Durability of concrete with CFRP wrapping

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Abstract. Carbon fibre-reinforced polymer (CFRP) material has a high strength-to-weight ratio and good resistance to corrosion and environmental attacks. It has been widely used in rehabilitation of aged infrastructure. However, the durability of the strengthened system has not been yet assessed thoroughly since most of the previous study was conducted based on accelerated tests while the long-term investigation was less reported. This paper investigated the effect of CFRP wrapping on the axial behaviour of concrete cylinders subjected to different environments for more than 13 years. The specimens were exposed to five different conditions, including standard curing, immersion in distilled water, immersion in saturated Na2SO4 solution, outdoor sheltered from the rain, and outdoor without shelter from the rain. Axial compression tests were performed on the wrapped concrete cylinders. The load-bearing capacity and stress-strain responses were recorded. It was found that CFRP wrapping could effectively improve the ultimate strength and ductility of the columns. Though scatter existed, no significant effect of the environmental exposure on the load-bearing capacity of the cylinder specimens was observed which indicates a good durability of the strengthening system.

1 Introduction

When subjected to combined effects of service load and environmental attack, damage accumulation generally occurs to infrastructure, leading to deteriorated structural performance. The maintenance and retrofitting of aged infrastructure, therefore, become a major concern of community in civil engineering.

Recently, external bonding with carbon fibre-reinforced polymer (CFRP) materials has been an attractive choice attributed to the high strength-to-weight ratio, excellent resistance to fatigue and corrosion damage as well as ease of installation. Confining concrete with CFRP is proven effective to enhance both the strength and ductility of the material and extensive research has been performed to investigate the strength model as well as the stress-strain behaviour of CFRP confined concrete in the last two decades [1-6].

However, one of the main limitations to the more widespread use of CFRP in rehabilitating application is the uncertainty in the long-term durability of the CFRP/concrete system upon exposure to service environments [7-10].

Toutanji [8] tested concrete cylinder columns wrapped with four types of fibre-reinforced polymer (FRP) composite and two types of epoxy matrix. The effects of two environmental conditions, i.e., room temperature and 300 cycles of wetting and drying in sea water and hot air at 35 °C, respectively, were compared. Test results implied that CFRP confinement was durable in both strength and ductility, regardless of the type of epoxy used. However, the durability of glass FRP (GFRP) confined specimens was more dependent on the profile of the adhesive.

Bae and Belarbi [9] focused more on the effect of combined environmental conditions. Both small and mid-scale reinforced concrete (RC) cylinder columns wrapped with either CFRP or GFRP sheets exposed to freeze-thaw cycles, high-temperature cycles, high-humidity cycles, ultraviolet (UV) radiation, and saline solution were loaded by uni-axial compression. GFRP wrapped specimens were witnessed a variation of compressive strength from -14% to 5% while CFRP confined ones experienced a maximum deterioration of 5% which demonstrated that CFRP confinement was less vulnerable to environmental attack than GFRP. Prediction for the axial capacity of FRP confined RC columns and strength reduction factors to account for the effects of various environmental conditions were proposed.

In Subhani and Al-Ameri [10], the performance of CFRP wrapped squarer columns subjected to wet/dry cycles of salty water and elevated temperature was examined. It was concluded that the confined compressive strength of the column deteriorated due to the reduction of Young modulus, ultimate tensile strength and failure strain of the FRP. Decrease of 8.23% and 0.88% was observed for specimens with normal and modified epoxies after 126 days’ exposure, respectively, and the detrimental effect was supposed to start from 84
days. A reduction factor was derived to incorporate the effect of marine exposure in estimation of the columns’ strength.

Micelli et al. [7] summarised approximately 760 pure axial compression tests of FRP confined concrete columns from 17 experimental studies. The parameters included the geometry of section, mechanical properties of reinforcement longitudinal bars, mechanical properties of FRP fibres, mechanical properties of concrete, cylindrical strength and environmental agents. The reliability of ACI 440-2 R/2008 and CNR DT-220/2013 design-oriented models in predicting the long-term safety of FRP-confined concrete columns were critically assessed by comparison with experimental results.

However, most of the previous study was conducted based on accelerated tests while few attempts have evaluated the long-term effects. In this study, the axial compressive behaviour of CFRP confined concrete cylinder columns exposed to five different environmental conditions was recorded up to 13 years. The confinement was proven effective in enhancement of compressive strength and ductility. Though scatter existed, no significant deterioration was witnessed for the load-bearing capacity of the cylinder specimens which indicates a good durability of the strengthening system.

2 Experimental program

A total of 55 columns were tested for a comprehensive investigation of the long-term behaviour of CFRP confined concrete.

2.1 Specimen configuration and materials

The specimens were 100 mm in diameter and 300 mm in height. The concrete mix ratio of cement : sand : gravel : water = 1 : 2.63 : 4.29 : 0.54 and the designed 28-day cubic compressive strength of the concrete was 45 MPa. After curing cured for 28 days at a temperature of 20±3°C and a relative humidity (RH) in excess of 90%, the cubic and prism compressive strength of the concrete were tested as 51.0 MPa and 36.3 MPa, respectively.

Based on the manufacturers’ datasheet, the primer had a bond strength (steel to steel) larger than 10 MPa, and the structural adhesive had a tensile strength larger than 40 MPa, a normal bond strength larger than 30 MPa, and a shear bond strength larger than 18 MPa. The CFRP sheet adopted had a nominal thickness of 0.111 mm and the mechanical properties were obtained through flat coupon tests. Its tensile strength was 5095 MPa and the Young’s modulus was 345 GPa.

2.2 Specimen preparation

The concrete surface was first ground by an angle grinder to remove any weak areas and then cleaned with acetone. The column was brushed by the primer to repair any defects and left to dry before CFRP jacketing to prepare a smooth contact surface. Afterwards, one layer of CFRP sheet was manually lay-up with the fibres oriented in the hoop direction. The overlap length was set at 116 mm. Both ends of 50 mm wide were locally strengthened by CFRP sheet to avoid premature failure during loading (Fig. 1). The wrapped specimens were kept in the laboratory air-conditioned environment at a temperature of 16°C for one week before environmental exposure.

![Fig. 1. Specimen configuration and dimensions.](https://doi.org/10.1051/matecconf/2018199090009)

Five different environmental conditions were adopted in the experimental program, i.e., standard curing condition (20 ± 3°C, RH≥90%), immersion in distilled water, immersion in a saturated Na₂SO₄ solution, outdoor sheltered from the rain, and outdoor without shelter from the rain. They were mainly used to simulate the scenarios occurred to highway bridge structures. Generally, the piers or foundations serve in soil or rivers, which lead to an attack of sulfate or water; the piers and decks are subjected to outdoor condition with or without rain. Therefore, the test program was designed according to Code for anticorrosion design of industrial constructions (GB50046-95) [11].

![Fig. 2. Five environmental exposure conditions.](https://doi.org/10.1051/matecconf/2018199090009)

2.3 Testing and instrumentation

The exposure tests started from December 2004 and are still ongoing, which have lasted for more than 13 years. The compressive tests on FRP-confined concrete specimens were perforomed at a certain interval by using a 1000 kN electro-hydraulic servo universal testing machine. Two thick and flat steel plates were mounted at the top and bottom of the specimen. Two strain gauges
were installed on the front and back sides to detect the hoop strain of the CFRP, and two linear variable differential transformers (LVDTs) were placed on left and right sides to obtain the axial deformation of the specimen, as shown in Fig. 3.

All the specimens were tested under a displacement control mode at a fixed rate of 0.3 mm/min.

**Fig. 3.** Test set-up and instrumentation.

### 3 Experimental results and discussions

Table 1 presents a summary of the compressive strength of all the test specimens. Eleven batches from 125 days to 3759 days were selected. The specimen nomenclature is as follows: SC=standard condition, DW=distilled water, SS=sulfate solution, OS=outdoor sheltered from rain, and OR=outdoor without shelter. The number after the hyphen indicates the time period of exposure at the test. \( f'_{ca} \) and \( \varepsilon_{ca} \) represent the compressive strength and the ultimate axial strain of the aged specimens, respectively; \( f'_{a} \) and \( \varepsilon_{a} \) denote the axial strength and the ultimate axial strain of a concrete cylinder without confinement cured in the standard condition for 28 days which is considered as the control specimen, respectively, i.e., 40.81 MPa and 2141 με.

**Table 1.** Compressive strength of all the test specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( f'_{ca} )</th>
<th>( (f'<em>{ca} - f'</em>{a})/f'_{a} ) (%)</th>
<th>( \varepsilon_{ca} )</th>
<th>( (\varepsilon_{ca} - \varepsilon_{a})/\varepsilon_{a} ) (%)</th>
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<tr>
<td>SC-125</td>
<td>72.66</td>
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<td>107.45</td>
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</table>

Note: N/A indicates that the strain data was missing due to the malfunctioning of the LVDT.

#### 3.1. Failure mode

As the compression force increased, minor fracture of CFRP was heard and the concrete columns finally crushed simultaneously after rupture of CFRP. The overlapping zone was kept intact and no delamination was observed. The failure occurred at around the mid-height of the specimen and Fig. 4 shows a typical view tested at 3759 days. According to the experimental findings, exposure period and conditions did not affect the failure mode of the CFRP-confined columns.

**Fig. 4.** A typical failed specimen
3.2. Effect of CFRP confinement

By comparing the test results listed in the third row of Table 1, the compressive strength of the CFRP confined concrete was improved by 5.4% to 123.3%, with a mean value of 85.7% and a coefficient of variation (COV) of 0.28. With respect to the ultimate strain recorded in the fourth row, most of them increased in comparison with that of the control specimen, although decline of the compressive strain of specimens SC-750 and OR-213 was witnessed. The followed tests on specimens SC-1203 and OR-289 showed that the peak strains increased by 217.38% and 119.06%, respectively. Therefore, it was concluded that the CFRP confinement could effectively improve the deformability of the columns.

Fig. 5 plots a typical stress-strain curve of the specimen DW-3759, including the axial strain and the hoop strain recorded by the LVDT and strain gauges on CFRP, respectively. Subjected to adequate lateral confinement, the column displayed an obvious strain-hardening behaviour.

![Fig. 5. A typical stress-strain relationship of the confined column (DW-3759)](image)

3.3. Effect of environmental exposure

Taking the experimental data of the concrete column cured in the standard condition for 125 days as the baseline, the variation of the compressive strength subjected to five environmental conditions up to 3759 days is illustrated in Fig. 6. The compressive strength ratio ranges from 0.59 to 1.25, with a mean value of 1.04 and a COV of 0.13.

The maximum deterioration occurred in the specimen OR-213, where the compressive strength was decreased by 41%. However, the followed test on the specimen OR-289 showed a recovery.

In order to have a closer look at the effect of different environmental conditions, the compressive strength ratio of specimens subjected to standard condition, distilled water, sulfate solution, outdoor sheltered from rain and outdoor without shelter had mean values of 1.02, 1.04, 1.06, 1.08 and 1.02, respectively and COV values of 0.11, 0.15, 0.10, 0.11 and 0.19, respectively.

Although scatter exists, all the specimens had endured 3759 days’ exposure to water immersion, sulfate attack and outdoor condition. The compressive strength ratio fluctuated around 1.0 and no apparent deterioration of the ultimate load bearing capacity was witnessed.

![Fig. 6. Compressive strength ratio versus exposure time.](image)

The variation of the ultimate strain ratio with respect to the value of the specimen cured in the standard condition for 125 days is depicted in Fig. 7. In comparison with the compressive strength, the scatter of the ultimate strain is much larger. However, no apparent trend was found and the value also fluctuated around 1.0.

![Fig. 7. Ultimate strain ratio versus exposure time.](image)

Based on the current experimental program, it was implied that the long-term exposure had no significant effect on the compressive behaviour of the cylinder specimens and the five environmental conditions involved in this study had little difference.

4 Conclusions

This study presents an experimental study on the long-term behaviour of CFRP-confined concrete columns. The specimens were exposed to five different environmental conditions for more than 13 years and tested under compressive load.

In comparison with the specimens without CFRP wrapped which was cured in standard condition for 28 days, the compressive strength was improved up to
123.3% and the ultimate axial deformation was also pronouncedly extended.

A total of 11 intervals were selected from 125 days to 3759 days to record the durability of the CFRP-confined cylinders. Based on the current experimental program, though scatter exists, no significant deterioration of compressive strength and ductility were observed. The strengthening system showed a good durability and is a promising technique for engineering practice.

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References