainly caused by the degradation of the FRP tubes. On the other hand, the strength of SS did not change after being exposed to 40 °C saltwater for 6 months.

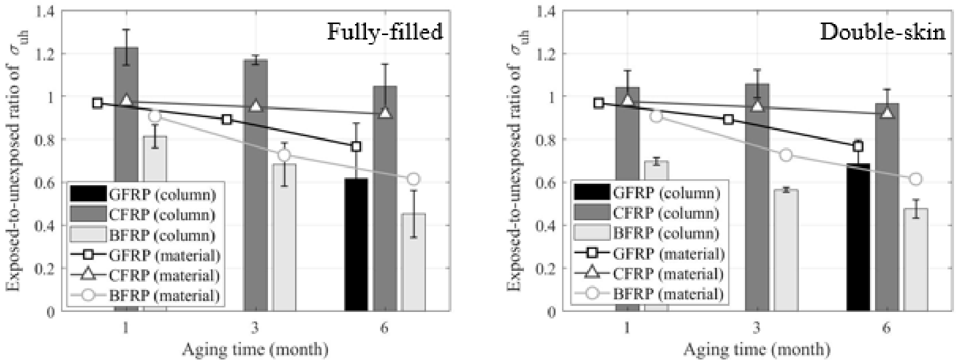


Figure 2. Durability of FRP materials and SWSSC-filled FRP tubular columns in 40 °C 3.5% saltwater: exposed-to-unexposed ratio of rupture strength (Li et al. 2018d)

KEYWORDS
Hybrid construction; columns; seawater sea sand concrete (SWSSC); fibre reinforced polymer (FRP); stainless steel

ACKNOWLEDGEMENTS
The work presented in this paper was sponsored by the Australian Research Council through a Discovery Grant (DP160100739) jointly held by the first author, Professor Raman Singh at Monash University, Professor Jin-Guang Teng at the Hong Kong Polytechnic University and Professor Gang Wu at Southeast University.

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Field Exposure Test Study on Civil Engineering Materials in Marine Environment

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Fly ash is commonly used in traditional marine concrete because it may significantly improve durability and workability of concrete. Over the past few decades, a large number of studies have been conducted to understand the macro performance of high-volume fly ash (HVFA) concrete. The most of the existing studies were concerned with the short-term macro performance of HVFA concrete in lab and only a limited number of studies have been reported to date on the long-term macro performance of HVFA concrete in field exposure environment. Moreover, it has been shown that the evolution of microstructure strongly influences the time-varying macro mechanical and chloride diffusion properties of concrete. Unfortunately, the relationship between the evolution of microstructure and time-varying macro performance of HVFA concrete is still not clear. In order to reveal the time-varying formation mechanism of long-term performance of HVFA concrete, a systematic study on the long-term macro and micro performance of VHFA concrete as well as their relationship is essential.

This paper presents the long-term results of a study investigating the mechanical, durability and microstructure properties of HVFA concrete exposed to Zhanjiang harbor marine exposure site. Meanwhile, tests were undertaken to establish the compressive strength and apparent chloride diffusion coefficient (Da) at different exposure times. Mercury intrusion porosimetry (MIP), X-ray diffraction (XRD), thermal gravimetric analysis and differential scanning calorimetry (TG-DSC), scanning electron microscopy and energy-dispersive X-ray spectroscopy (SEM-EDS) were performed to measure the microstructure of ordinary Portland cement (OPC) concrete and HVFA concrete with exposure time. Furthermore, the relationship between time-varying apparent diffusion coefficient and microstructure parameters was established.

With the increasing shortage of fly ash, fresh water and river sand, the importance of development of new engineering materials is recognised. The FRP-reinforced seawater sea-sand concrete (FRP-SSC) has attracted the attention of an increasing number of researchers over the past few years, which is a great alterative to traditional marine concrete. As the FRP-concrete interface is not only the crucial element of transferring stresses but is also vulnerable to debonding, which can result in the failure of the whole structure. Thus, it is extremely necessary to investigate the long-term durability of the FRP-concrete bond system in marine environment.

Field exposure test for FRP-SSC structures will be carried out in the next stage, which including flexural members and compression members. The flexural members are exposed to marine splash zone, which including ordinary reinforced concrete, glass FRP-reinforced seawater sea-sand concrete (GFRP-SSC) and carbon FRP-reinforced seawater sea-sand concrete (CFRP-SSC). The compression members with externally bonded FRP are exposed to marine tidal zone.

The main conclusions are as follows.

1. The incorporation of FA greatly increased the resistance to chloride-ion penetration. After 12 years exposure, the chloride penetration depth of HVFA concrete with water-binder ration of 0.35 is less than 30 mm, and the value of Da is less than 0.5×10-12m2/s. Compared with HVFA concrete, the chloride penetration depth of OPC concrete with water-binder ration of 0.35 is more than 45 mm, and the value of Da is more than 2.5×10-12m2/s.

2. The addition of FA in concrete not only decreased the total capillary porosities and average pore diameter, but also optimized the pore distribution. The Pozzolanic reaction of SiO2 and Al2O3 in fly ash take place consuming CH and forming additional C-A-S-H with low Ca/Si and high Al/Si ratio gel, which results in a dense microstructure.

3. For HVFA concrete at the exposure periods of 12 years, the peaks of Ca(OH)2 gradually weaken with replacement of fly ash in terms of XRD pattern, and the same phenomenon is observed in terms of DSC diagram. For OPC concrete at the exposure periods of 28 years, when the water-to-cement ratio is not less than 0.55, the peaks of Ca(OH)2 are not observed, and the pore solution pH value of concrete is below 12, which indicates that the calcium leaching of cementitious material is so serious that the durability damage tends to occur.

4. The compressive strength of concrete increases with exposure time. Compared with compressive strength at the curing periods of 28 days, the compressive strength at the exposure periods of 3 years increase by 47%.

5. Chloride diffusion coefficient is closely related to the porosity, average pore diameter and pore size distribution. With the increase of exposure time, total porosity, average pore diameter and the capillary pores with the size of 100~1000mm gradually decrease, which result in a smaller chloride diffusion coefficient. There is a good correlation between apparent diffusion coefficient and microstructure parameters (total porosity, average pore diameter, capillary porosity).

KEYWORDS
HVFA; marine exposure site; long-term performance; microstructure

Durability Investigation of FRPs in Marine Environments

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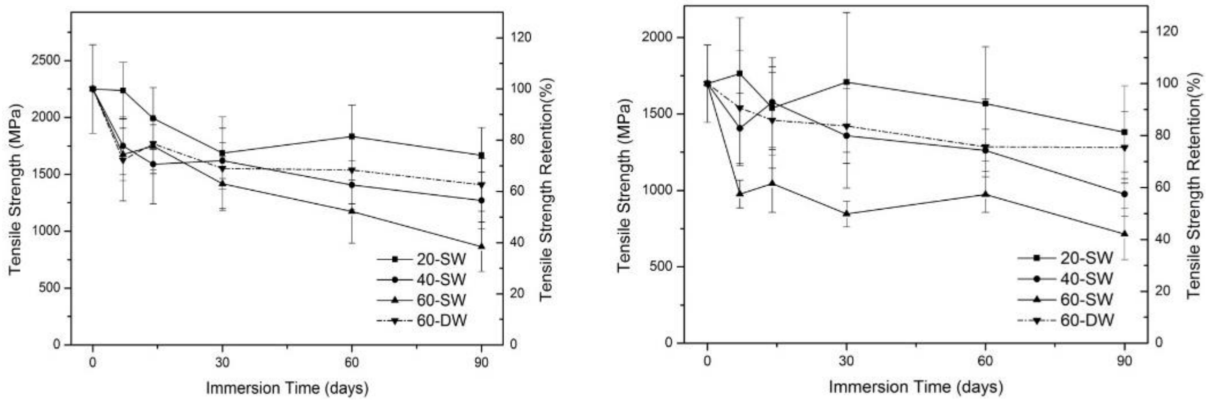
Many advantages of using fibre reinforced polymer composites (FRPs) in marine environments, such as FRP reinforced seawater sea sand structures. One of them is the asserted excellent durability performances of FRPs, compared to steel. As indicated in the previous studies, FRPs do not face rust problems, while degradation in harsh environments is in-avoidable. This problem needs to be well revealed and summarised for acceptance, safe design and applications. The present paper invested the durability performances of FRPs in various scenarios for marine applications.

1. Basalt and glass fibres immersed in seawater

Basalt- and glass- FRP bars have been used for reinforcements of seawater and sea sand concrete structures. Seawater resistance of basalt and glass fibres was tested through single fibre tensile test method. The seawater immersion brings in obvious decrease of tensile strength for both basalt and glass fibres. It is worth noting that seawater seems to be more corrosive to the fibres compared to distilled water.



(a) (b)

Figure 1. Evolution of tensile strength of basalt fibres (a) and glass fibre (b) immersed in seawater (SW) or distilled water (DW) at 20, 40 and 60ºC. Note, 20-SW means immersed in seawater at 20ºC, other similar.

2．FRP bars immersed in seawater

Bare BFRP bars or cement covered BFRP bars were immersed in seawater or distilled water. Compared to the bare BFRPs bars, the cement covered ones show more degradation. The alkaline environments inside of cement is attributed to the serious degradation. It is noted that the epoxy resin matrix used for BFRP bars is susceptible to the strong alkaline, through hydrolysis of the resin matrix, and fibre surface etching (Wang et al., 2017).

3) FRPs and FRP bar – seawater and sea sand concrete beams exposed to sea

It is interesting to see how the properties change of FRPs and FRP bar-concrete beams exposed to sea.

Some BFRP bars, and FRP bar reinforced seawater and sea sand concrete exposed to the Weihai coast (yellow sea). The BFRP bars exposed to yellow sea show similar tends. Degradation of FRP covered by concrete is much more serious than bared bars. The alkaline environments inside concrete beam is responsible for the degradation of the bars (Lu et al., 2020).

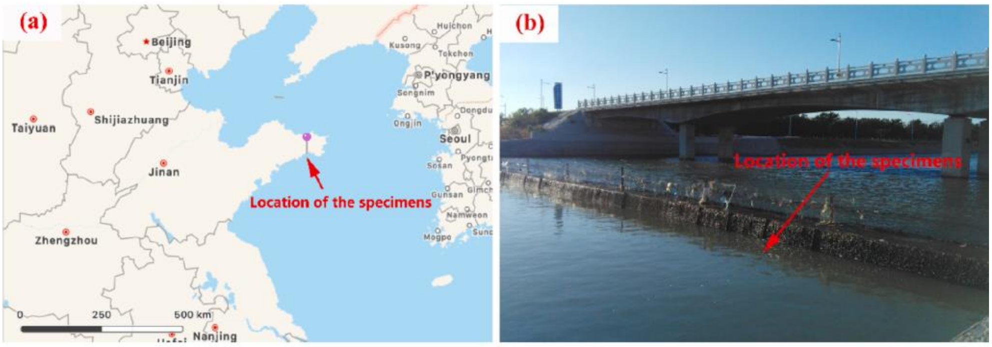


Figure 2. Location of specimens in ocean water and laboratory: (a) overview map; (b) details.

4. Life cycle assessment (LCA) of FRP reinforced SSC beam

LCA performed to compare FRP reinforced SSC beam with steel bar reinforced conventional concrete beam. The result clearly indicates FRP – SSC beams show better environmentally friendly, especially considering the longer service life.

KEYWORDS

Durability; seawater sea-sand concrete (SSC); FRP; life cycle assessment

ACKNOWLEDGEMENTS

The author gratefully acknowledges the financial support by National Key Research and Development Program of China (2017YFC0703007).

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Nanotechnology and Surface Coating

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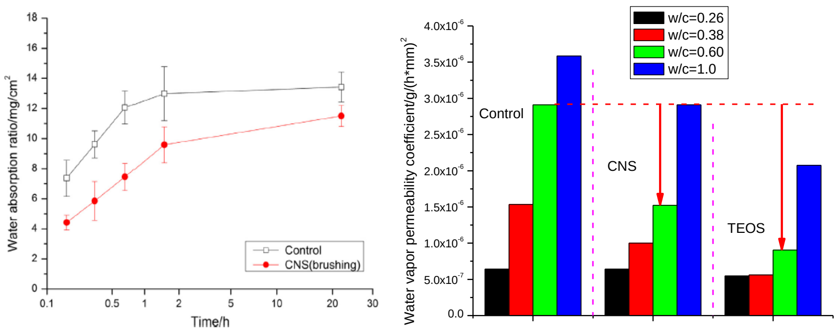
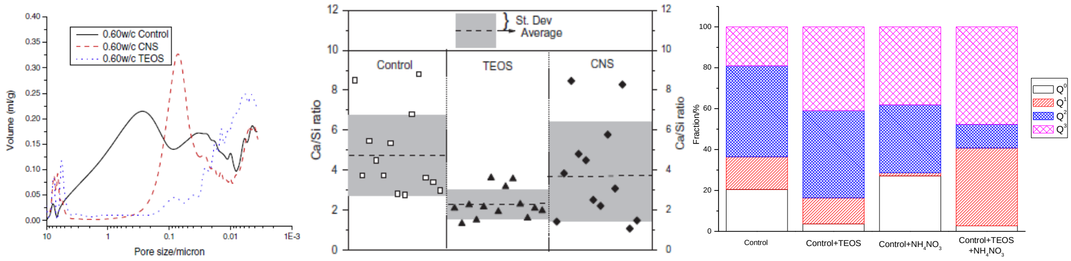
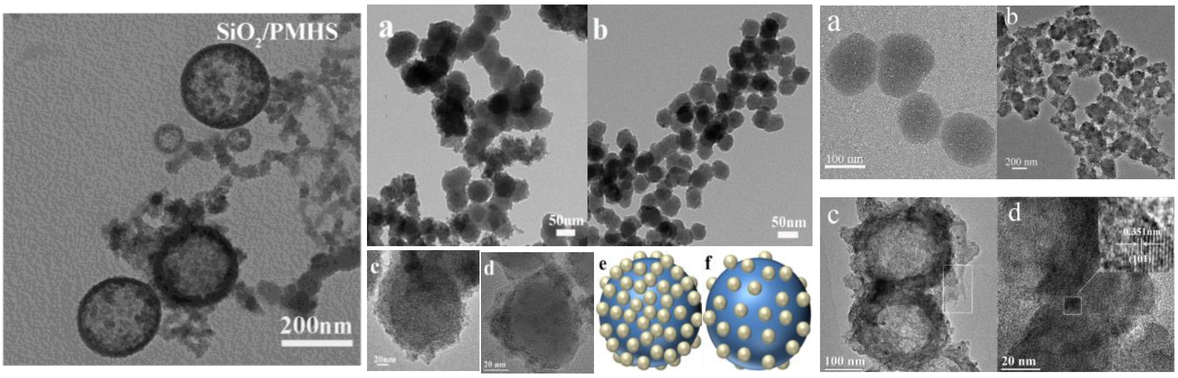
Nanoparticles have shown great potential of improving the properties of cement-based materials due to their modification effects on the hydration and hardening performances of cement. One of the good examples is nanosilica, which shows extremely high pozzolanic reactivity and hydration acceleration effect when mixed in cement. In this presentation, modification effect of nanosilica on cement concrete will be firstly shown on its novel effects on improving the quality of surface concrete by surface treatment. Performances on the reduction of water absorption rate and water vapor transport property will be presented, followed by the investigations on the mechanisms exploration. Results demonstrate that nanosilica particle is capable of reducing the porosity of surface concrete, but its performance is surpassed by its precursor, i.e., TEOS, which hydrolyses in-situ of the pores and potentially reduces the porosity to a greater extent, as well as modifies the physiochemical properties of the surface concrete. In the second part of the presentation, design of silica-based hybrid nanoparticles possessing both pozzolanic reactivity and certain functions for surface treatment of concrete will be demonstrated. By taking advantage of the hybrid structure of the nanocomposites, the surface concrete can be made of multi-functionalized through the graft of the functional nanoparticle constituents, making the concrete surface super hydrophobicity, photocatalysis, and wave-absorbing. On the other hand, by taking the advantage of the silica constituent of the hybrid nanocomposites, the surface treatment quality in terms of the durability of surface functionalisation can be potentially improved due to the chemical reaction of silica nano particle with the hardened cement introduced by its high pozzolanic reactivity.



Effects of nanosilica surface treatment on the water absorption rate and water vapor permeability coefficient



Effects of surface treatment on the physiochemical properties of hardened cement



Hybrid-structured nanoparticles for surface treatment of concrete

KEYWORDS
Cement concrete; nanomodification; surface treatment

Microstructure and Mechanism Investigation of Cementitious Composites Made with Seawater

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This research focuses on the mechanism investigation and microstructure characterisation of cementitious paste made with seawater. Firstly, the early age properties and reaction mechanism of seawater cement paste samples was investigated through setting time, hydration heat measurement, compressive strength, thermal analysis, and microstructural studies. The hydration kinetics was also studied by isothermal calorimetry. The results indicated that sea water accelerated the hydration of C_3A and C_3S resulting in earlier setting time. Seawater also improved the hydration attributes and early-age strength development. Chloride and sulphate ions in seawater promote faster hydration at early age. Friedel's salt, the Cl-AFm phase, becomes unstable at later ages followed by decrease in physically adsorbed chlorides. Seawater concrete showed denser, thicker and more compact microstructure with more cement hydrates. The primary difference between the seawater and fresh water cement matrix in hydration process was due to the different in heat generation rate and total amount of heat generated. The seawater samples showed faster setting time and increased hydration rate. Molecular dynamics simulation was performed study the interactions of sodium and calcium atom in gel system.

Secondly, the properties of matured seawater cement paste samples are investigated. Different samples made with different percentage of salt and pozzolans are tested for compressive strength properties, thermal loss, X-ray diffraction and microstructures & morphology. ^{29}Si and ^{27}Al nuclear magnetic resonance (NMR) test was conducted on seawater cement paste samples to investigate the structure and atomic co-ordination of the seawater system. The study revealed that seawater cementitious system has no peaks of Q4 and Q3 and Al is present in tetrahedral and octahedral co-ordination.

Thirdly, the durability of pozzolans seawater system was investigated by storing the samples in corrosive solutions for 6 months. Based on the observations, seawater samples made with slag and fly ash binders showed superior performance in corrosive solution. The limestone calcined clay (LC2) sample suffered the maximum weight loss of 13.5% in sulphate solution. The properties of seawater samples improved when pozzolans were added to the system.

Lastly, studies were performed on geopolymer seawater cementitious system. The performance of geopolymer with seawater was comparatively better. But the samples were affected by excessive carbonation, which was also the case for Portland cement samples made with seawater.

KEYWORDS
Early-age properties; cement paste; sea water; hydration; microstructure

ACKNOWLEDGEMENTS
The authors would like to acknowledge the financial support from the China Ministry of Science and Technology under grant (2015CB655104) managed by HKUST Shenzhen Research Institute Science and Technology; Science and Technology Development Fund from Macau (FDCT-078/2017/A2); Research & Development Grant for Chair Professor (CPG2017-00029-FST), and Start-up Research Grant (SRG2017-00093-IAPME) from University of Macau.

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Performance and Degradation Risk of Sea-Sand Concrete Structures

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The exploitation of seawater and sea-sand resources is a vital step towards alleviating the shortage of fresh water and natural aggregate for construction projects on remote islands and offshore sites. For example, in Pearl River Delta region, China, sea-sand has been largely used to replace river sand. Extensive research concerning the incorporation of seawater and sea-sand in concrete production has been carried out.

The existence of soluble salts in seawater and sea-sand could not only lead to non-negligible influence on the hydration process of concrete but also trigger the corrosion of steel rebars in concrete. Nevertheless, sea-sand concrete (SSC) still exhibits comparable workability and mechanical properties to concrete incorporating river sand or desalted sea-sand, as shown in Table 1, which indicates that sea-sand is the most viable alternative to river sand for concrete production.

Table 1. Comparison of the properties of concrete incorporating different kinds of sand.

Properties of concrete	River	Pearl river mouth		Yantian Port	
		Desalted	Original	Desalted	Original
Workability	Almost the same				
Compression strength	A little Higher when sand containing chloride ion being used				
Flexural strength	A little Higher when sand containing chloride ion being used				
Elastic modulus	Almost the same			Slightly low	

In viewing of Table 2, the direct replacement of freshwater and desalted sand by raw materials of seawater and sea-sand contributes to the slight decrease of compressive strength of concrete. It is remarked that the characteristic strength of seawater and sea-sand concrete (SWSSC) decreases with the increase of total ion concentration in corresponding mixing water. Although showing a slight decrease by comparison with ordinary concrete, the compressive strength of concrete made with seawater and sea-sand from Neilingding Island still met the target strength. This indicates that the substitution of desalted sand and tap water by sea sand and sea water does not necessarily deteriorate the mechanical properties of concrete. The SWSSC does represent one kind of sustainable eco-friendly material.

Table 2. Statistical characteristics of the compressive strength of concrete made with seawater and sea-sand from different regions.

	Mean	Std. Deviation	95% confidence intervals for mean value	95% confidence intervals for standard deviation
Reference	48.64	2.75	(47.57, 49.70)	(2.17, 3.74)
Neilingding Island	47.49	2.94	(46.33, 48.65)	(2.32, 4.03)
Daya Bay of Huizhou	45.77	3.17	(44.52, 47.03)	(2.50, 4.35)
Pearl River Estuary	43.22	2.82	(42.11, 44.34)	(2.22, 3.87)

The main concern of using SWSSC is the corrosion of steel rebar due to the high content of salts in seawater or sea-sand, which could cause detrimental effect on the properties of ordinary reinforced concrete. Instead, the chloride content in sea-sand subjected to desalination process can meet the standard requirement, thus, desalted sand has been extensively used for the construction of concrete structures. However, under the combined effect of carbonation and residual chloride penetration, the steel rebar still has the potential risk to be corroded. As demonstrated in Figure 1, the corrosion of steel rebar is mainly caused by the redistribution of chloride ions owing to the carbonation process.

In this study, according to the theory of chloride diffusion, a new model considering several parameters, including the releasing of bounding chloride as free chloride and the variation of porosity and saturation degree after the carbonation, is proposed to simulate the process of the redistribution of chloride ions when concrete structure being exposed to CO_2 atmosphere. The obtained results in Figure 2 illustrate that the simulated curve fitted well with the experimental data. Due to the release of bounding chloride ions, the decrease of pH value and the redistribution of chloride ions after carbonation, the steel bar may also be corroded though the original content of chloride ions in concrete is lower than the critical value for steel corrosion. The mathematical model proposed in this study could be used for predicting the durability performance of SWSSC structure exposed to atmospheric environment.

KEYWORDS
Chloride; carbonation; strength; sea sand concrete (SSC); seawater and sea sand concrete (SWSSC)

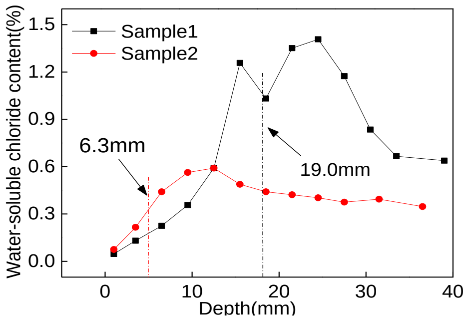

Figure 1. Water-soluble chloride profiles of concrete samples obtained from actual engineering project.

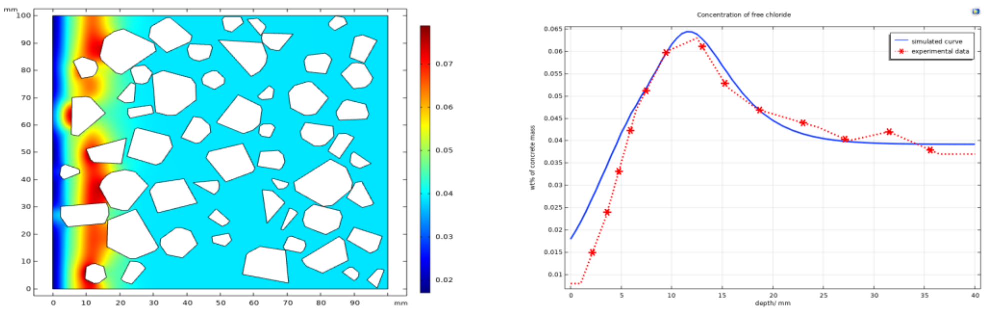

Figure 2 Verification of the proposed model.

ACKNOWLEDGEMENTS
This research was financially supported by the National Natural Science Foundation of China (51978408, 51478271).

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Identification of Bond Behaviour and Structural Damage Mechanism of Concrete Structures Reinforced with FRP Bars Using Piezoceramic Transducers

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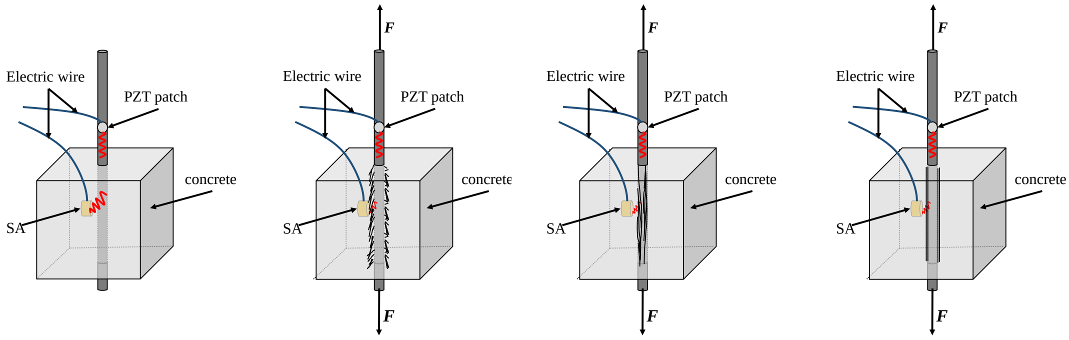
The corrosion of reinforcement embedded in concrete has been the cause of major deterioration and of high costs in repair and maintenance. Fibre Reinforced Polymer (FRP) bars, exhibiting high corrosion resistance in combination with high strength and light weight, provide an excellent alternative reinforcement. It has been well reported in the literatures that the low modulus of FRP bars can yield to large crack widths and deflections (Zheng et al. 2019). As a result, the design of FRP reinforced concrete components is governed by the serviceability limit state criterion. In addition, the bond behaviour of FRP-concrete has strong effect of the serviceability behaviour of FRP reinforced concrete structures (Baena et al. 2009). In this paper, the piezoceramic transducers are used to identify the bond failure (see Figure 1) and structural damage mechanism (see Figure 2) of FRP reinforced concrete structures using active sensing method based on stress wave propagation (Xu et al. 2018; Taghavipour 2017). The experimental test results reveal that the damage mechanism and failure modes of bonding behaviour between reinforcing bars and concrete can be identified and the peak of bond stress can be predicted by using piezoceramic sensors (see Eq.1 and Figure. 3). The bending stiffness levels of FRP reinforced concrete beam can be quantified (see Eq.2 and Figure 4), and the corresponding load and location of each crack occurrence can be captured by using Smart Aggregate (SA) transducers based on piezoceramics. The test and analytical results establish the feasibility of identifying the bond behaviour and structural damage mechanism of concrete structures reinforced with FRP bars using piezoceramic transducers.



(a) healthy state (b) concrete damage (c) reinforcing bar damage (d) debonding damage

Figure 1. The propagation of stress wave under different interface damages

Wavelet energy ratio index (WERI): $K = E_i / E_0$ (1)

$$E_i = \sum_{j=1}^{j=n+1} E_{i,j} = E_{i,1} + E_{i,2} + \cdots\cdots + E_{i,n+1} ; E_0 = \sum_{j=1}^{j=n+1} E_{0,j} = E_{0,1} + E_{0,2} + \cdots\cdots + E_{0,n+1}$$

where i is the time index and j is the frequency band. The E_i and the E_0 represent the total energy of the ith received signal and the total energy of the received signal in the initial state.

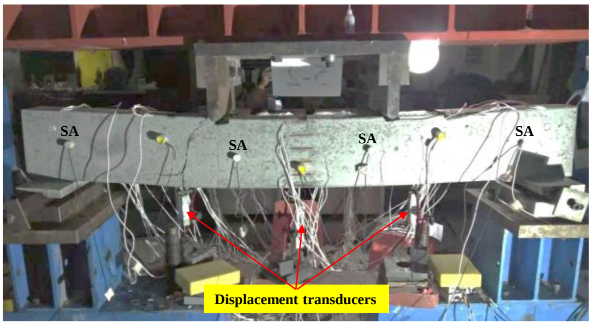


Figure 2. Loading configuration of concrete beam in this test

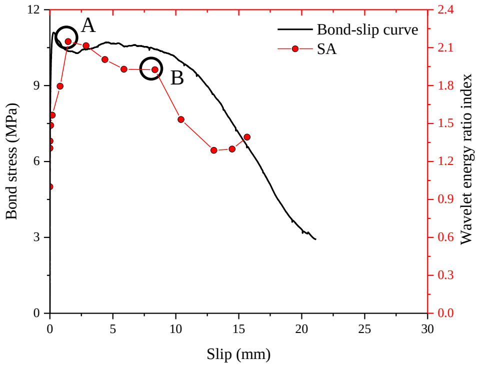


Figure 3. The WERIs and the bond-slip curves between FRP bars and Concrete

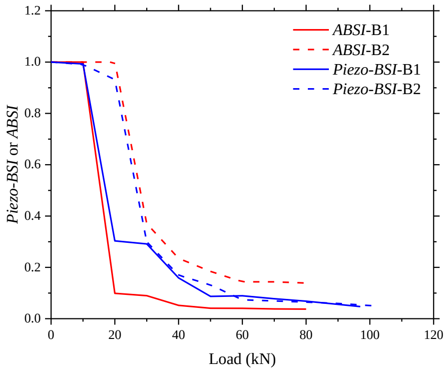


Figure 4. The comparison of the actual bending stiffness index and the *Piezo-BSI* values

$$Piezo\text{-}BSI = \sqrt{\sum_{j=1}^{n}(x_j^i)^2 \Big/ \sum_{j=1}^{n}(x_j^0)^2} \tag{2}$$

where the x_j represents the value of the received signal in time domain. The value for the damage state at the time *i* is defined as x_j^i and for the initial (healthy) state is defined as x_j^0.

KEYWORDS
FRP; concrete structures; piezoceramic transducers; bond behaviour; damage mechanism

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the financial support provided by Natural Science Foundation of China (51678149).

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Blast Resistance of Concrete Structures Reinforced with FRP Bars: State of the Art

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Concrete structures reinforced with steel bars usually have excellent blast resistance. To improve the corrosion resistance of the costal concrete protective structures, steel bars are replaced by fibre reinforced polymer (FRP) bras. As the FRP bars are brittle, the blast resistance of concrete protective structures reinforced with FRP bars is evaluated by explosion experiments. It is found that the long elastic deformation of the FRP bars lets the FRP bar reinforced protective structures have even blast-resistant performances, including higher load carrying capacity, longer elastic deformation, more uniformly-distributed and finer cracks and greatly reduced spalling areas. In this report, recent progresses of Fan's group (Gao et al. 2020; Liu et al.2019; Liu et al. 2019) in Blast resistance of concrete structures reinforced with FRP bars are reviewed based on three publications.

1. Blast resistance of FRP reinforced sea-sand seawater concrete slabs (Gao et al., 2020)

Avoiding steel corrosion in seawater sea-sand concrete (SSC) members, basalt fibre reinforced plastic (BFRP) bars reinforced members have advantages in coastal structures. One-way BFRP-bar reinforced SSC slabs (BRSSs) were designed to investigate their responses under close-in explosions. The SSC blocks have comparable compressive strength with plain concrete blocks. The BRSSs have comparable flexural strength and identical failure mode with the BFRP bars reinforced plain-concrete slabs (BRPSs). Under close-in explosions, the BRSSs have comparable blast resistance and similar failure modes with the BRPSs. Together with the excellent anti-corrosion ability, the BRSS is an ideal selection for costal protective structures, as shown in Figure 1 (Gao et al., 2020).

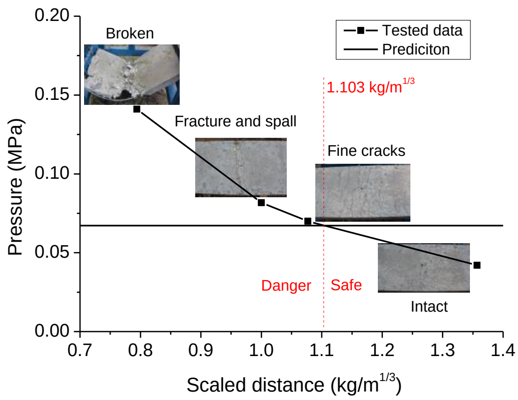

Figure 1 Critical scaled distance for BFRP bars sea-sand seawater concrete slabs (Gao et al., 2020).

2. Blast resistance of FRP reinforced concrete beams (Liu et al. 2019a)

Glass fibre reinforced polymer (GRFP) bars have advantages in corrosion resistance. They can be used as reinforcements in concrete structures to replace steel bars. GRFP bars reinforced concrete beams (GRCBs) were designed, cast and tested. As a reference, steel bar reinforced concrete beams (SRCBs) of the same flexural rigidity were also designed, cast and tested. Under close-in explosions, the GRCBs have smaller deflections than the SRCBs, for the GFRP bars are still in elastic state while the steel bars enter into plastic deformation. The residual load capacity of each beam was evaluated, quantitively revealing the damage degree of the exploded concrete beams. In current research the explosion produces negligible damage to the GRCBs, while the load capacity the SRCBs reduces at a level of 28% at the most. The research proves that the GRCB has greater blast-resistance, as shown in Figure 2 (Liu et al. 2019a).

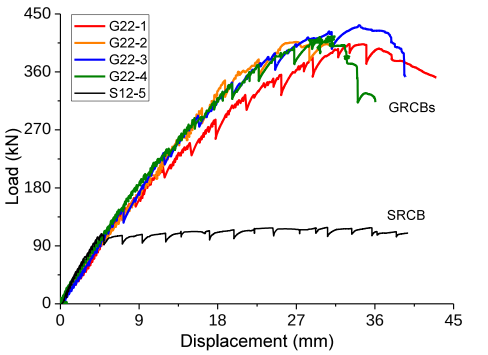

Figure 2 Flexural behaviours of exploded FRP reinforced concrete beams (Liu et al. 2019a)

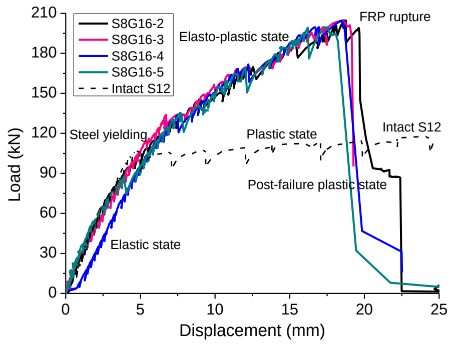

Figure 3 Flexural behaviours of exploded steel-FRP reinforced concrete beams (Liu et al. 2019b)

3. Blast resistance of Steel-FRP reinforced concrete beams (Liu et al. 2019b)

Steel-GFRP composite bars (SGCBs) have priorities in high load-bearing capacity and corrosion-resistance endowed by the GFRP component, as well as ductility from the steel. They can be used to reinforce the concrete protective structures. Two composite-bar reinforced concrete beams (CRCBs) were designed and tested. Composite bars greatly reduce the residual deflection compared with steel-bar reinforced concrete beams (SRCBs). Anti-blast ability is evaluated by the residual load carrying ability of the exploded beams by quasi-static four-point-bending experiments. Intact CRCBs have typical elastic, elastoplastic and post-plastic deformation stages and fail when the mid-span flexural crack almost penetrates the beam. GFRP bars let the CRCB have much greater capacity in load carrying than the SRCB. Exploded CRCBs have similar deformation and failure styles with the unexploded beams and even have greater load capacity than the unexploded SRCB. Having both excellent ductility and high load carrying capacity, the SGCBs are much better than the steel bars in protective structures in some cases, as shown in Figure 3 (Liu et al. 2019b).

KEYWORDS:
Blast resistance; protective structures; FRP reinforcement

ACKNOWLEDGEMENTS
Supports from National Natural Science Foundation of China (51778622, 11672130, and 11972184), Social Development Project of Science and Technology Department of Jiangsu Province (BE2017780), and State Key Laboratory of Mechanics and Control of Mechanical Structures (MCMS-0217G03) are gratefully acknowledged.

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Life Cycle Green Building Structure Evaluation System for Tropical Island Buildings Constructed by FRP-SSC Structures

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A large number of Green Building Evaluation Systems (GBES) have been developed around the world in order to evaluate and certify green buildings. In order to decrease the energy consumption and reduce the carbon emission raising from the construction industry, a rational life cycle green building evaluation system is essential because the energy consumption of structures may be various corresponding to the environment and structural demands. A well designed GBES leads to both the structure itself and the environment to be sustainable. However, the previous GBES mostly focus on the building design and building technology aspects. Building structures take approximate 40% of cost and energy consumption. The performance of building structures has significant impacts on the maintenance cost and the adaptability of building technology. Therefore, it is imperative to develop a life cycle green building structure evaluation system to evaluate and rate the structural performances in different life stages. A life cycle green building structure evaluation system is thus established corresponding to the four stages, design, construction, maintenance, termination or extension.

Buildings on the tropical island usually suffer a harsh environmental condition due to the high temperature, high humidity, high chloride environment, abundant rainfall, and monsoon environment. The green building structure evaluation index of buildings on the tropical island is significantly different from these on the mainland. In order to evaluate the building structure on the tropical island, the proposed life cycle green building structure evaluation system was furtherly improved and optimized.
It is essentially to use the local raw construction materials to control the cost and energy consumption from the logistics and construction. The sea-water and sea-sand are thus received more interests to be attempted as the replacements of the conventional construction materials on the island. The fibre-reinforced polymer (FRP) is a super corrosion free material with other excellent mechanical properties, which makes it is preferentially to be employed in the tropical island environment. Recently, the application of the combination of sea-sand, sea-water and FRP as the construction material has attracted more interests, such as, FRP-reinforced seawater sea-sand concrete (FRP-SSC) structures.

The advantages of the FRP-SSC structure in terms of corrosion and structural performance have been investigated. However, it is clear lack of the study on the green building structures evaluation of FRP-SSC structures. Therefore, this research aims to develop a green building structures evaluation system for tropical island buildings and conduct a case study by comparing a building constructed by conventional materials and FRP-SSC structures.

Initially, a specified life cycle green building structures evaluation system for tropical island buildings was established by introducing rational evaluation index. A reinforced concrete structure on a tropical island was then selected as a case study to quantitatively evaluate its green performance on the whole life cycle. A comparison study was produced by reevaluating the structure if it is constructed using FRP-SSC.

The analysis can draw the following conclusions: (1) The carbon emissions of building structures in each stage of life cycle is as follows: building materials production, construction, operation and maintenance, demolition, recycling and life extension. (2) Carbon emissions in the production, operation and maintenance phases of building materials account for more than 90%, which dominate the green performance of the structure. (3) The use of FRP-SSC structure shows a better green performance than that constructed using conventional materials in most stage of life cycle, the level is determined by the construction cost. (4) The use of FRP-SSC structure donates positive contribution on low carbon emission in the material production stage as expected, but the level is related to the logistics system. (5) The differences of the green performance of structures constructed using FRP-SSC or conventional materials are mostly from the maintenance and life extension stages.

Improving Flexural Performance of Full FRP Bar Reinforced Concrete Beam

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FRP bar is the potential reinforcement replacing the steel rebar for concrete structures subject to marine environment (Ganga Rao, Faza, Kumar, & Allison, 1995; Lau & Oral Büyüköztürk, 2010; Won, Yoon, Hong, Choi, & Lee, 2012) or structures using sea sand seawater concrete (SSC) in coastal region for better sustainability (Teng 2018). The majority researches on FRP bar reinforced concrete structures focused on the improvement of ductility and serviceability for beams, which is one of the key barriers for the general acceptance in the engineering practice. The service load vs ultimate load ratio for normal FRP bar reinforced concrete beam is only around 20~30%, rather lower than that in steel bar reinforced concrete beam which is over 65%. It will result in the design of beam determined by the SLS performance and leaving higher margin for ultimate strength (Nanni, 2003; Rafi, Ali Nadjai, Faris Ali, & Didier Talamona, 2008; Saikia, Phanindra Kumar, Job Thomas, K.S. Nanjunda Rao, & Ananth Ramaswamy, 2007). To increase the ratio, it needs to enhance the ductility to decreases the value of denominator. Several attempts have been done and demonstrated to be successful such as using steel and FRP bars, hybrid FRP bars, compression yielding mechanism. More importantly, it needs to improve the capacity at service limit state (SLS) to increase the numerator of ratio. Based on the literature review, prestressing technique is the only approach to improve the serviceability, but not an ideal one for low rise buildings.

In this study, two-step works have been done. First step work is to determine the mixture design of SSC. For standardizing the construction of SSC, the survey has been conducted on the sea sand market in the city Zhoushan. The basic properties of sea sand samples from different factories were investigated. A two-phase study was conducted on the properties of SSC focusing on different water/cement ratio effect with original sea sands and durability with controlled resources. The mixture design criterion for SSC obtained in the first phase study was established for the further study on the beam's flexural performance.

Table 1. Properties of test specimens

Specimen ID	Diameter of FRP tensile bar(mm)	UHDCC layer (mm)	Longitudinal reinforcement ratio (%)
SSC-6	6	0	0.17
SSC-8	8	0	0.30
SSC-12	12	0	0.69
SSC-UHDCC-6	6	60	0.17
SSC-UHDCC-8	8	60	0.30
SSC-UHDCC-12	12	60	0.69
SSC-UHDCC-plain	/	60	/

The second step work is to investigate the solution for improving SLS performance of FRP SSC beam. The factors causing lower-capacity at SLS were analysed. One of the key governing factors is cracking width, except the deflection. Accordingly, one type of ECC, ultra-high ductile cementitious composite (UHDCC, rupture strain larger than 7%), was adopted to replace concrete cover at tensile side for the full FRP bar reinforced SSC beam (Figure 1). Such composite beams have been studied by Yuan et al. (2013), but it was the first attempt focusing on the flexural performance at SLS. To investigate the flexural performance of the composite beam, seven simply supported beams under four-point load were designed (Table 1). The test results showed that the introducing of ECC layer can serve as the flexural reinforcement equivalent to FRP bars with 0.17% reinforcement ratio with well cracking control. It further improved the flexural behaviour (load capacity and deformability) of FRP bar reinforced concrete beam. The capacity of SLS can be improved by 30%~170%, with different reinforcement ratio.

It also found the potential of improving the stressing evenness in the FRP bars after concrete cracking due to ECC layer.

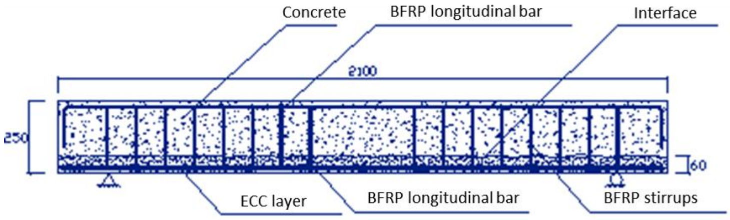

Figure 1. Full FRP bar reinforced concrete beam with ECC layer

KEYWORDS
Sea sand and seawater concrete; FRP bar; flexural performance; engineered cementitious composite

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the technical support from Dr S.F. Liu and financial support provided by Distinguish Young Scholars Program 51325802, Ministry of Housing and Urban-rural Development of the PRC program K12018142, National Natural Science Foundation of China (Projects No. 51478362 and No. 51778461) and Natural Science Foundation of Shanghai (Project No: 19ZR1460900).

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High-Sensitivity Humidity sensor based on A D-shaped Fibre Coated with Polyvinyl Alcohol Film

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A surface plasmon resonance (SPR) sensor based on a D-shaped single mode fibre coated with polyvinyl alcohol (PVA) is demonstrated for relative humidity (RH) sensing. A resonant dip was observed after coated with PVA, where the resonant wavelength shifted to a longer wavelength as the thickness of the PVA film increased. When RH changes, the resonant dip of the sensor with different film-thicknesses exhibits different characteristics. The humidity sensor exhibited a red-shift with increasing RH when the resonant wavelength is between 550 nm and 750 nm. And the averaged sensitivity increases firstly and decreases, showing a maximal sensitivity of 1.01 nm/RH%. Once the initial wavelength of the SPR sensor exceeds 850 nm, an inflection point of the resonant wavelength shift can be observed with RH increasing, and the resonant dip shifts to shorter wavelengths for RH values exceeding this point, and sensitivity as high as - 4.97 nm/RH% can be obtained in the experiment. The sensor is expected to have potential applications in highly sensitive humidity sensing.

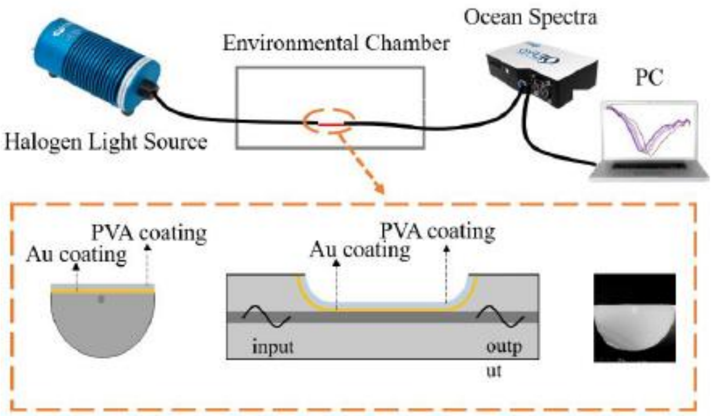

Figure 1. Schematic diagram of the relative humidity (RH) sensing system. Lower insets show the geometries in cross-section view, side view, and the microscopic image in cross-section view of the polyvinyl alcohol (PVA) coated surface plasmon resonance (SPR) sensor, respectively

A standard SMF with a core diameter of 8.2 µm and a cladding diameter of 125 µm was used to fabricate the SPR humidity sensor. The SMF was side-polished to a D-shaped geometry by a fibre- polished system. Then the fabricated SPR sensor was immersed into one of these solutions and coated with PVA by the dip-coating technique, with a constant withdrawal speed of 4 cm/s. To investigate the response to RH, the fiber SPR sensor was placed in a homemade RH chamber, with one end connected with a halogen light source (400–2000 nm, Ocean Optics) and the other end connected with a fiber spectrometer (Ocean Optics), respectively, as shown in Figure 1. In the RH chamber, there was a humidifier and drier for increasing and decreasing RH, respectively, a fan for homogenisation and stabilisation, and an electric hygrometer for calibration. The transmission spectra of the sensor were collected by the spectrometer and recorded and post-processed by a personal computer (PC) in real-time during the test. Meanwhile, the RH data collected by the electric hygrometer for calibration were also recorded by the PC simultaneously.

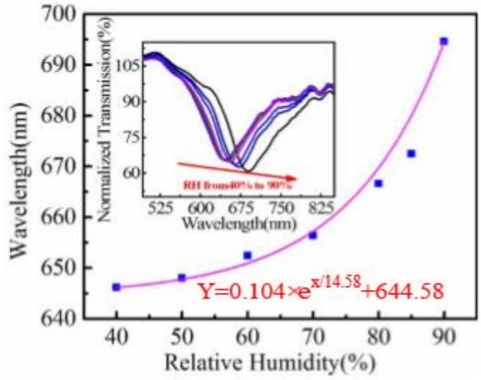

Figure 2. Resonant wavelength shifts and spectrum evolution of a fibre SPR sensor with RH increasing. The purple curve is an exponential fitting to the experimental

Figure 2 shows the resonant wavelength shift of a SPR sensor with an initial wavelength near 650 nm in ambient air (fabricated by dip-coating with a 3% (wt/wt) PVA solution). The resonant dip shifts from 645.52 nm to 695.94 nm with increased RH from 40% to 90%. Note that the temperature in the chamber is kept constant to avoid temperature cross-sensitivity. For RH between 40% and 70%, the resonant wavelength of the sensor shifts to longer wavelengths nearly linearly with a sensitivity of ~0.36 nm/RH%. However, the sensitivity increases rapidly for RH from 70% to 90%, then achieves 4.69 nm/RH% for that between 85% and 90%. The averaged sensitivity of the sensor can be roughly estimated to be 1.01 nm/RH% in the RH range between 40% and 90%. The shift of dip wavelength can be more appropriately fitted with an exponential function as shown in Figure 2. The total wavelength shift of the sensor is 50.42 nm, which is comparable to that of the most sensitive fibre RH sensor reported so far.

KEYWORDS
Fibre optics sensors; relative humidity; polyvinyl alcohol

Investigation of Corrosion Mechanism of Seawater Sea-Sand Concrete Using Piezoelectric Transducer Array

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Nowadays, steel reinforced concrete structures are widely used in the construction industry. However, the fabrication of conventional concrete consumes a lot of fresh water and river sand/crushed stone fines, causing irreversible negative impact on environment. Due to its economic benefit and environmental friendliness, seawater sea-sand concrete (SSC) has got much potential to replace conventional concrete in the future. However, there is abundant chloride in SSC which will intensify the corrosion process of the steel that is used to reinforce SSC. To ensure the safe operation of steel reinforced SSC (SCC-steel) structures, the corrosion mechanism of steel that is embedded in SSC needs to be fully understood. Current *in situ* research methods for corrosion normally rely on measurements of electrochemical properties of materials. If these methods are to be used to investigate the corrosion mechanism of steel embedded in SSC, researchers would have to make subjective predictions of the physical changes that steel would undergo during corrosion. As a result, the findings would exhibit much uncertainty.

To break through the limitations of the conventional research methods for corrosion, an ultrasonic testing (UT) based corrosion monitoring setup has been established in our previous work. Using a single piezoelectric transducer, a nanometre precision has been achieved for measurements of mean wall thickness losses (Zou and Cegla 2017; Zou and Cegla 2018a; Zou and Cegla 2018b). The monitoring setup is shown in Figure1.

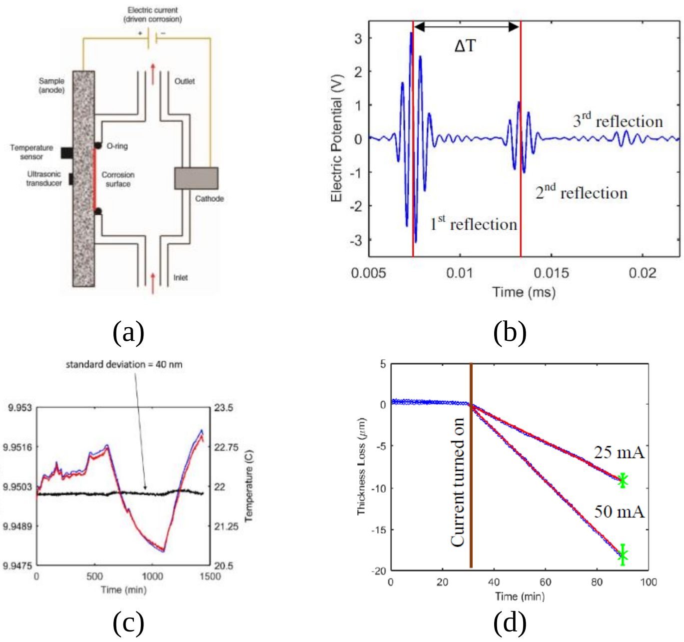

Figure 1. (a) Detailed view of the monitoring setup. An ultrasonic transducer and a resistance temperature detector are installed on the non-working surface of the specimen used. A corrosion cell with an opening is attached on the working surface of the specimen. During a corrosion experiment, an electrolyte is circulated through the cell to cause corrosion to the specimen. (b) A typical ultrasonic signal that is acquired in pulse-echo mode from the monitoring setup. Based on the time-of-arrival's of the wave packets, the instantaneous thickness of the specimen used can be calculated. (c) Temperature

(red), and uncompensated (blue) and compensated (black) ultrasonic thickness measurements of an uncorroded sample. In the presence of temperature compensation, the standard deviation of the thickness measurements reaches 40 nm. (d) The ultrasonic thickness measurements (blue) of corrosion specimens that were subjected to galvanostatic corrosion. The ultrasonic measurements were validated by analytical predictions (red) and optical measurements (green). (Zou and Cegla 2018; Zou and Cegla 2017)

Building upon the previous work, a novel piezoelectric transducer array, which consists of several piezoelectric transducer elements, has been designed to monitor the morphological changes that steel undergoes during corrosion. Figure 2 shows the installation of a transducer array on a flat SSC-steel specimen. A piezoelectric transducer array is attached on the inner surface of the steel plate in order to monitor the corrosion surface. Each one of the transducer elements monitors a specific area and tracks its thickness change. By fusing the thickness change that is recorded by each transducer element, a 3D reconstruction of the overall morphological change of the corrosion surface can be established in real time. The size of the transducer elements and the frequency at which ultrasonic wave at excited were selected based on the Huygens' Principle (Wilcox et al. 1998).

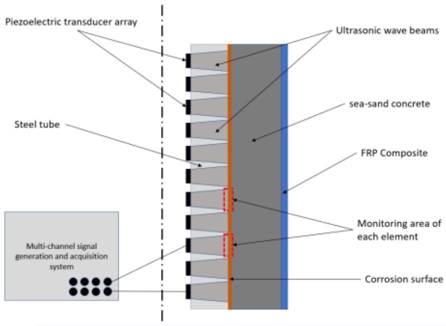

Figure 2. Schematic diagram of a SCC specimen on which a piezoelectric transducer array is installed.

In the next phase of this project, the abovementioned UT based research platform will be used, in collaboration with conventional electrochemical analysis, to conduct comprehensive investigations on the corrosion mechanism of steel embedded in SSC. We will strive to reveal the effect of various environmental factors (e.g. pH value, chloride concentration and load) and material related factors (e.g. mix proportion of SSC, type of steel, effect of coating material and corrosion inhabitant) on the corrosion induced morphological changes that steel undergoes.

KEYWORDS
Seawater sea-sand concrete; corrosion, non-destructive evaluation, ultrasonic testing, piezoelectric transducer array

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Experimental Research on Compressive Behaviour of Seawater and Sea Sand Concrete-Filled RRC Tubes

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To address the dilemma of existing structures constructed with seawater and sea sand concrete (SWSSC) including insufficient durability and high cost, an innovative composite column, named SWSSC-filled reactive powder concrete (RPC) tube (SFRPC tube), is proposed and studied in this paper. This hybrid system is comprised of a prefabricated RPC thin wall hollow tube containing fibre reinforced polymer (FRP) hoops and infilling SWSSC. Attributed to the ultra-high performance of RPC, the prefabricated tube can carry considerable axial load and improve stiffness of the composite column as well as serving as the permanent formwork for casting inner SWSSC. Moreover, FRP hoops in the RPC tube confine the lateral expansion of the SWSSC and activate the confinement effect. A total of 24 relatively large-scale short columns were tested in axial compression to investigate the compressive performance of the composite column. SFRPC tube columns exhibited a multi-crack failure mode on the surface of RPC tube without obvious peeling of RPC cover. The results reveal that the load carrying capacity of the SFRPC tube column is essentially equal to the sum of the results SWSSC infill and the RPC tube. Whole section of RPC tube can effectively carry the axial load whether it exists in effectively confined zone or not. A special confinement model is also proposed for SFRPC tube columns and is shown to exhibit accurate prediction. The SFRPC tube system effectively utilizes the ultra-high mechanical properties and excellent corrosion resistance of RPC and FRP as well as combining confinement effect from hoops. It is a promising SWSSC hybrid system potentially suitable for being applied in marine engineering.

KEYWORDS
Seawater and sea sand concrete (SWSSC); composite columns; reactive powder concrete (RPC); Fibre reinforced polymer (FRP); Confinement

ACKNOWLEDGEMENTS
This research reported in this article was carried out under the support of the National Natural Science Foundation of China (51678228, 51278180). Helps provided by the staffs of the MOE Key Laboratory of Building Safety and Efficiency at Hunan University are warmly appreciated.

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Compressive Behaviour of Sea Sand Filled CFRP Tubular Columns

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Using desalted sea sand to replace river sand in coastal areas and islands is an increasingly common practice due to the depletion of river sand (Xiao et al. 2017), but the desalting process of sea sand requires a large quantity of fresh water to meet stringent requirements (e.g., the Chinese sea sand concrete code (MOHURD 2010) specifies that the Cl^- in desalted sea sand must not exceed 0.03% in mass). This has led to inappropriate use of sea sand which is either un-desalted or substandard in structural concrete, causing extensive concerns on the safety and durability of the affected structures (Cagatay 2005). Chloride and sulfate ions exist in un-desalted sea sand with the former causing corrosion to steel reinforcements in reinforced concrete (RC) and the latter leading to expansion and associated cracking/spalling of concrete due to the effects of its hydration productions such as $CaSO_4 \cdot 2H_2O$ (Huang et al. 2008) and $3CaO \cdot A1_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ (Gao 2010) which results in the expansion of concrete, and $3CaO \cdot SiO_2 \cdot SO_3 \cdot CO_2 \cdot 15H_2O$ (Deng et al. 2006) which may lead to the deterioration/loss of concrete strength. To tackle these problems, Professor JG Teng proposed a combined use of sea sand concrete (SSC) or seawater and sea sand concrete (SWSSC) and fibre-reinforced polymer (FRP) composites in 2011 (Teng et al. 2011). Among the many advantages of using FRP in combination with SSC or SWSSC, a salient one is that the corrosion issue caused by chloride ions can be well avoided due to the good corrosion resistance of FRP.

This lecture presents the results of an experimental study on the axial compressive behaviour of SSC-filled FRP tubular (SSCFFT) columns considering the long-term effect of sea sand. In this study, the sea sand used was collected from a beach located in at the Dameisha Beach Park in Shenzhen, China. A total of 92 short cylinder columns with a nominal height-to-diameter ratio of 2 (H/D=2.0) were tested, and the effects of two important factors, namely the curing age (28days, 9 months and 24 months) and the column size (with diameters of 150mm, 200mm and 300mm) were investigated. In order to figure out the effect of sea sand on the long-term behaviour of the prefabricated CFRP tubes, a number of CFRP-confined concrete columns with the same size were also tested in which the CFRP wraps were applied following a wet lay-up procedure at 7 days before testing.

The test results showed that the failure of the SSCFFT columns was governed by FRP rupture outside the overlapping zone (similar to that of concrete filled CFRP tubes), and the curing age does not have a significant effect on the failure mode. The stress-strain curves of the SSCFFT columns were also similar with those of concrete filled CFRP tube, both are bi-linear featured by a first elastic stage followed by a second hardening stage; and the existing stress-strain model (Teng et al. 2011; Teng et al. 2009) developed for FRP-confined concrete (normal concrete) can provide reasonably accurate predications on the stress-strain curves. It was also found that the maximum rupture strain in hoop direction of the prefabricated CFRP tubes changed very slightly from 28 days to 24 months, which proved the reliability and durability of the prefabricated CFRP tubes for long-terms use in SSCFFT columns. No obvious differences (in terms of failure mode and stress-strain behaviour) were found between CFRP wrapped specimens and SSCFFT columns specimens, except that the ultimate hoop strain of prefabricated CFRP tubes was slightly smaller than that of FRP wraps at 28 days. Furthermore, no obvious size effect was observed for both SSCFFT specimens and FRP-wrapped specimens.

KEYWORDS
Long term behaviour, compressive behavior; FRP-confined concrete; sea sand concrete; prefabricated CFRP tube

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the financial support provided by the National Natural Science Foundation of China (Project No. 51578423).

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Understanding Creep Behaviour of Fibre/Matrix Interface via Molecular Dynamics Investigation

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Carbon fibre reinforced polymer (CFRP) composite has an increasing usage in civil engineering, including the external reinforcements and internal rebars in civil infrastructures, and the load-bearing materials in composite structures, in which the CFRP composite is inevitably subject to constant loads. The external loads on the CFRP composite cause the forces in the interfacial region, which lead to the slip between carbon fibre and epoxy matrix, that is, the interfacial creep between fibre and matrix. The interfacial creep under the constant loads deteriorates the interfacial integrity and weakens the long-term durability of CFRP composites. In order to avoid the composite failure resulted from the interfacial creep, the fundamental understanding of the interfacial microstructural changes during the creep is essential. This study aims to investigate the microscopic creep behaviour of carbon fibre/epoxy interface under different shear and tensile loads using molecular dynamics (MD) simulations. This study provides molecular insights into the creep behaviour of carbon fibre/epoxy matrix interface, which advances the understanding of the interfacial integrity of CFRP composite during the long-term service-life.

The molecular interface model is constructed by bonding the epoxy molecular model to the graphite sheets representing carbon fibre outer-layer, with the size of 7.6 nm × 7.6 nm × 6.4 nm, as shown in Figure 1 (Tam et al., 2019 and Wu et al., 2019). The molecular interface model is subject to different constant load levels along *x*- and *z*-direction to simulate the interfacial shear and tensile creep respectively.

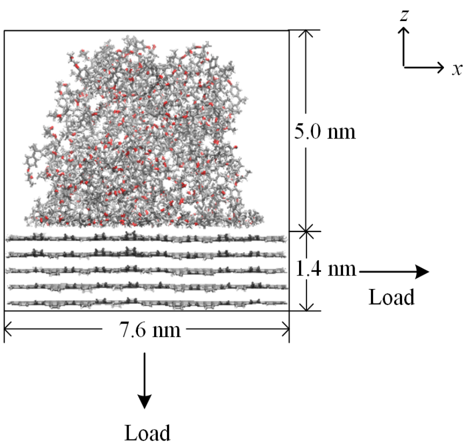

Figure 1. Fibre/matrix molecular interface under constant loads along *x*- and *z*-direction to simulate the interfacial shear and tensile creep respectively

The simulation results reveal that there are threshold stresses for the onset of shear and tensile creep respectively. Meanwhile, by fitting the displacement-force curve, the energy barriers for the onset of shear and tensile creep are calculated. Furthermore, the recorded strain-time curves during the creep simulation are correlated to the changes of the interfacial structure to understand the mechanism of the interfacial creep behaviour.

KEYWORDS
CFRP; interfacial creep behaviour; interfacial debonding; molecular dynamics simulation

ACKNOWLEDGEMENTS
This work was supported by the National Natural Science foundation of China under Grant [number 51608020 and 51808020]; and the China Postdoctoral Science Foundation under Grant [number 2017M620015 and 2018T110029]; and the Thousand Talents Plan (Young Professionals) in China.

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A Review on the Durability of FRP Bars Reinforced Seawater and Sea Sand Concrete

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FRP reinforced seawater sea sand concrete (FRP-SWSSC) combines the advantages of corrosion-free FRP bars in the marine environment and the direct utilization of seawater and sea sand, which can lead to a more sustainable and economic-efficient construction material. This paper reports a comprehensive overview of the current works on the workability of SWSSC, mechanical properties of FRP bare bars and FRP bars embedded-SWSSC (tensile, interlaminar shear, transverse shear, and flexural strength), bond behaviour, durability, and applications of FRP-SWSSCs. The results indicated that exposure to the saline/alkaline environment is the main threat to the long-term performance of SWSSC. Furthermore, the type of FRP and resin materials, surface protection, and concrete can also affect durability performance. Typically, the surface enhancement of the FRP bars can enhance its durability performance under saline environment. Nowadays, mainly focuses on the application of glass fibre reinforced polymer (GFRP) in SWSSC, while the basalt fibre reinforced polymer (BFRP) bars have gained less attention due to until now not incorporated into design codes and standards. Also, GFRP demonstrated better resistance to both simulated concrete pore solution and saline condition than BFRP. FRP-SWSSC is most suitable to be used in marine/coastal construction applications. However, there are very few field applications conducted on FRP-SWSSC systems. The future research directions on FRP-SWSSC systems are recommended based on the summarization of current studies and field application. According to published works, it can be summarized that currently, the applied FRP materials in SWSSC were mainly the GFRP and BFRP bars (Benmokrane et al. 2015; Dong et al.2019; Guo et al. 2018; Hassan et al. 2016; Robert et al. 2013; Wang et al. 2017), while the study on using CFRP bars is quite limited (Zhou et al. 2019). GFRP bars have been incorporated into concrete code designs and standards, while no design standards have been proposed for concrete reinforced with BFRP bars. Furthermore, the interface issues in BFRP have not been clarified yet, which is a crucial factor prohibiting its wide application.

Based on the summarization that shown in Figure 1, the shapes of FRP bars that have been used in concrete include rods, bars, tubes, stirrups, plates, roving, mesh, sheets, and discrete FRP needles.

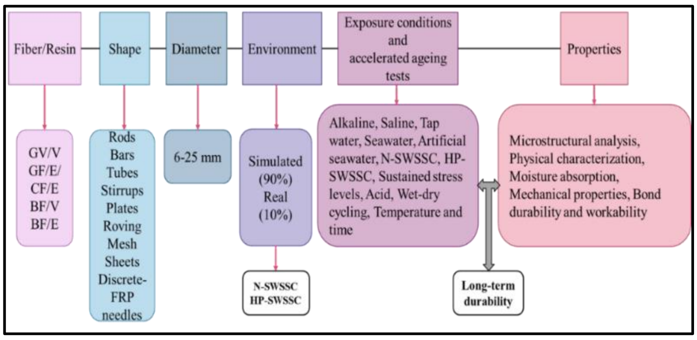

Figure 1. Schematic of FRP-SWSSC research

Moreover, the diameter of the applied FRP bare bars was in the range of 6 to 25 mm. It has been shown that many works used simulated environments rather than real environments for the durability analysis of FRP reinforced SWSSC due to the time-efficiency of the accelerated aging tests. The utilized simulated conditions for the durability analysis include exposure to the alkaline solution, saline solution, acid solution, tap water, real seawater, and artificial seawater, ordinary, and high-performance SWSSC solution. In addition, the wet-dry cycling and elevated temperature can be applied to accelerate the exposure test further. The degradation level of the FRP bars after an accelerated degradation test was mainly characterized by microstructural analysis, physical characterization, and mechanical tests. SEACON project funded by EU-US applied GFRP bar reinforced sea sand concrete with sensors in bridge construction (see Figure 2) for the health monitoring, which can promote the safe utilization of seawater and salt-contaminated aggregates (natural or recycled). The demonstration projects and field applications of GPRP-SWSSC have already been carried out in bridges, parking garages, water-treatment plants, and concrete pavement.

Figure 2**.** Demonstration project with SWSSC

KEYWORDS
FRP; seawater; sea sand; seawater sea sand concrete (SWSSC); durability

ACKNOWLEDGEMENTS
The work was supported by the National Natural Science Foundation of China (Grant No. U1806225, 51778220), National Key R&D Program of China (2017YFC0703006), and High-level Talent Gathering Project in Hunan Province (2018RS3057).

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Axial Compression Tests on Steel-Free Concrete Columns Longitudinally Reinforced with Hybrid Bars

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Fibre-reinforced polymer (FRP) composites have become increasingly popular as a durable construction material in civil engineering applications. However, the use of FRP bars as longitudinal reinforcement in reinforced concrete (RC) columns has been rather limited due to their substantially inferior performance in compression than in tension (Afifi et al. 2014; Mohamed et al. 2014; Hadi et al. 2016; Hales et al. 2017). Existing design guidelines generally recommend that the compressive resistance of FRP reinforcement be ignored in evaluating the load carrying capacity of the member (e.g. CSA S806 2012), or do not recommend the employment of FRP bars as compressive reinforcement (e.g. ACI 2015). In order to effectively utilize the FRP material in compression, the authors' group recently developed the so-called steel-free hybrid bar, which consists of an outer FRP confining tube, a central FRP bar and a layer of high-strength cementitious material in the annular space between them (Teng et al. 2018). In such a hybrid bar, fibre micro-buckling and overall buckling of the central FRP bar are both constrained by the surrounding cementitious material and the outer FRP tube so that the compressive capacity of the FRP bar can be properly exploited.

This paper presents a pilot experimental study on concrete columns reinforced longitudinally with such hybrid bars under axial compression (Figure 1). The columns are herein termed hybrid bar reinforced concrete columns or HBRCCs. A total of 22 column specimens were prepared and tested, including 18 RC specimens longitudinally reinforced with either hybrid bars or glass FRP (GFRP) bars as well as four plain concrete reference specimens. The hybrid bars used in the present study were fabricated using a GFRP bar (as the central bar), a GFRP tube (as the outer tube) and ultrahigh performance concrete (without steel fibres) as the annular layer. To better reveal the role played by the longitudinal reinforcing bars, a small concrete cover of 5 mm was used in all these columns. The main test variables included the type of longitudinal reinforcement (i.e., hybrid bars or GFRP bars), the external confining system of the column (i.e., GFRP spiral or FRP tube, see Figure 1), the pitch (centre-to-centre spacing) of the GFRP spiral (i.e., 40 mm, 80 mm or 160 mm), the type (i.e., GFRP or PET FRP) and thickness (i.e., comprising 4 or 8 plies) of the external FRP tube of the column. The test results demonstrated that the HBRCCs are superior in load carrying capacity to the corresponding GFRP bar RC columns, but both types of columns achieved good deformation capacities (Figure 2). As expected, the load carrying and deformation capacities of both the HBRCCs and GFRP bar RC columns increase with an increase in the thickness of external FRP tube or a decrease in the pitch of GFRP spiral.

KEYWORDS
FRP bar, ultrahigh performance concrete, hybrid bar, reinforced concrete, confinement, FRP spiral.

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the financial support provided by the Hong Kong Research Grants Council (T22-502/18-R and PolyU 152634/16E), and the Natural Science Foundation of Guangdong Province (No. 2019A1515011637).

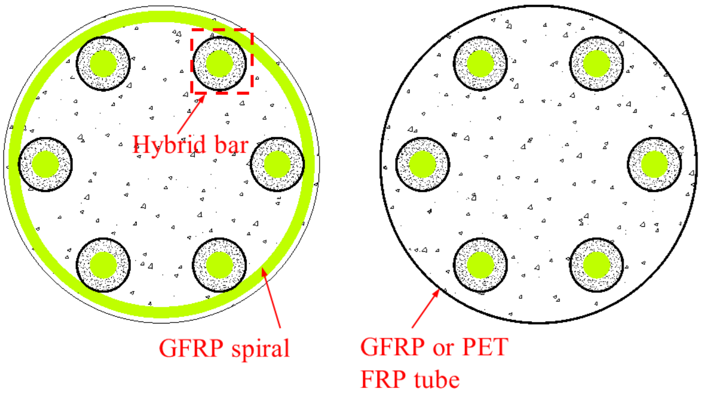

Figure 1. Cross-sections of column specimens with hybrid bars

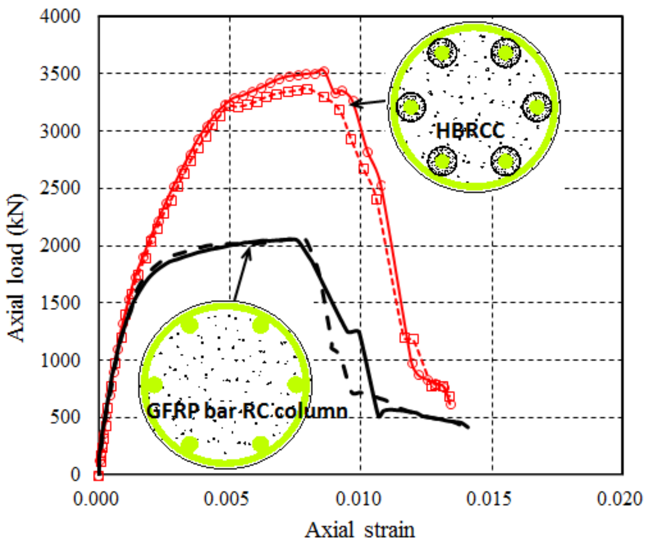

Figure 2. Typical axial load-strain curves

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