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Comparison of Concrete Strengthened with Carbon Fibre-Reinforced Polymer (CFRP) and Carbon Textile-Reinforced Mortar (CTRM)

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ABSTRACT

Applying new composite material for strengthening and repairing existing structures is an important research topic. Carbon Fiber Reinforced Polymer/Plastics (CFRP) and Carbon Textile Reinforced Mortar (CTRM) are two common structural external reinforcement materials. 18 concrete specimens strengthened with CFRP and CTRM are prepared in this study. The quasi-static single-sided shear tests combined with the Digital Image Correlation (DIC) method is applied. The results show that the interface bonding strength of CFRP strengthening (0.76-0.96 MPa) is 65.0% to 74.8% higher than the CTRM-concrete interface (0.43-0.63 MPa). The ductility and energy dissipation capacity of CTRM strengthening is better than that of CFRP strengthening, and the effective bonding length is 125 to 300 mm. In practical work, CFRP is preferred for improving the strength of concrete components, while CTRM is preferred for improving ductility and seismic resistance.

Keywords: Carbon fibre-reinforced composites (CFRP); Carbon textile-reinforced mortar (CTRM); Digital image correlation method (DIC); Single-sided shear test

INTRODUCTION

The global building stock comprises many historic constructions that require repair and structural strengthening. This requirement arises from the need to improve the original performance of these structures under existing loads or to increase their load-bearing capacity to satisfy changes in use and increase their service life. Applying new composite material for strengthening and repairing existing structures is an important research topic. Carbon fibre-reinforced polymer (CFRP) and carbon textile-reinforced mortar (CTRM) have recently been applied in structural strengthening (Koutas, 2019; Zampieri, 2018). CTRM comprises carbon textiles combined with an inorganic mortar matrix. CFRP comprises CFRP sheet and epoxy resin. The mechanical behaviour of TRM depends on the material properties of the fibre and the bond behaviour between the fibre and the substrate (Raoof, 2006). The FRP/TRM–concrete bond performance is critical for ensuring the safety and efficiency of the strengthening (Yuan, 2004; Yao, 2007; Ueda, 2005; Su, 2021). The single shear pull-out test (Oliveira, 2010; Zhou, 2020; Yang, 2017) has been widely used in the laboratory to characterise the FRP-concrete bond behaviour, which adequately reproduces the loading conditions in service.

The typical failure modes of composite strengthened concrete have been identified in the literature (De Felice, 2018): (1) damage of the substrate, (2) debonding at the fiber-substrate interface, and (3) fibre rupture. However, a comparison of the bond behaviour of CFRP and CTRM is still lacking (Wang, 2020; Wang, 2023). In this study, the bond behaviour of CFRP and CTRM to concrete was investigated experimentally by using single-sided shear tests.

MATERIALS AND METHODS

Carbon textile and CFRP

Five carbon textile and CFRP sheet samples are prepared for mechanical characterisation tests. The length and width of the sample are 230 mm and 50 mm, respectively. Each sample is bonded and gripped with two aluminium taps of 50 mm in length. The failure patterns are shown in Figures 1 and 2. The test results are listed in Table 1.

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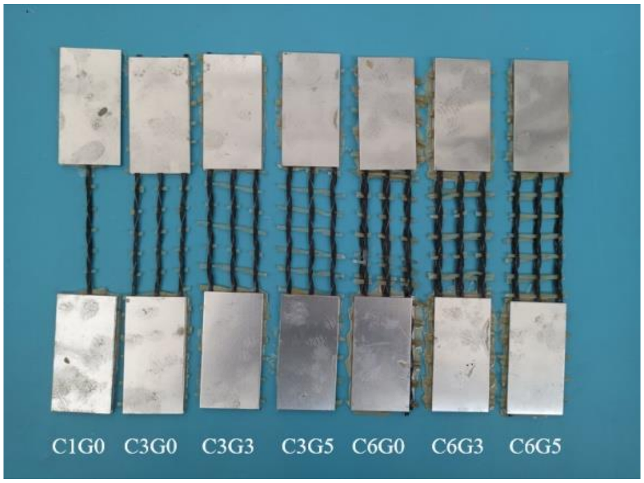
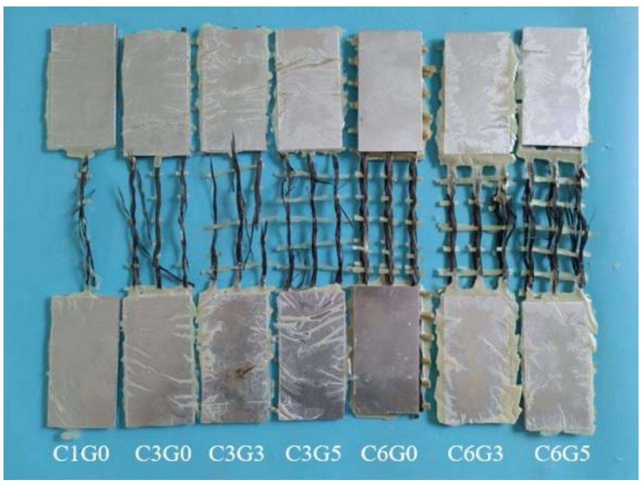


(a) Sample preparation



(b) Failure pattern

Figure 1. Tensile sample of carbon textile

(a) Sample preparation

(b) Failure pattern

Figure 2. Tensile sample of CFRP sheet

Table 1. Tensile mechanical properties of carbon textile and CFRP sheet

Specimen No.	Peak load (kN)	Tensile stress (MPa)	Peak strain (%)	Elastic modulus (GPa)
C1G0	2.30 (0.02)	1121.96	1.3 (0.05)	121 (5.7)
C3G0	6.34 (0.16)	1124.63	1.6 (0.05)	76 (2.2)
C3G3	6.70 (0.05)	1188.73	1.8 (0.06)	81 (2.1)
C3G5	6.66 (0.22)	1180.73	1.8 (0.05)	77 (1.5)
C6G0	9.57 (0.27)	848.36	2.0 (0.05)	58 (0.9)
C6G3	9.81 (0.65)	869.49	2.3 (0.12)	53 (1.5)
C6G5	9.51 (0.28)	842.90	2.1 (0.03)	55 (1.1)
CFRP sheet	6.045 (0.05)	3630	/	/

Coefficients of variation (CoV) in brackets

Preparation of specimen

Figure 3 shows the procedure for preparing a CTRM strengthened concrete specimen. The concrete block dimensions are 300 mm or 400 mm ×100 mm ×100 mm, the corresponding bond length is 250 mm or 350 mm, and the width is 50 mm. Pre-cut carbon textiles were laid onto the first layer of mortar, and finally, another layer of mortar was applied to the textile to finish the process (Figure 3). The total thickness of the CTRM is 15 mm.

Figure 3. Preparation of CTRM strengthened concrete specimen

Test setup

The single-lap shear bond test (Zhang, 2023) was applied to the wet lay-up unidirectional CFRP and CTRM strengthened concrete elements. Figure 4 shows a test setup of the single-lap pull-out tests, according to the recommendation of RILEM Technical Committee 250-CSM (De Felice, 2018). The loading was applied from the unembedded textile to the CTRM and concrete. The unembedded textile was pulled out monotonically by the testing machine. The digital image correlation measures the surface displacement and strain distribution of the test specimen.

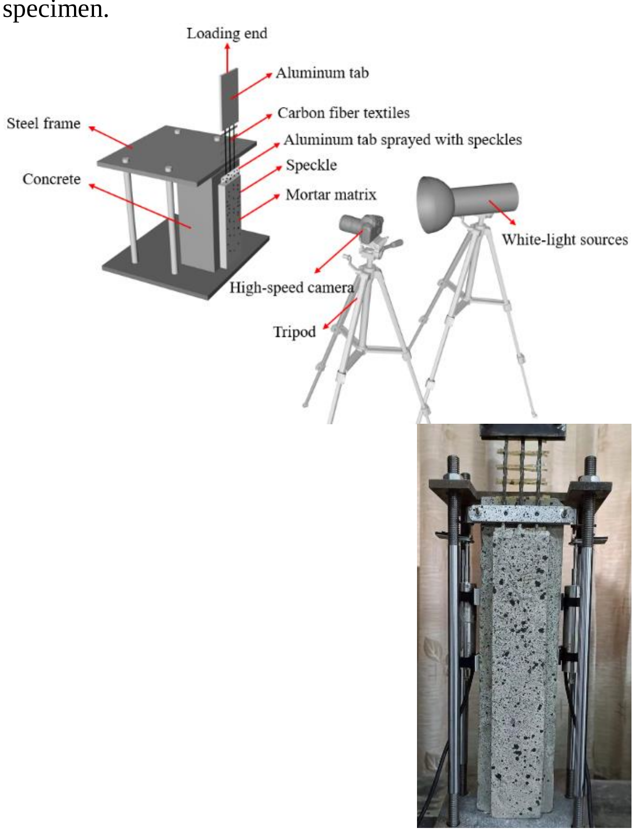


Figure 4. Test setup.

RESULTS AND DISCUSSION

Test results for each specimen are listed in Table 2 and Table 3. For the CTRM strengthened concrete, the average initial cracking and peak loads at the loading end were 8.11 kN and 9.01 kN, respectively. For the CFRP strengthened concrete, the average initial cracking load and peak load at the loading end were 12.87 kN and 15.13 kN, respectively. The failure mode of TRM strengthened concrete was a mixed damage failure with matrix crack and textile rupture. The bond strength of 6 specimens of Type I (T2I and T3I) is relatively higher than that of 6 specimens of Type II (T2II and T3II), indicating that its bonding length is greater than the effective bonding length. This is because the protective layer of Type I is thicker, which makes its effective bonding length shorter.

In contrast, the failure mode of 6 specimens of CFRP strengthened concrete (F2 and F3) was a debonding failure, as shown in Figure 5. The results show that the interface bonding strength of CFRP strengthening (0.76-0.96 MPa) is 65.0% to 74.8% higher than the CTRM-concrete interface (0.43-0.63 MPa), indicating that the bond of CFRP is stronger than that of CTRM.

Figure 6 compares the experimental load-slip responses of CTRM and CFRP-strengthened concrete. The load-slip curves show that CTRM strengthening has better ductility and energy dissipation capacity than CFRP strengthening. Figure 7 shows the strain contours obtained by DIC of the specimens at different load levels, Pu is the peak load. The length of failure was conducted from the DIC results, which is the length of strain distribution at peak load. The strain contours show that the effective bonding length is 125 to 300 mm.

Table 2. Test results of CTRM strengthened concrete

No.	FL (mm)	FM	CL (kN)	PL (kN)	BS (MPa)
T2 I -1	128	Mixed failure	6.86	9.89	0.66
T2 I -2	120		6.08	9.39	0.63
T2 I -3	125		7.76	9.16	0.61
T3 I -1	126	Mixed failure	7.68	9.42	0.45
T3 I -2	131		9.11	10.13	0.48
T3 I -3	129		9.37	9.37	0.45
T2 II -1	250	Mixed failure	7.32	7.37	0.49
T2 II -2	250		7.99	7.99	0.53
T2 II -3	250		8.07	8.07	0.54
T3 II -1	302	Mixed failure	9.12	9.12	0.43
T3 II -2	296		8.79	8.79	0.42
T3 II -3	306		9.19	9.40	0.45

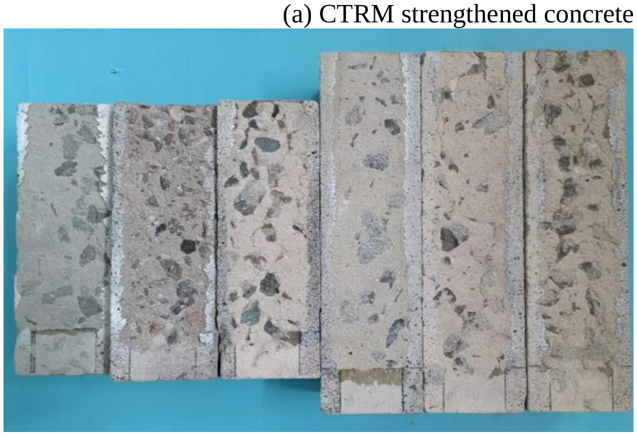
FL, FM, CL, PL BS are failure length, failure mode, crack load, peak load, and bond strength.

Table 3. Test results of CFRP strengthened concrete

No.	FL (mm)	FM	CL (kN)	PL (kN)	BS (MPa)
F2-1	250	CFRP debond	12.13	14.35	0.96
F2-2	250		12.06	15.18	1.01
F2-3	250		11.85	13.51	0.90
F3-1	350	CFRP debond	13.22	14.56	0.69
F3-2	350		14.68	17.55	0.84
F3-3	350		13.29	15.61	0.74

FL, FM, CL, PL BS are failure length, failure mode, crack load, peak load, and bond strength.

(a) CTRM strengthened concrete



(b) CFRP strengthened concrete

Figure 5. Failure mode

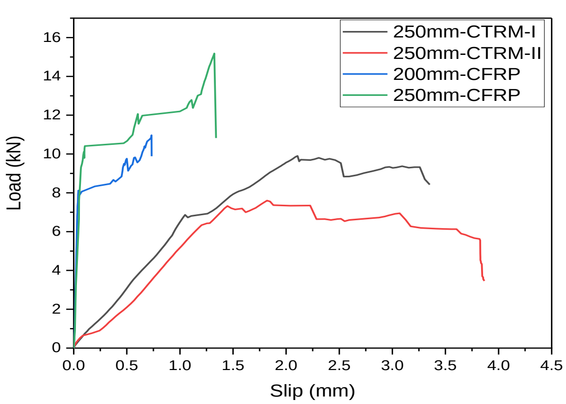
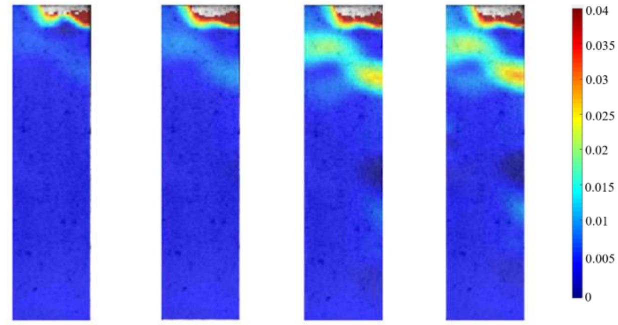
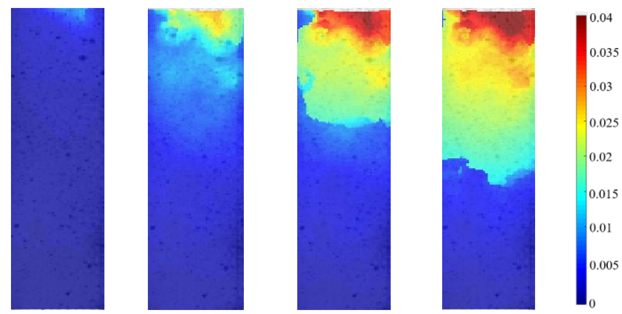


Figure 6. Comparison of the experimental load-slip curves



0.2 Pu 0.6 Pu 0.8 Pu Pu

(a) CTRM strengthened concrete



0.2 Pu 0.6 Pu 0.8 Pu Pu

(b) CFRP strengthened concrete

Figure 7. Strain contours at different load levels (DIC)

CONCLUSIONS

This study conducted 18 quasi-static single-sided shear tests on concrete specimens strengthened with CFRP and CTRM, combined with the Digital Image Correlation (DIC) method. The results show that the interface bonding strength of CFRP strengthening (0.76-0.96 MPa) is 65.0% to 74.8% higher than the CTRM-concrete interface (0.43-0.63 MPa). The ductility and energy dissipation capacity of CTRM strengthening is better than that of CFRP strengthening, and the effective bonding length is 125 to 300 mm. In practical work, CFRP is preferred for improving the strength of concrete components, while CTRM is preferred for improving ductility and seismic resistance.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Authors' contribution

First Author performed the experiments, analysed the data obtained and wrote the manuscript. Second and Third Author designed the experimental process and revised the manuscript. Both authors read and approved the final manuscript

Competing interests

The authors declare no competing interests in this research and publication.

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