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Research Paper

Concrete beams using seawater and sea sand reinforced with steel and GFRP rebars exposed to marine environment: An experimental study

Duy Nguyen Phan [a]***, Hiep Dang Vu*** [b]***, Anh Vu Ngoc*** [c]***, An Le Vinh*** [d,*]

[a] *Faculty of Civil Engineering, School of Engineering and Technology, Van Lang University*

[b] *Faculty of Civil Engineering, Hanoi Architectural University, Hanoi, Vietnam*

[c] *Science - Technology and Environment Department, Ministry of Construction*

[d] *Faculty of Civil Engineering, University of Transport and Communications, Hanoi, Vietnam*

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ABSTRACT

Using fresh water and river sand in concrete mix composition makes a lot of negative impacts on resources and the environment while the source of sea sand and sea water is abundant and less harmful to the environment. However, sea sand and seawater in concrete can cause severe corrosion of the reinforcement, reducing the durability and bearing capacity of the structure. This paper illustrates the results of a comparative study on the flexural behavior of six corroded seawater sea-sand concrete (SWSSC) beams. The corrosion process of two concrete beams reinforced with traditional steel bars and four concrete beams reinforced with a combination of glass fiber reinforced polymer (GFRP) and steel bars was coupled by the effect of seawater exposure and sustained load. It was found that after exposure to a marine environment during the period of 60 months the GFRP bar retains surface integrity, meanwhile, the steel bars were significantly corroded with a cross-sectional area loss of approximately 13.93%. The decrease in bending stiffness, yield load, and ultimate load of the RC beams was found due to the deterioration of SWSSC and corrosion of steel bars.

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1 Introduction

Reinforced concrete (RC) structures used in a corrosive environment, especially in marine conditions, are suffered from corrosion of steel rebars and chloride-induced corrosion is considered one of the most frequent problems, resulting in the damage of concrete structures [1, 2]. It's well known that the volume of corrosion products is about two to six times greater than that of the original steel depending on the mechanism of corrosion [3, 4]. By the time the volumetric expansion occurs

* *Corresponding author. Tel.: +84888.68.10.18*
E-mail address: levinhan@utc.edu.vn

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between the rebars and the concrete, which induces internal pressure in the concrete. As a result, the load-bearing capacity and durability of structures decrease, then the structure needs to be repaired and strengthened the structure [5]. Therefore, the corrosion problem of RC structures attracts the attention of many researchers around the world recently[2, 6, 7].

The most effective methods of corrosion protection for concrete are: permeability reduction of the concrete; corrosion inhibitors; galvanized reinforcing; epoxy-coated reinforcing; stainless steel reinforcing (non-corrosive bars); cathodic protection and non-corrosive reinforcing bars[8, 9]. Among non-corrosive reinforcing bars, fiber reinforced polymer (FRP) bars including carbon FRP (CFRP) bars, glass FRP (GFRP) bars, basalt FRP (BFRP) bars and aramid FRP (AFRP) bars are one of the most suitable for replacing traditional steel rebars [9-15]. Recent studies [16-19] show that GFRP performs better than conventional steel reinforcements in many situations.

Using concrete mixes with river sand and freshwater resources are increasingly limited due to the depletion of these natural mineral resources[20]. Therefore, many researchers are trying to find alternative sources of materials, in which the use of seawater and sea sand has also received a lot of attention. The contents of chloride ions in seawater and sea sands are high, exceeding the allowable limit for normal concrete [21-24]. That is why FRP bars have been considered to be an ideal material to replace steel bars as reinforcements. The results of the critical review conducted by Xiao, and Qiang [25] show that in comparison with traditional concrete, seawater and/or sea sands concrete has similar workability, higher strength in early age and comparable long-term strength, lower freeze-thaw resistance, more drying shrinkage, both types of concrete have almost the same carbonation resistance.

Although concrete made of seawater and/or sea sands along with using FRP reinforcements for marine environments were intensively investigated, the effect of SWSSC on steel bar corrosion and then the behaviour of SWSSC beams are not enough examined. Furthermore, a long-term corrosion process performed on SWSCC beams without the use of any corrosion acceleration methods would provide exactly the real behaviour of these beams. As a consequence, experimental data will also aid researchers and investors to make better decisions when they construct concrete structures in marine climates. For this purpose, this paper investigates experimentally the flexural performance of SWSSC beams reinforced with steel and GFRP bars exposed to the saline condition. It should also be aware that the corrosion process conducted in this study naturally occurred in the presence of loading that is always existed in in-situ structures.

2 Experimental program

A total of three simply-supported steel reinforced SWSSC and three simply-supported GFRP reinforced SWSSC beams were cast. All beams have the same rectangular cross-section of b × h = 150 mm × 250 mm. The total length (l) of the beam was 2500 mm (Fig. 1).

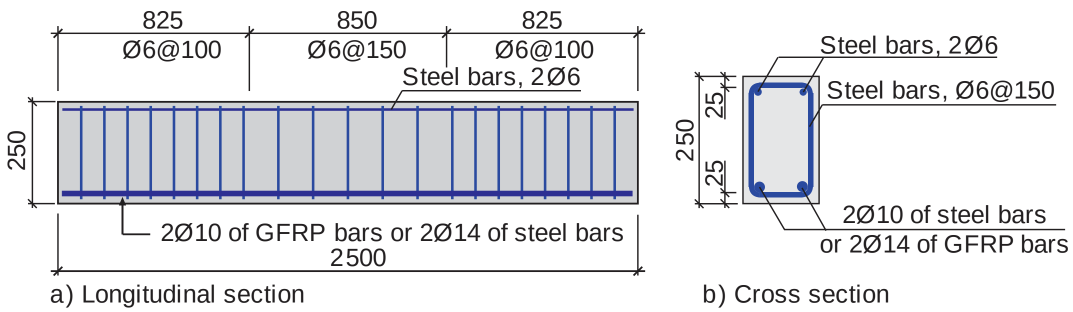


Fig. 1 – Geometric and reinforcement details of tested beams.

The steel RC and GFRP RC concrete beams were preliminarily designed as under reinforced beams with reference to ACI 318 [26] and ACI 440.1R [27], respectively, so that their load-carrying capacities are almost the same. As a result, the GFRP and steel RC beams were reinforced with two 10 mm diameter GFRP bars and two 14 mm diameter steel rebars in the tension zone, respectively (Fig. 1). Two 6 mm diameter steel bars were used as compressive reinforcement. Details of testing beams were shown in Table 1. The concrete cover for both compressive and tensile rebars is 20 mm. Two-legged stirrups from 6 mm plain round steel bars were used to avoid shear failure. According to the preliminarily designed results, the stirrup spacings were taken 100 mm in the shear span and 150 mm in the midspan (Fig. 1).

Table 1 – Details of testing beams.

No	Beam's ID	Dimensions		Tensile rebars		Compr. rebars	Notes
		b, mm	h, mm	Type	Dia-meter		
1	B1-G-0	150	250	GFRP	2Ø10	2Ø6	Control beam in the natural environment
2	B2-G-12m	150	250	GFRP	2Ø10	2Ø6	Exposure to the marine environment for 12 months
3	B3-G-60m	150	250	GFRP	2Ø10	2Ø6	Exposure to the marine environment for 60 months
4	B4-S-0	150	250	Steel	2Ø14	2Ø6	Control beam in the natural environment
5	B5-S-12m	150	250	Steel	2Ø14	2Ø6	Exposure to the marine environment for 12 months
6	B6-S-60m	150	250	Steel	2Ø14	2Ø6	Exposure to the marine environment for 60 months

Note: The beam's notation consists of three parts: the first part (B1…B6) denotes the order of the beam; the second part (G or S) identifies the types of longitudinal tensile reinforcement, G stands for GFRP bars, and S denotes steel bar; and the last part shows the time period (month) of beam specimens exposing to the aggressive environments.

The concrete used for testing beams was made of Portland cement blended, crushed stones, seawater and sea sand. The SWSSC composition is shown in Table 2. The compressive strength of concrete was evaluated by testing cubic 150 × 150 × 150 mm fabricated with beam specimens. Accordingly, the average compressive strength of concrete was 36.5 MPa. A 14 mm diameter ribbed GFRP bar used for testing beams was provided by Vietnam FRP Products, JSC. According to the manufacturer's specification, the average tensile strength and tensile elastic modulus of GFRP bar are 970 MPa and 44300 MPa, respectively [28]. The yield strength, ultimate tensile strength and the elastic modulus of the deformed steel bar were 471 MPa, 640 MPa and 200 GPa, respectively. While, the yield stress, ultimate tensile strength and elastic modulus for 6 mm diameter plain round steel bar were 340 MPa, 438 MPa, and 200 GPa, respectively. The principal constituents of seawater that are used for the concrete mix and spraying system are given in Table 3.

Table 2 – Material mix proportions of SWSSC.

Portland cement blended (PCB40),kg	Sea sand, m^3	Crushed stone, m^3	Seawater, l	Admixture (Sika Viscocrete 3000-20), l	W/C
367.8	0.508	0.3834	162.1	3.45	0.44

Table 3 – Principal constituents of seawater.

Ions	Weight	pH
Cl^-	13.35 (g/l)	7.76
Na^+	-	
SO_4^{2-}	1.12 (g/l)	
Mg^{2+}	0.055 (g/l)	
PO_4^{2-}	0.013 mg/l	
NH_4^+	0.009 mg/l	

3 Sustained loading of beams and exposure conditions

All tested beams were cured in natural conditions for 28 days. Then, the beams were loaded in a three-point loading scheme until occurring cracks in the tension zone. A couple of beams B2 and B5 were loaded together with the loading system shown in Fig. 2. This method of loading has also been used by Prof. François and his team in research on corrosion [29, 30]. When the maximum crack width reached 0.2 mm, the load was kept instant and the beams (B2, B3, B5, and B6) were kept in the marine aggressive environment generated by a spray system of seawater located along the beams in an empty room with a roof. Meanwhile, beams B1 and B4 were reloaded and tested until failure. During the first 12 months, the beams were subjected to wetting–drying cycles in order to accelerate the corrosion process, accordingly one day of spraying and

one day of drying (Fig. 2). After 12 months, the beams B2 and B5 were tested until failure, and the remained beams B3 and B6 were released from spraying system and kept outdoor under initial sustained loads for 48 months.

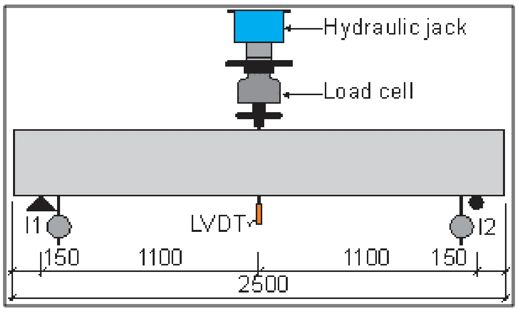
Fig. 2 – Seawater spraying system on testing beams.

Observation of the beam surfaces after 12 months of exposure to seawater showed that no new cracks appeared in both GFRP and steel RC beams. The same results were found on GFRP RC beam after 60 months (Fig 3a). However, after 60 months of exposure to seawater, the steel RC beams were significantly damaged with a longitudinal crack along the beam length located in the tensile steel bar level due to corrosion consequences (Fig 3b).

a) GFRP RC beam B3-G-60m

b) Steel RC beam B6-S-60m

Fig 3 – Beams after 60 months of exposure.



a) Test setup


b) Testing frame

Fig. 4 – Thee-point bending test.

4 Test results and discussion

4.1 Loading of beams

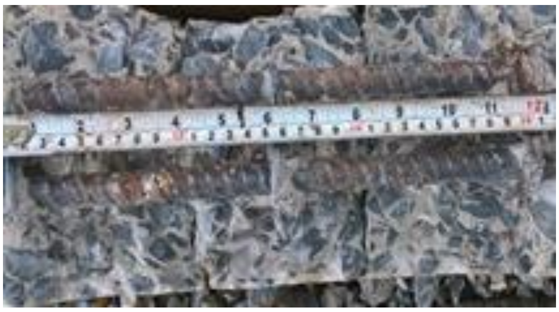
After a period of corrosion under loading, all beams were tested up to collapse under a monotonic load on three-point flexure as shown in Fig. 4. One LVDT was placed in the midspan to record the maximum deflection at the midspan, and two dial indicators (I1 and I2) placed at both ends of the beam were used to eliminate possible support displacements. A load cell was used to measure load values from the hydraulic jack. Data from LVDT and load cell are recorded by a data logger connected to a computer.

4.2 Diameter loss of rebars

As mentioned above, one of the outstanding advantages of FRP reinforcement is their corrosion resistance. Indeed, it can be seen in Fig. 5a, and Fig. 5b that the surface GFRP rebars in RC beams exposed to the marine environment in 12 months and 60 months remains intact without any signs of corrosion damage. In contrast to GFRP reinforcement, the steel bars in RC beams exposed to seawater were significantly damaged (Fig. 5d).

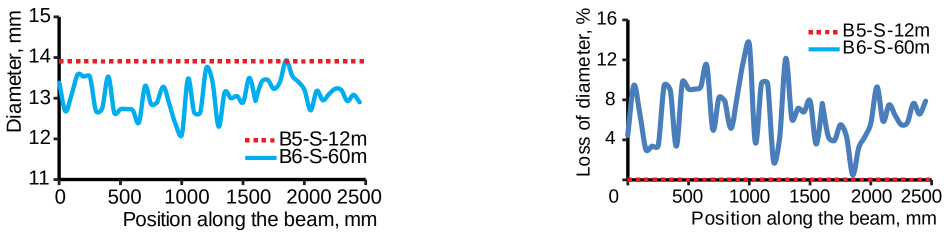

a) GFRP bars after 12 months


b) GFRP bars after 60 months


c) Steel bar after 12 months


d) Steel bar after 60 months

Fig. 5 – Corrosion of steel and GFRP bars in RC concrete beams.



a) Residual diameter

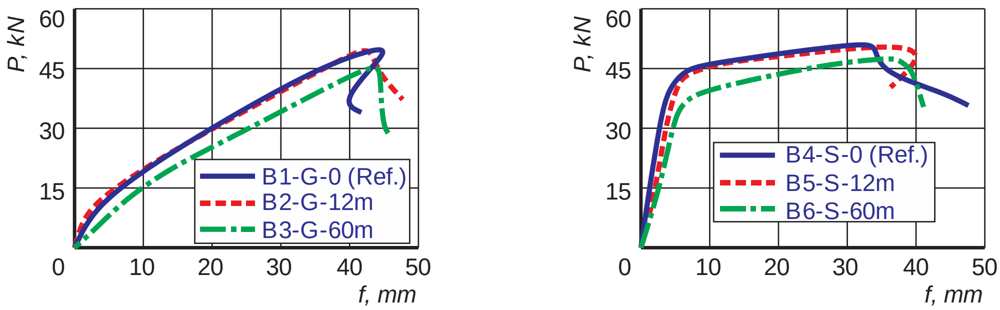
b) Loss of diameter

Fig. 6 – Loss of diameter of steel reinforcement along the length of steel RC beams.

The concrete was completely removed from the steel bars to measure the loss of diameters using a vernier caliper. Fig. 6 depicts the loss of diameter for steel RC beams B5-S-12m and B6-S-60m. For the steel RC beams exposed to seawater during a period of 12 months, the corrosion process of steel bars has just initiated and the diameter of the steel bar was generally unchanged from the sound diameter. For the beam exposed to seawater for 60 months, the steel rebars were significantly corroded. The maximum loss of the diameter is approximately 13.93%.

4.3 Flexural response and load-carrying capacity

The load versus midspan deflection curves of tested beams were shown in Fig. 7. Interestingly, after 12 months of exposure, the load-carrying capacity of beams B1-G-0 and B2-G-12m are almost the same but the load-carrying capacity of beams B3-G-60m reduced 9.1% in comparison with the reference beam (Table). It can be seen that the stiffness of B3-G-60m beam exposed to seawater in 60 months relatively reduced in comparison with the control beam and the beam exposed only for 12 months.



a) GFRP RC beams

b) Steel RC beams

Fig. 7 – Load-midspan deflection of tested beams.

This can be attributed to the decrease in bond strength between the GFRP bar and the concrete surrounding with time as explored by Dong et al.[31]. The reduction in flexural stiffness, load-carrying capacity, and yield load are also observed in steel RC beams.

Table 4 – Test results.

No	Beam ID	Yield point		Ultimate point	
		P_y, kN	M_y, kNm	P_u, kN	M_u, kNm
1	B1-G-0	-	-	49.5	28.5
2	B2-G-12m	-	-	48.9	28.1
3	B3-G-60m	-	-	45.1	25.9
4	B4-S-0	42.8	24.6	51.5	29.6
5	B5-S-12m	41.3	23.7	50.3	28.9
6	B6-S-60m	37.3	21.4	47.3	27.2

The yield load and load-carrying capacity of beams B4-S-0 and B5-S-12m were almost the same. Meanwhile, the yield load and load-carrying capacity of beams B6-S-60m reduced by 9.1% and 8.1%, respectively, in comparison with the reference beam (B4-S-0). This can be due to the loss of longitudinal reinforcement area combined with the decrease in concrete strength induced by corrosion cracking which results in a sharp decrease in the flexural strength of corroded RC beams.

5 Conclusions

The effects of seawater environments on the flexural behaviour of SWSSC beams reinforced with GFRP and steel bars were presented in this study. Corrosion is maintained under external loads for up to 60 months. The results of the experiment show that: (i) The effect of the marine environment on the GFRP bars over a period of 60 months is negligible. However, at the same time, the marine environment caused considerable corrosion of steel bars both along the lengths of the rebars. (ii) During a period of 12 months of exposure, the loss of cross section area of steel bars is generally inconsiderable. (iii) The load-carrying capacity of GFRP reinforced SWSSC beam is reduced by 9.1% after 60 months of exposure. (iv) The yield load and load-carrying capacity of steel reinforced SWSSC beam are reduced by 9.1% and 8.1%, respectively after 60 months of exposure.

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