Dual function carbon fibre fabric strengthening and impressed current cathodic protection (ICCP) anode for reinforced concrete structures

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Dual function carbon fibre fabric strengthening and impressed current cathodic protection (ICCP) anode for reinforced concrete structures

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Abstract

A novel technique has been proposed and researched in which carbon fibre reinforced polymers (CFRP) are employed to provide both structural strengthening and electrochemical corrosion protection to reinforced concrete (RC) elements suffering from corrosion related damage. In this paper, CFRPs fabric was used for both flexural strengthening of pre-corroded reinforced concrete beams and operated in a dual functional capacity as an impressed current cathodic protection (ICCP) anode. After a period of ICCP operation at high current density either at constant value or adjusted values, the beams were subjected to flexural testing to determine the load- deflection relationships. The potential decays of the steel met recognised ICCP standards and the CFRP fabric remained effective in strengthening the corroded reinforced concrete beams. The bonding at CFRP fabric anode and concrete interface was improved by using U-shaped wrapping and therefore the ultimate strength of dual function of CFRP fabric with U-shaped wrapping increased significantly.

Keywords: Reinforced concrete, corrosion, CFRP, epoxy, cathodic protection, strengthening.

1. Introduction

Corrosion of reinforcing steel in concrete is one of the main reasons causing damage to reinforced concrete (RC) structures. Steel in concrete is normally in a passive state due to the high alkalinity of the surrounding cement paste, but the influence of factors such as carbonation and chloride ions can result in the production of rust which occupies a volume several times greater than the original steel and cause internal stress that results in cracking, delamination and spalling of the concrete cover [1-3]. The corrosion of reinforcement can eventually lead to loss in steel cross-sectional area and reduce the service life of the structure [4-6].

A number of technologies have been developed to tackle the corrosion of steel reinforcement in concrete, with cathodic protection (CP) (Fig.1) widely accepted as one of the most effective solutions [7-10]. An important consideration in CP design is the selection of a suitable anode for the system, especially when it is to be employed in reinforced concrete with its high resistivity. There are a variety of anodes which are currently used for CP systems in such applications including conductive carbon loaded paints, thermal sprayed zinc or aluminium alloys, coated titanium expanded mesh or mesh ribbon in a concrete overlay, coated titanium expanded mesh ribbon mortared into slots chased into the concrete, internal conductive ceramic titania or coated titanium (discrete) anodes and conductive cementitious overlays containing nickel-plated carbon fibres [11].

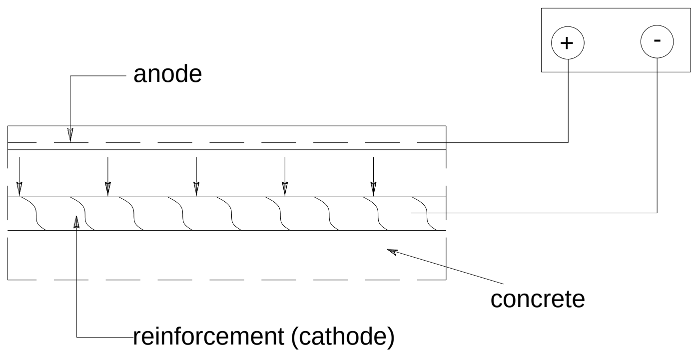


Fig.1: Schematic illustration of impressed current cathodic protection (ICCP) of reinforced concrete[10]

In parallel, the development of carbon fibre-reinforced polymers (CFRPs) has provided an effective solution for strengthening concrete structures suffering from deterioration. There are many concrete structures around the world that have been strengthened by CFRPs. With many advantages including high strength and light weight, FRPs are being used to increase the bending moment capacity of beams and slabs by adding fibre composite materials to the tensile face; increase the shear capacity of beams by adding fibre composite materials to the sides in the shear tensile zone; increase the axial and shear capacity of columns by wrapping fibre composite materials around the perimeter [12-16]. Carbon fibre reinforced polymer (CFRP) has been proven as the electrical conductive materials and can be used as the ICCP anode for RC structures [17].

This paper presents a novel approach in which CFRPs fabric not only provide structural strengthening to the element being repaired but also work as an anode capable of passing current to electrochemically protect the steel within the structure.

2. Experimental programme

The test programme consisted of 12 beams, divided into two groups as shown in Table 1. For each group, five beams were subjected to 2.5% pre-degree of accelerated corrosion of the steel bars. The sixth element was the un-corroded control beam. Group 1 investigated the dual function CFRP fabric which was used for both flexural strengthening of the pre-corroded reinforced concrete beams and for providing an impressed current cathodic protection (ICCP) anode. Specimen 1.1 was an un-corroded control beam while specimen 1.2 was a corroded control beam which was accelerated to 2.5% degree of corrosion, without CFRP strengthening and ICCP application. Beams 1.3 and 1.4 were strengthened with longitudinal CFRP fabric bonded to soffit of beams by epoxy. Beams 1.5 and 1.6 were dual function fabric beams as longitudinal

CFRP fabric was used for both strengthening and ICCP anode for pre-corroded beams. Group 2 consisted of a further 6 beams to evaluate the improvement of bonding at CFRP fabric anode and concrete interface by using U-shaped wrapping. Specimen 2.1 was an un-corroded control beam while specimen 2.2 was a corroded control beam which was accelerated to 2.5% degree of corrosion, without CFRP strengthening and ICCP application. Beams 2.3 and 2.4 were strengthened with longitudinal CFRP fabric bonded to soffit of beams by epoxy and U-wrapping was added. Beams 2.5 and 2.6 were dual function fabric beams as longitudinal CFRP fabric and U-wrapping fabric was used for both strengthening and ICCP anode for pre-corroded beams.

Table 1 Details of test programme

Group	Beam ID	Pre-degree of Corrosion (%)	Repair method		Comments
			CFRP fabric strengthening	ICCP	
1	1.1	0	None	None	Un-corroded control
	1.2	2.5	None	None	Corroded control
	1.3	2.5	CFRP fabric in epoxy	None	Strengthening only
	1.4	2.5	CFRP fabric in epoxy	None	Strengthening only
	1.5	2.5	CFRP fabric in epoxy	ICCP	Dual function
	1.6	2.5	CFRP fabric in epoxy	ICCP	Dual function
2	2.1	0	None	None	Un-corroded control
	2.2	2.5	None	None	Corroded control
	2.3	2.5	CFRP fabric in epoxy, U-shaped wrapping	None	Strengthening only
	2.4	2.5	CFRP fabric in epoxy, U-shaped wrapping	None	Strengthening only
	2.5	2.5	CFRP fabric in epoxy, U-shaped wrapping	ICCP	Dual function
	2.6	2.5	CFRP fabric in epoxy, U-shaped wrapping	ICCP	Dual function

2.1 Test specimens

The specimens were designed as under-reinforced concrete beams, each 900mm long, rectangular cross-section 150 mm depth and 100mm width. Each beam was reinforced by two plain steel bars of 10 mm diameter. There was no shear reinforcement (Fig. 2)

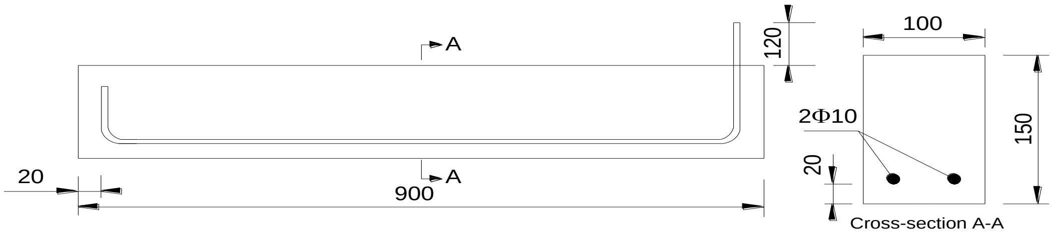


Fig. 2 Detailed dimensions of beam specimens (All dimensions in mm)

2.2 Material properties

The 28 day compressive strength of concrete ranged from 34.8MPa to 40.4MPa for group 1 and from 36.9MPa to 47.7MPa for group 2. There is considerable variability between groups. This is considered to be due to a number of factors such as variability in compaction, moisture content of the aggregates, curing, and possible residual water in the mixer. However, the beams were designed for failure by yielding of reinforcement steel, this different compressive strength of concrete will not affect the bending test results. Plain reinforcement bars of diameter 10mm, yield strength (grade) 250MPa were used.

Sika Wrap Hex 103C carbon fibre fabric with a tensile strength of 3793MPa, elongation at break of 1.5% and modulus of elasticity of 234.5GPa was used. Sikadur300, which is a two-component 100% solid, moisture-tolerant epoxy has a tensile strength of 55MPa, tensile modulus of elasticity of 1724MPa and elongation at break of 3%.

2.3 Accelerated corrosion

After 28 days of casting of the specimens, the longitudinal tensile steel reinforcement was subjected to general corrosion by means of an anodic impressed current provided by a DC power supply. The layout of the corrosion set up is shown in Fig. 3. The polarity of the current was such that the steel reinforcement served as the anode and stainless steel plate worked as the cathode. The corrosion process took place in a plastic tank where 3.5% NaCl solution was used as the electrolyte. The solution level in the tank was adjusted to ensure adequate submersion of the steel bars, while ensuring sufficient oxygen for the corrosion process to proceed.

For each beam the current density and corrosion period were adjusted to give the required degree of corrosion according to Faraday's Law. The percent reduction in reinforcing bar diameter in T years, $\frac{2RT}{D}\times 100(\%)$, defined as the degree of reinforcement corrosion (see Table 1) [18]. The current supplied to each beam was checked daily and any drift was corrected. A current density of 1mA/cm^2 was used to simulate general corrosion. This current density was previously adopted in earlier experiments [18], and was found to provide an appropriate level of corrosion, similar in nature and composition to the naturally occurring process but within a reasonable timescale. The current was applied for 94 hours to achieve nominally a 2.5% degree of corrosion.

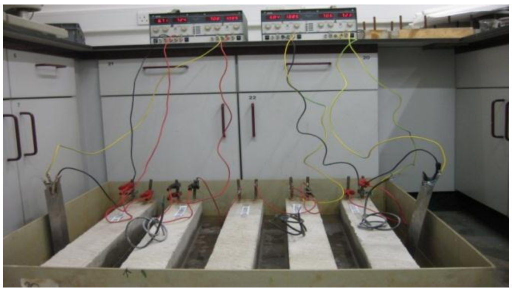


Fig. 3 Accelerated corrosion of reinforcing steel

2.4 Application of CFRPs

Two pattern of CFRP fabric were used to repair the corroded reinforced beams. The first group was strengthened in flexure by applying CFRP fabric to the soffit of corrosion damaged beams. The fabric was bonded to the surface of beams by epoxy using a 'dry lay-up' method in accordance with the manufacturer's recommendation. A layer of epoxy was applied to the surface using a roller brush. CFRP fabric was applied to the side to the concrete over the epoxy using a roller to remove any air bubbles. After that a second layer of epoxy was applied using a roller over the installed CFRP fabric in order to saturate the fabric with epoxy, ensuring full impregnation. The beams were checked to ensure no blistering or lifting of the fabric. The un-bonded ends of the fabric were then cut to length. The second group had the same pattern as the first one plus U-wrapping (Fig. 4).

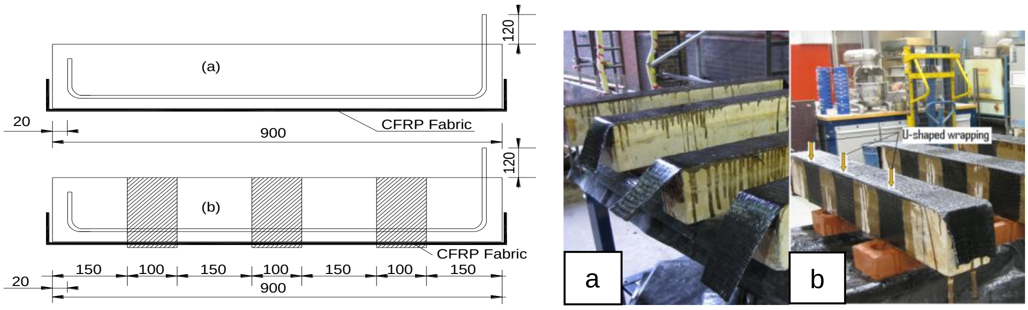


Fig. 4 Beams repaired by CFRPs fabric: a) Group beams 1; b) Group beams 2

(All dimensions in mm)

2.5 Application of impressed current cathodic protection (ICCP)

ICCP was applied to the corroded reinforced concrete beams by connecting the reinforcing steel to the negative terminal and the CFRPs fabric anode to the positive terminal of the multi-channel power supply. The system was cathodically protected at room temperature (nominally 20^{o}C) and 60% relative humidity (plus or minus 5%). These conditions ensured the resistivity of the concrete remained high, representing site environment. The applied current densities were128.4mA/m^2 of steel surface area for beams 1.5 and 1.6 (group 1- Table 1) and the applied current densities were fluctuated from 125mA/m^2 and 200mA/m^2 of steel surface area for beams 2.5 and 2.6 (group 2- Table 1). The current was checked and the on and instant -off potentials of the embedded steel were recorded daily. The schematic of ICCP application is shown in Fig. 5.

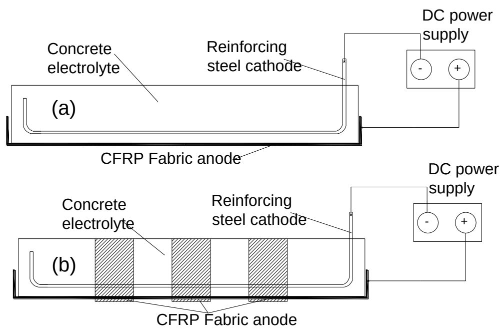


Fig. 5 Schematic ICCP Application to corroded reinforced concrete beams

a) Group beams 1; b) Group beams 2

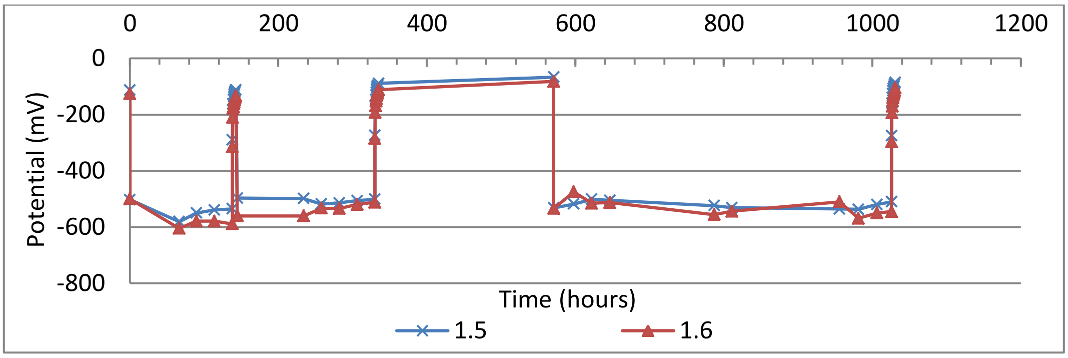
3 Results and Discussion

3.1 Visual monitoring

For group 1, after 984.25 hours of application of ICCP, a very small gaseous and yellow liquid deposit appeared on the surface of CFRP fabric anode. For group 2, the gaseous and yellow liquid deposit appeared earlier at 474 hours due to higher applied current density, compared with group 1. This could, if more widespread, result in the de-bonding of the CFRP fabric anode from the concrete interface.

3.2 Cathodic protection monitoring

For beams 1.5 and 1.6 (group 1), during 1026 hours of operation of ICCP, the on- potential and potential decays of steel bars were recorded using embedded Ag/AgCl/0.5M KCl reference electrodes and high impedence digital voltmeter (DVM). The total period is plotted in Fig. 6. The ICCP was interrupted three times at 138 hours, 330 hours and 1026 hours. At 330 hours, the ICCP was interrupted for 241 hours before it was run again to 1026 hours. The potential decays at these three occasions were monitored and are shown in Table 2.



(Reference electrode: Ag/AgCl/0.5M KCl)

Fig. 6 Potential of steels during operation of ICCP (beams 1.5, 1.6-group 1), constant applied current density of 128.4mA/m^2 of steel area)

For beams 2.5 and 2.6, during 2,103 hours of operation of the ICCP, the applied currents were adjusted and recorded daily to optimise the effect of current to bonding at the CFRP fabric and concrete interface. The applied current densities were plotted in Fig.7. The current densities were approximately 125mA/m^2 for nearly 100 hours before the value was increased to over 200mA/m^2 to polarise the potential steel effectively. However, at 642 hour, in order to optimise the effect of these currents to bonding at CFRP fabric and concrete interface, these current densities were reduced to approximately138mA/m^2. These current densities were adjusted based on the capacity of polarisation of steel potential and optimisation of the de-bonding at CFRP fabric and concrete interface. The on potential and potential decays of the steel bars of beams 2.5 and 2.6 were recorded and the total period was plotted in Fig. 8. The ICCP was interrupted three times at 520, 1,624 and 2,103 hours (see Fig. 8) and potential decays were recorded at these occasions (Table 2).

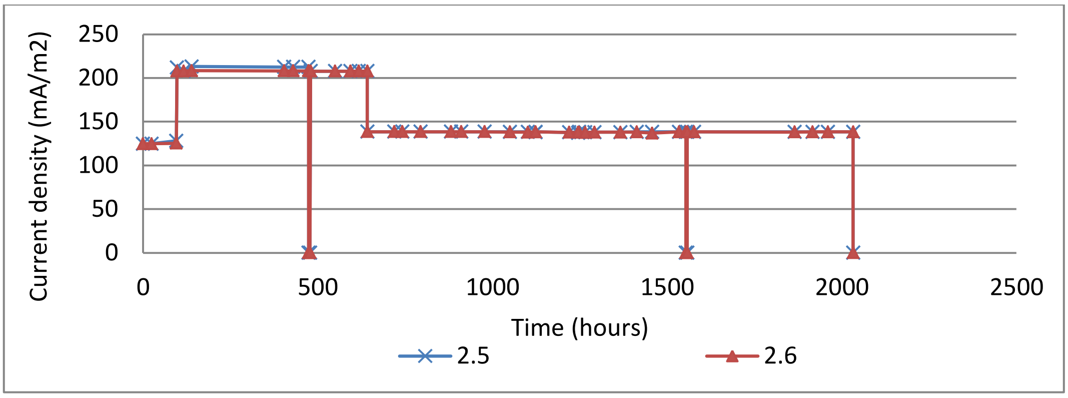
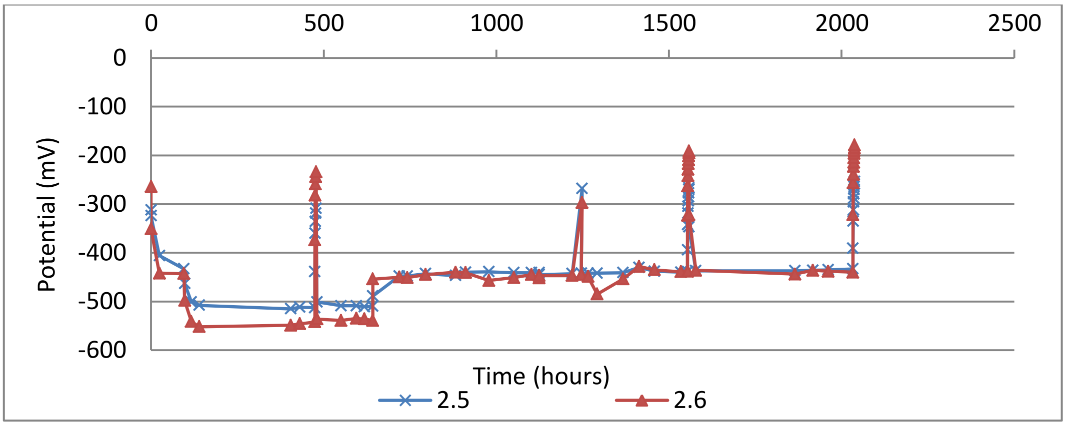


Fig. 7 ICCP applied current density (mA/m^2 of steel surface area) (Beams 2.5 and 2.6)



(Reference electrode: Ag/AgCl/0.5M KCl)

Fig. 8 Potential of reinforcing steel during ICCP application (Beams 2.5 and 2.6)

From the Fig. 7, the applied current was adjusted to three different values of 9mA, 15mA and 10mA corresponding of current densities of 124.7mA/m^2, 207.8mA/m^2 and 138.5mA/m^2 of reinforcing steel surface area at three periods. These adjustments were aimed at minimising any negative effect of the protection current on the bonding at the CFRP fabric and concrete interface. From Fig. 8 it can be seen that the rest potential of steel shifted positively from -312mV to -254mV for Beam 3.5 and from -264 mV to -179mV for Beam 3.6. Fig. 7 and Fig. 8 show that the potential of the steel bars increased when the applied current densities increased. A current density of 138.5mA/m^2 was found to be sufficient to adequately polarise the steel bars to the required potential.

Table 2 Potential decays in the three periods.

Beams	Time At (hours)	Potential (Ref electrode: Ag/AgCl/0.5M KCl) Instant off mV	After 4 hours mV	Decays mV
1.5	138	-290	-117	173
	330	-274	-96	178
	1026	-275	-92	183
1.6	138	-315	-139	176
	330	-285	-118	167
	1026	-297	-114	183
2.5	520	-439	-309	130
	1624	-394	-267	127
	2103	-391	-259	132
2.6	520	-374	-234	140
	1624	-323	-191	132
	2103	-322	-185	137

From Tables 2, the potential decays are more than 150mV after 4 hours at the three times of monitoring for four beams 1.5, 1.6, 2.5 and 2.6. According to the Concrete Society Technical Report No.73 [11], this demonstrates that CP of the embedded steels has been successfully achieved.

3.3 Load- deflection curves.

The deflection at mid-span of each beam was recorded by LVDTs (linear variable differential transformer) and it was used to plot the load-deflection relationships. The ultimate load capacities and deflections of beams are shown in Table 3. In general, the ultimate strength decreased when the cross-section of reinforcement decreased due to corrosion.

Table 3 Ultimate load capacity and deflection of beams

Group	Beam ID	Age at test	Actual degree of corrosion	Failure load	Deflection	Mean failure load	Increase in strength, compared to corroded control
		(days)	(%)	(kN)	(mm)	(KN)	(%)
1	1.1	220	0	44.7	4.00	44.70	-
	1.2	205	2.10	41.4	5.49	41.40	0
	1.3	220	2.16	82.1	6.29	84.65	104.5
	1.4	221	2.20	87.2	6.88		
	1.5	235	2.20	68.8	5.07	73.20	76.8
	1.6	244	2.16	77.6	5.28		
2	2.1	219	0	53.9	5.60	53.90	-
	2.2	219	2.23	51.0	5.37	51.00	0
	2.3	219	1.97	105.0	6.50	106.95	109.7
	2.4	219	2.19	108.9	6.10		
	2.5	215	2.20	106.1	6.76	107.80	111.37
	2.6	215	2.07	109.5	6.54		

3.3.1 Group 1

The load-deflection relationships of group 1 beams are plotted in Fig.9.

The ultimate load and deflection at failure of these beams is given in Table 3.

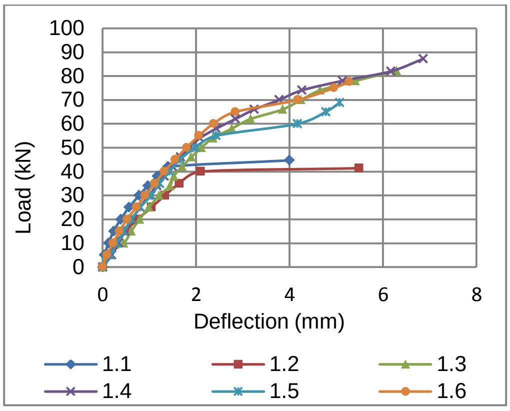


Fig. 9 Load-deflection curves of group 1 beams

From Fig. 9 and Table 3, the ultimate strength of beams 1.2 with 2.5% corrosion decreased by 7.4% compared with the control beam 1.1 with 0% corrosion. The corresponding ultimate deflection of beam 1.2 was 37.2% greater than the ultimate deflection of the un-corroded control beam 1.1. The mean ultimate strength of beams strengthened with CFRP fabric without CP (1.3 & 1.4) is approximately 104% higher than the ultimate strength of un-strengthened beam 1.2. Both beams 1.3 and 1.4 failed due to delamination of the cover concrete before flexural failure. The mean ultimate deflection of beams 1.3 and 1.4 was about 20% higher than the ultimate deflection of beam 1.2. However, in the first stage of loading from zero to 41.4kN (failure load of beam 1.2), the deflection of beams 1.3 and

1.4 are smaller than the deflection of 1.2. This demonstrates that the stiffness of the beam strengthened with CFRP fabric (without CP) increased compared with the stiffness of the un-strengthened beam. Moreover, beams 1.3 and 1.4 showed more ductile behaviour (large deflection) before failure than beam 1.2.

Beams 1.5 and 1.6 used the dual function CFRP fabric for both strengthening and ICCP. The average ultimate strength of the dual function beams (1.5 &1.6) increased by approximately 77% compared to the un-strengthened beam 1.2. Both beams 1.5 and 1.6 failed due to the de-bonding or peeling of CFRP fabric (Fig.10). The average ultimate deflection of specimens 1.5 and 1.6 was about 6 % less than the ultimate deflection of specimen 1.2.

Therefore, the mean ultimate strength of dual function CFRP fabric strengthened beams (1.5 and 1.6) is approximately 13.5 % smaller than the mean ultimate strength of CFRP fabric reinforced beams without CP (beams 1.3 and 1.4). This appears to be due to the ICCP affecting the bond at the CFRP fabric anode and concrete interface, and as a consequence beams 1.5 and 1.6 failed due to de-bonding of the CFRP fabric.

The mean ultimate deflection of beams 1.5 and 1.6 was approximately 21% less than the mean ultimate deflection of beam specimens 1.3 and 1.4. This is also attributed to the application of ICCP by which the CFRP fabric appeared to become more brittle after having been operated as an ICCP anode.

Fig. 10 Debonding of CFRP fabrics after load testing

3.3.2 Group 2

The load-deflection relationships of group 2 beams are plotted in Fig. 11. The ultimate load and deflection at failure of these beams is given in Table 3.

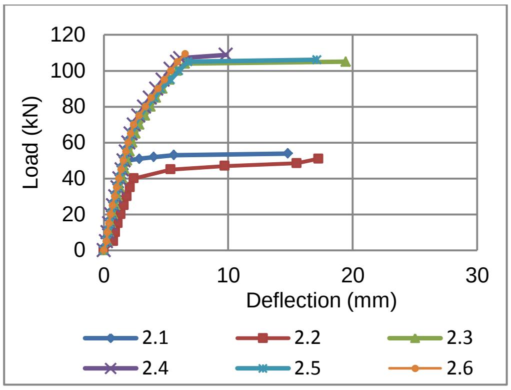
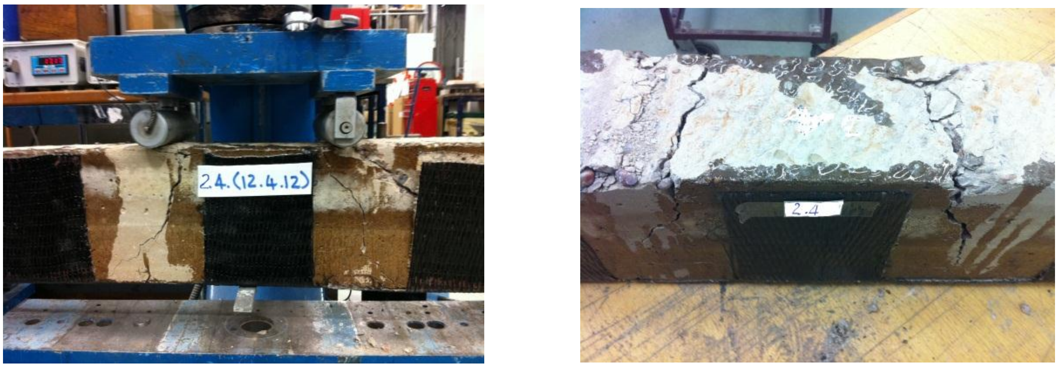


Fig. 11 Load- deflection curves- Group2

From Fig. 11 and Table 3, the ultimate strength of beams 2.2 with 2.5% corrosion decreased by 5.4 % respectively compared with the control beam 2.1 with 0% corrosion. The corresponding ultimate deflection of beam 2.2 reduced by 4.1% in compared with beam 2.1. The mean ultimate strength of beams strengthened with CFRP fabric (U-shaped wrapping) and without CP (beams 2.3 and 2.4) is approximately 109.7% higher than the un-strengthened beam 2.2. The mean ultimate strength of strengthened beams with CFRP fabric (U-shaped wrapping) with CP (beams 2.5 and 2.6) is approximately 111.37% higher than the un-strengthened beam 2.2. Therefore the strength of dual function beams (2.5 and 2.6) is approximately 0.79% is apparently higher than strengthened beams with CFRP but without CP (2.3 and 2.4).

All beams were tested to failure and the failure modes were monitored and recorded. Figs.12a to 12d show the failure modes of 4 CFRP strengthened beams. Although there were some shear cracks occurred for beams 2.4 and 2.6, the flexural failure happened before shear failure. Flexural failures of CFRP strengthened beam 2.3 included de-bonding of U-wrapping, following by steel yielding, delamination of cover concrete and CFRP fracture at the mid-span (Fig.12a). The failure mode of beam 2.4 included de-bonding of U-wrapping, delamination of cover concrete and de-bonding of a long section of CFRP at the end point (Fig. 12b). The failure mode of beam 2.5 is similar to that of beam 2.3, however, it has been noticed that the CFRP fabric was ruptured at the areas where yellow deposits appeared. It was noted that the deposit is directly above three large pieces of aggregate with little or no cement paste present (Fig.13). In a similar manner to beam 2.4, beam 2.6 failed in flexure due to end cover delamination, de-bonding of U-wrapping and longitudinal CFRP (Fig. 12d). The failure of the concrete layer between the CFRP and steel and peeling of CFRP from the concrete surface appears to be very brittle in nature. The prevention of brittle failure is an important criterion for safe and effective CFRP strengthening.

a: Beam 2.3



b: Beam 2.4

c. Beam 2.5

d. Beam 2.6

Fig. 12 Photographs of failed beams

Fig. 13 Area beneath yellow gaseous deposit (circled)

From Fig. 12, CFRP fabrics were used full strength as they failed by rupture (Figs.12a & 12c). The failure modes of these beams are analysed above. Most of these beams failed due to delamination of the cover concrete plus de-bonding at the CFRP fabric and concrete interface. However when using the U-shaped wrapping, this de-bonding was restricted and the strength of the strengthened beams increased (increase of 109.7% and 111.37% for U-wrapping in compared with 104% and 77 % without U-wrapping as described in group 1). This demonstrates that the use of U-wrapping for the dual function CFRPs is an effective solution for increasing the bonding at the CFRP fabric anode and concrete interface and significantly enhances the effectiveness of this technique.

3.4 Improving bonding at carbon fibre and concrete interface through the addition of U-wrapping

Table 3 shows the ultimate strength of the dual function CFRP fabric beams where group 1 consist of dual function CFRP fabric with longitudinal fabric only, and group 2 consists of dual function CFRP fabric with longitudinal fabric and U-wrapping. Because groups 1 and 2 were cast and tested separately at different times, the ratio between strengthened beam either with or without ICCP and the pre-corroded control beam (without strengthening) is used to evaluate the effectiveness of U-wrapping. It is apparent from Table 3 that by employing U-wrapping the ultimate strengths of the repaired beams have increased significantly. With respect to CFRP strengthening only (without ICCP) the ultimate load of strengthened CFRP fabric with U-wrapping increased by 109.7% compared with the corroded control beam, and by 104.5% for CFRP fabric without U-wrapping. In term of the dual function CFRP fabric, the ultimate load of CFRP fabric with U-wrapping increases 111.37% compared with the corroded beam while it is only 76.8% for CFRP fabric without U-wrapping anode.

4. Conclusion

The main conclusions from the results reported in this paper are as follows:

1. CFRP fabric anode is capable of operating at very high current densities >128mA/m^2 of steel area with only a small loss of mechanical bonding
2. CFRP fabric can be used to strengthen corroded RC beams, maintaining the structural integrity and increase the ultimate strength of damaged beam. CFRPs increase the stiffness of beams and reduce their ultimate deflection
3. The ultimate strength of reinforced concrete beams incorporating dual function CFRP anodes without U-wrapping is approximately 13.5% less than the corresponding beams with CFRP strengthening only without U-wrapping.
4. U-wrapping is an effective method of reducing the de-bonding at the CFRP fabric anode and concrete surface interface. The dual function technique works more effectively when this de-bonding is reduced, therefore the strength of dual function beams increase significantly by 111.37% compared to the corroded control beam.
5. The applied current density should be optimised, based on the distribution to the protected steel. There is presently no parameter to calculate the minimum and maximum of this applied current density based on theory.
6. In comparison with traditional CP for reinforced concrete, the CFRP anode appears to be capable of operating at much higher current densities. By combining the function of strengthening and CP within a single component, the system is significantly simpler and should also deliver cost savings in addition to easier maintenance.

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