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THE BEHAVIOR OF CARBON FIBER REINFORCED POLYMER (CFRP) STRENGTHENED BEAMS UNDER A MARINE ENVIRONMENT

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ABSTRACT: Marine concrete structures are subjected to a harsh environment and potential climate change variables. Deterioration of the structure demands drastic measures for repair and rehabilitation. Advanced composite materials exhibit unique advantages compared to conventional construction materials. Over the years, carbon fiber reinforced polymer (CFRP) composite material has been used widely for the repair and rehabilitation of structures. Many studies have been conducted on the performance of FRP flexural strengthened reinforced concrete (RC) members. Still, experimental studies investigating the performance of shear strengthening under real environmental conditions are lacking. This paper helps fill this gap because it is an experimental investigation of the behavior of CFRP shear strengthened RC beams under a marine environment. Specimens were exposed to cyclic (wet/dry) and full exposure to the elements for a 3-month period. Six strengthened beams and one unstrengthened beam were tested; the tested control beam failed due to a diagonal-tension crack. The increase in the concrete shear capacity of the strengthened specimens was in the range of 14–18% compared to the control beam. Thus, the results lead to the conclusion that CFRP strengthening increases the shear capacity of specimens considerably.

Keywords: Concrete reinforced structures, Carbon fiber reinforced polymer (CFRP), Marine environment

1. INTRODUCTION

Reinforced concrete (RC) structures often have reduced serviceability under harsh and corrosive environments. Corrosive environments are commonly encountered in marine structures, wherein splash (tidal) zones are frequently subjected to repeated wetting and drying by seawater. Corrosion of steel reinforcement occurs due to the lack of contact between the reinforcement and the surrounding concrete [1, 2] . Chloride-induced corrosion is a major issue in marine concrete structures. Corrosion either decreases the cross-sectional area or exerts substantial tensile forces on the surrounding concrete, and the corroded material occupies a larger volume than the original steel. Corrosion deteriorates the reinforced concrete structure by cracks or spalling off the concrete. The chloride-induced corrosion in steel reinforcement of an RC beam increases when it is exposed to salt-water. Medeiros, Gobbi [3] reported that in RC structures wet/dry cyclic exposure has a significant effect on chloride-ion content. This content is about 3 to 8 times higher than in structures that are not exposed to wet/dry exposure. This finding demands that drastic measures must be taken to strengthen the deteriorated marine concrete structures.

Steel plates are the most common conventional technique for flexural and shear strengthening. However, due to the poor application, corrosion, and heavy weight, this practice has gradually declined. Therefore, the application of fiber reinforced polymer (FRP) composite materials has increased in the past few decades for strengthening concrete structures. This increase is due to the exceptional properties of CFRP material, such as being non-corrosive, non-conductive, non-magnetic, and highly resistant to chemicals, light weight, high tensile strength and stiffness. One important advantage of using CFRP is its corrosion resistance property [4, 5].

Externally bonded fiber reinforced polymer (EBFRP) and the near surface mounted (NSM) technique are the most popular FRP strengthening techniques. Easy installation, lower costs, less clearance loss, and prevention of chloride-ion penetration into concrete are the advantages of the EBFRP technique compared to the NSM technique. CFRP application as an alternative technique is the most useful technique for improving the shear strength of RC beams. It increases the shear capacity of the beam significantly [6]. Many studies have shown that CFRP strengthening increases the ultimate load capacity of RC members [7-9].

A considerable number of studies have been conducted to investigate the reliability performance of CFRP flexural strengthened RC beams [10-12]. However, limited experimental work has been devoted to investigating the performance of the CFRP shear strengthened RC beams compared to the CFRP flexural application. Furthermore, limited data are available regarding the effect of marine environment exposure on the performance and behavior of various CFRP shear strengthening schemes. This paper investigates the effectiveness of using CFRP sheets to improve the shear capacity of RC beams in a marine environment.

2. EXPERIMENTAL PROGRAM

2.1 Sample Preparation

The experimental program is summarized in Table 1. Six rectangular RC beams were tested. One unstrengthened beam served as a control beam (CON). Two beams were strengthened with CFRP U-wrap (UC-0) and 2-sided wrap (2SC-0) schemes as a baseline beam. The control and baseline beams were exposed to the ambient temperature. Three strengthened beams with two different schemes (U-wrap and 2-sided wrap) were exposed to a marine environment. UC-CY-3 and 2SC-CY-3 were referred to the continuous U-wrap and continuous 2-sided wrap strengthened RC beams under cyclic exposure, respectively. The continuous U-wrap strengthened RC beam under full-immersion was labelled as UC-FU-3.

All the fabricated beams had a rectangular cross-section with a size of 150 mm x 250 mm and a 2000 mm length. Each beam was reinforced with two 16 mm diameter longitudinal tension bars and two 12 mm diameter hanger bars. No. 6 steel bars were used as a shear reinforcement (stirrups) with a two-legged rectangular-shape with standard hooks and stirrups spaced center-to-center at 200 mm. A typical clear cover of 25 mm was used all around the stirrups. The beams setup, typical dimensions and reinforcement details are shown in Fig.1.

Table 1 Description of the test program

Beam No	Wrapping scheme	Environmental Condition	
		Type	Duration (months)
UC-0	U-wrap	Control	---
UC-CY-3		Cyclic	3
UC-FU-3		Full	
2SC-0	2-sides	Control	---
2SC-CY-3		Cyclic	3
CON	---	---	---

The specimens were cast with ready-mixed concrete. After 28 days, the average of three concrete cylinders' compressive strength was f'c=22.13 MPa. Tension and compression reinforcements were tested under uniaxial tension load via a Universal Testing Machine (UTM) to determine the yield strength. Table 2 presents the material properties of the steel reinforcements and concrete.

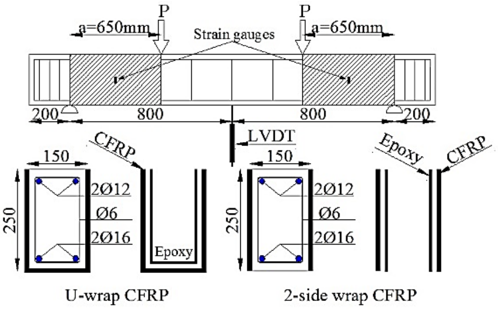

Fig.1 Test specimen reinforcement configuration and schematic of strengthening schemes

Table 2 Material properties

Material	Diameter of bar (mm)	Average strength (MPa)	f'c (MPa)
Rebar 16	16	556	-
Rebar 12	12	550	-
stirrup	6	247	-
Concrete	-	-	22.13

2.2 CFRP Strengthening Procedure

Initially, any loose particles and uneven surfaces were removed by grinding the surface. After grinding, sand paper was used to smooth the surface. Then, the concrete surface was prepared via an acetone application. The epoxy resin used was Sikadur-330, which was prepared following the manufacturer's instructions. The epoxy was applied onto the concrete surface using a small paint roller. A hand roller was used to squeeze out any excessive air voids between the concrete surface and CFRP fabric. All the CFRP bonded specimens in this study were bonded with one layer of CFRP unidirectional SikaWrap-231C fabric. The beams strengthened at shear span of 650 mm as shown in Fig.1. After the CFRP fabric was completely applied, the specimens were allowed to cure for 7 days at the ambient temperature before they were subjected to environmental conditions, as detailed in the next section. The mechanical properties of the CFRP composite are listed in Table 3.

The two different strengthening schemes investigated in this study comprised bonding CFRP to the sides of the beam only (2-sided wrap) and bonding CFRP to three sides (two sides and tension face, U-wrap). CFRP sheets were installed continuously for all wrapping schemes.

Table 3 Mechanical properties of carbon fibers

SikaWrap–231C		
Thickness (mm)	Tensile strength (MPa)	Modulus of elasticity (GPa)
0.127	4900	230

2.3 Environment Exposure

To accelerate the degradation of the specimens subjected to marine exposure conditions, an accelerated aging process [13] was applied in this study. The marine environmental conditions of 100% humidity and 3.5% salinity were simulated via three stainless steel water tanks at the civil structural laboratory of Universiti Teknologi PETRONAS (UTP). Three stainless steel water tanks with dimensions of 2500 mm length, 1500 mm width, and 1500 mm height were constructed. Full details of the water tank setup are shown in Fig.2.

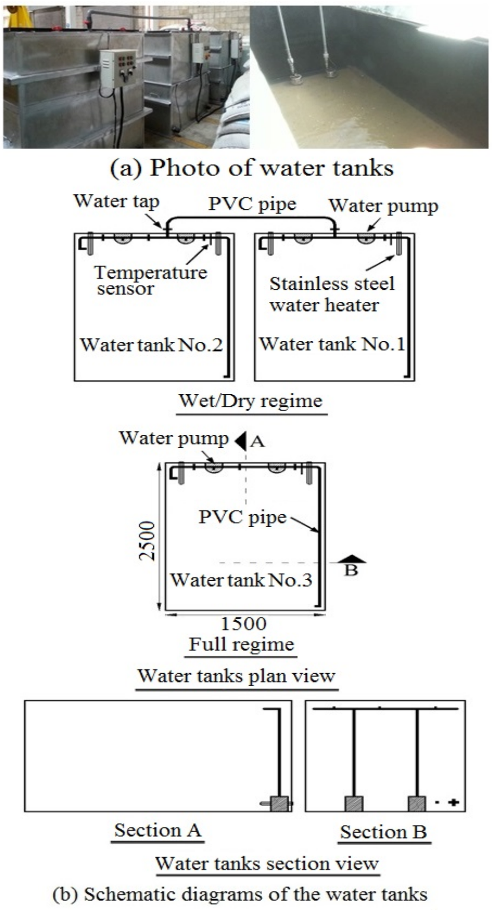

Fig.2 Stainless steel water tanks used in the accelerated aging process

The salt-water was prepared by dissolving coastal salt in tap-water. Each tank had two heaters to maintain the temperature of the solution as per ASTM standards; one thermocouple was installed to continuously monitor the solution temperature and two pumps were located at opposing corners of the tank to circulate the water as shown in Figure 2. A salt-water solution with 3.5% salinity was used in this study to reproduce the average salinity level found in ocean seawater. The solution temperature was maintained at 60 ºC to accelerate the chemical deterioration process and moisture absorption.

The specimens were subjected to environmental conditions for a 3-month period including a wet/dry cyclic regime and full immersion. Each wet/dry cycle comprised 3 days of full immersion in the salt-water solution at 60 °C, followed by drying for 3 days at the ambient temperature in the laboratory. The fully immersed condition comprised fully immersed specimens in a salt-water solution at 60º C for a period of 3 months.

2.4 Loading and Measurements

The beams were transferred to the structural lab after environmental conditioning, which was instrumented via linear variable displacement transducers (LVDT) to determine the mid-span deflection. The instrumented specimens were subjected to a four-point loading test at a rate of loading 0.10 (Fig.3). The applied load on the beam was measured with a load cell of 500 kN capacity fixed between the test machine and steel roller. All the readings of the LVDT and load cell were recorded by a data acquisition system as shown in Fig.4.

Fig.3 Test setup

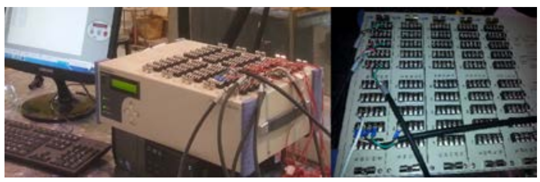

Fig.4 Data acquisition system

3. RESULTS AND DISCUSSION

Two different failure modes of the beams were noted as a result of the strengthening. The CON specimen failed in shear mode, whilst the baseline beams failed in flexural mode. Shear failure is commonly characterised by yielding of the stirrup reinforcements crossing the critical shears crack due to the large crack openings. The typical failure modes of CFRP strengthening consist of debonding or rupture of the CFRP. The failure modes have a considerably significant effect on the overall failure mode of the beam. The effectiveness of CFRP strengthening is subject to the severity of the CFRP sheet debonding. No CFRP strengthening failure mode was observed in this study. Fig.5 shows the failure mode of the reference beams.

Loading of CON was stopped at a shear of 121.85 kN. The cracks initially appeared at 37 kN. Then, the depths and widths of the cracks increased as the loads increased. The expected shear cracks appeared at the shear span when the load was around 82 kN. As the applied load gradually increased, a principal shear crack started to form and propagated. The results show that both the U-wrap and the 2-side wrap strengthened specimens show a good performance.

Fig.5 Failure mode of reference beams

Figs.6 to 8 illustrate the load–deflection relationships of the reference beams, and environmental conditioned beams. Table 4 presents the experimental results of the tested specimens. The control beam failed in shear at an applied load of 121.85 kN. The UC-0 and the 2SC-0 failed in flexure at an applied load of 138.74 kN and 143.44 kN, respectively. As a result of the strengthening, the failure load of UC-0 and 2SC-0 increased by about 14% and 18% respectively compared to that of CON. The experimental results of the beams show that strengthening RC beams with CFRP in shear enhances the strength of the RC beam.

Figs.6 and 7 show the mid-span deflection of continuous U-wrap strengthened RC beams under cyclic and full-immersion exposure. From the results, it was observed that environmental exposure resulted in load–deflection responses. The load–deflection graphs clearly show that all the CFRP strengthened beams performed significantly better in terms of both strength and mid-span deflection compared to the CON. The increment of strength is the main feature of strengthening the RC beams using CFRP sheets. The graphs show that the environmental condition yielded an increase of deformation capacity. Compared to the UC-0, the mid-span deflection of the UC-CY-3 and UC-FU-3 increased to 38.45 mm and 45.72 mm, respectively. The increase in deflection of the beam could be due to the decrease in the stiffness of the specimens. The results showed that the failure load of the specimens decreased after the 3-month exposure compared to the UC-0. The load–deflection curves showed that after 3 months of environmental exposure, the shear force decreased by 5.54% compared to UC-0. This reduction may be due to a crystallization of salts inside the concrete pores. The results are in agreement with a previous study by Grace and Singh [14].

Table 4 Experimental results

Beam No	Failure load	Deflection
CON	121.85	10.71
UC-0	138.74	17.05
2SC-0	143.44	17.57
UC-CY-3	131.05	38.45
UC-FU-3	136.85	45.72
2SC-CY-3	132.75	29.01

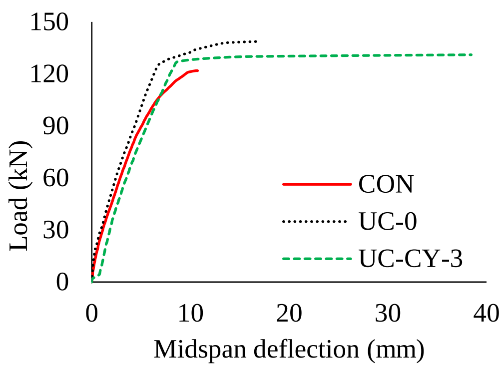

Fig.6 Load–deflection curve for CFRP U–wrap strengthened beam exposed to wet/dry cyclic regime

Fig.7 depicts the load–deflection results of U-wrap strengthened RC beams with a continuous

CFRP sheet under full immersion exposure. Specimen UC-FU-3 exhibited a significant improvement in deflection of about 168.15%. The environmental condition caused the increases in deflection.

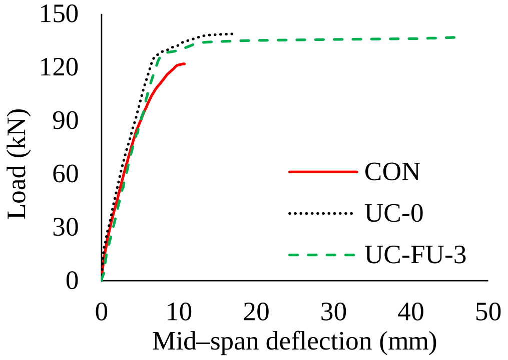

Fig.7 Load–deflection curve for CFRP U–wrap strengthened beam exposed to full regime

Fig.8 shows the mid-span load–deflection results of the 2-side strengthened RC beams exposed to cyclic exposure. The graphs show that all CFRP strengthened beams performed significantly better in terms of strength and deflection than CON. It was observed that the failure load of the 2-sided CFRP strengthened beam increased compared to the CON (approximately 18% reduction). The mid-span deflection of the 2SC-0 increased by about 64% compared to CON. The results showed that after the 3-month exposure the failure load decreased and mid-span deflection increased due to the exposure. The mid-span deflection of 2SC-CY-3 increased by about 65% compared to 2SC-0. However, the failure load decreased by about 7.5%. Therefore, among the tested exposed beams a considerable change in strength was observed in the 2SC-CY-3, with a failure load of 132.75 kN.

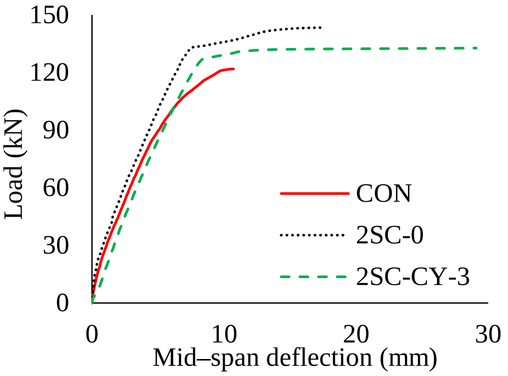

Fig.8 Load–deflection curve for CFRP 2–side wrap strengthened beam exposed to cyclic regime

The load versus the mid-span deflection curves of the strengthened beams that were subjected to marine environmental conditions show that the measured response of the specimens varied according to the strengthening scheme, exposure type, and exposure duration. However, in terms of failure load and maximum deflection, the U-wrap strengthened specimen with continuous CFRP results is similar to the 2-sided wrap strengthened specimen with continuous CFRP results. Overall, it can be noticed that the U-wrap or 2-sided strengthening with continuous CFRP considerably improved the shear capacity and structural behavior of the RC beams. It was discovered that the continuous CFRP application with U-wrap scheme was reliable and efficient for the beams subjected to the 3-month saltwater solution exposure.

4. CONCLUSION

This paper tested six RC beams and reports the behaviour of CFRP strengthened concrete specimens. The results revealed a significant strength improvement of the strengthened specimens. Three of the tested beams were exposed to a marine environment. Moisture and salinity conditions can markedly degrade a specimen's strength. The following conclusions summarize the results of this research:

- CFRP application significantly enhanced the performance of RC beams, with an increase in the load capacity.
- After a 3-month period of wet/dry cyclic and full-immersion exposure the deflection increased.
- The U-wrap bonded scheme deflection after the 3-month exposure was higher than that of the 2-sided bonded scheme.
- The U-wrap and 2-sided strengthening schemes are about the same in terms of shear strength gain and failure mode.
- The strengthened beams that were exposed to saltwater exhibited an increased load-carrying capacity compared to that of the baseline beams.

5. ACKNOWLEDGEMENTS

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6. AUTHOR'S CONTRIBUTIONS

The experiments were conducted by Hamed Fazli as part of his PhD research project, under the supervision of Dr. Airil Yasreen Mohd Yassin. The

draft of the manuscript was prepared by Hamed Fazli and revised by Dr. Airil Yasreen Mohd Yassin, Prof. Nasir Shafiq, and Dr. Teo Wee.

7. ETHICS

This article is original work and not under consideration for publication in any other journal. There are not conflict interest on this paper.

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