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# EXPERIMENTAL STUDY ON DURABILITY OF CFRP-CONCRETE BOND SUBJECTED TO TEMPERATURE, HUMIDITY AND OUTDOOR ENVIRONMENT

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## ABSTRACT

This paper presents experimental results and observations to-date of an ongoing research undertaken to investigate the long-term behaviour of bond between externally bonded Carbon Fibre Reinforced polymer (CFRP) and concrete. Carbon FRP strips were externally bonded to concrete prisms and were exposed separately to three different environmental conditions, namely, temperature, humidity and outdoor environment for extended durations. Single-lap-joint shear test (pull-out test) was conducted to investigate bond strengths of control (unexposed) and exposed specimens. Moreover, material characterisation of concrete cylinders and CFRP control and exposed coupons was carried out to observe the changes of mechanical properties with the time of exposure. Finally, experimental results of exposed specimens were compared to those of control specimens in terms of bond strengths and failure modes. Based on the results to-date, the most significant degradation of bond strength was observed in specimens exposed to outdoor environment. Whereas no significant effect of temperature cycles were found provided that the temperature is below the glass transition temperature of epoxy resin.

## KEYWORDS

FRP, CFRP-concrete bond, pull-out test, long-term, bond strength, strain-distribution, failure mode.

## INTRODUCTION

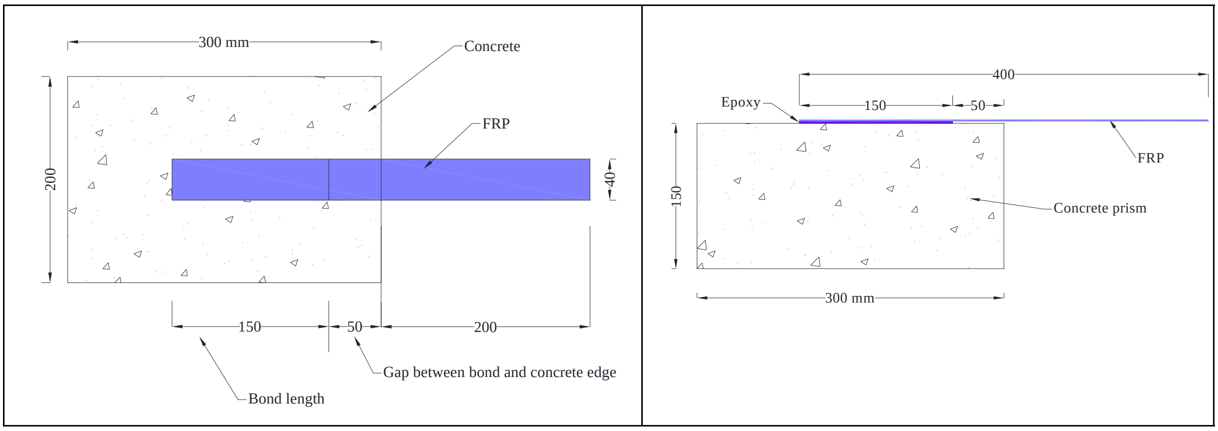
Fibre Reinforced Polymer (FRP) composites have become a popular choice for strengthening and repairing of reinforced concrete structures lately due to their advantageous properties such as high strength to weight ratio, high corrosion resistance and easy application process. However, one major limitation of FRP-strengthened concrete structures is premature failure by debonding of FRP from concrete which limits the effectiveness of FRP. This limitation necessitates studies on the effects of environmental conditions on FRP-concrete bond behaviour. Although extensive research has been conducted on strengthening of RC structures with FRP, research on long term performance of FRP-concrete bond is very limited. Some research have dealt with durability of concrete beams strengthened with FRP and showed the decrease in ultimate beam strength after various environmental exposures, whereas other research showed the degradation of bond strength between FRP and concrete under aggressive environment. Chajes et al. (1995), Toutanji & Gómez (1997), Myers et al. (2001) and Li et al. (2002) studied the long term performance of FRP strengthened concrete beams subjected to various environmental conditions such as freeze-thaw cycles, wet-dry cycles, combined environmental cycles, boiling water and UV radiation to investigate the degradation of ultimate strength and stiffness of beams. Homam et al. (2001), Dai et al. (2010), Benzarti et al. (2011) and Yun & Wu (2011) investigated FRP-concrete bond degradation under freeze-thaw cycles, temperature cycles, alkali solutions, moisture ingression, hydrothermal ageing with the help of various test set-ups such as pull-off, bend tests, single-lap-joint shear tests, etc. Also, Tuakta & Büyüköztürk (2011) studied the effect of moisture on FRP-concrete bond system by tri-layer fracture mechanics. They used peel and shear fracture tests for their study. Research studies by Litherland et al. (1981) , Dejke & Tepfers (2001) and Phani & Bose (1987) dealt with proposing long term prediction models for FRP and FRP in concrete environment based on the acceleration of degradation rate using high temperature. But Robert et al. (2010) stated regarding the use of high temperature as an accelerating factor that high temperature may amplify the reduction of the properties which may lead to conservative prediction of long-term properties. From the research stated above it can be understood that it is very difficult to compare the findings of these research studies as a variety of test set-ups and conditions were applied. Moreover, according to Benzarti et al. (2011), single-lap-joint shear test (pull-out test) is more sensitive to environmental conditions as it showed change of strength as well as change of failure modes and should be used for adhesive bonded joint. Therefore, more research needs to be carried out with similar test set-ups to create a large database of FRP-concrete bond behaviour under various environmental conditions.

The purpose of this research was to investigate effects of temperature cycles, humidity cycles and outdoor environment separately on FRP-concrete bond (both CFRP and GFRP) using single lap-joint shear test (pull-out test) for up to 18 months. This paper only presents the experimental results of CFRP bonded specimens. In addition, material characterisation of CFRP and concrete exposed to the same environmental conditions used for pull-out specimens was another objective of this investigation.

## EXPERIMENTAL PRGRAMME

### Fabrication of pull-out specimens

One hundred and fourteen concrete prisms with dimensions of 300 mm × 200 mm × 150 mm were fabricated from two batches of concrete. After concrete prisms had been cured, concrete surfaces were prepared by exposing the aggregates with the help of a needle-gun followed by blowing off dust particles with an air blow gun. Two plies of 150 mm long and 40 mm wide FRP strip were externally bonded with two part epoxy impregnation resin to the concrete prism as shown in Figure 1. The FRP bonded specimens are referred to as pull-out specimens from here onwards. The bond length chosen in this study was longer than the effective bond length calculated from the model provided by Chen & Teng (2001). A 50 mm gap between concrete edge and free end of the FRP was provided (Figure 1) to avoid local failure in concrete edge. Also, FRP strip was extended to 200 mm outside the concrete prism in order to be gripped by jaws of testing machine. Two types of FRP, namely, CFRP and GFRP fabric, were applied and 57 concrete prisms were used to fabricate pull-out specimens for each type of FRP. This paper only reports the results of CFRP bonded specimens. Apart from the pull-out specimens, concrete cylinders with diameters of 100 mm and 150 mm were cast to determine compressive strength and modulus of elasticity of unexposed and exposed cylinders according to Australian Standards (AS 1012.9, 1999; AS 1012.17, 1997). Moreover, CFRP coupons with 250 mm length (150 mm gauge length) and 15 mm width were prepared as per ASTM D3039/D3039M (2008) to investigate the tensile properties of CFRP in exposed and unexposed environments. Aluminium moulds were used for the fabrication of CFRP coupons. Before casting the coupons, adhesive tape was attached on the aluminium moulds to make the de-moulding easier.




(a) Plan (b) Elevation

Figure 1. Geometry of pull-out specimens

### Material properties

Concrete with a characteristic strength of 32 MPa and slump of 80 ± 20 mm was used to cast concrete prisms. Carbon FRP used in this research was MBrace CF 120 (CFRP). Sikadur 330 – 2 part, a thixotropic epoxy impregnation resin, was applied as matrix and adhesive and no primer was used as Sikadur 330 can perform the function of both primer and adhesive. Table 1 provides mechanical properties of concrete, CFRP and epoxy resin.

### Applied environmental conditions

Five pull-out specimens were used as control specimens and were kept under lab environment. The remaining specimens were subjected to three different types of exposure conditions – (i) temperature cycles (ii) humidity cycles (wet-dry cycles) and (iii) Sydney outdoor environment. Nine specimens (three for each duration) were subjected to temperature cycles consisting of 5 hours at constant 40$^{o}$ C followed by 7 hours at gradual decrease in temperature to 30$^{o}$ C and two cycles per day were maintained. Cyclic temperature specimens were exposed to 70 cycles (35 days), 180 cycles (90 days) and 728 cycles (364 days). Humidity cycles consist of 1 week wetting with at least 95% RH followed by 1 week drying. Wet environment was created by a humidifier in a small closed chamber. Humidity specimens were subjected to wet-dry cycles for 1 month, 6 months, 12 months and 18 months. For each of the durations, five specimens were exposed. Also, a total of 20 specimens (five per duration) were directly exposed to outdoor environment for 2 months, 6 months, 12 months and 18 months. In order to characterise the properties of concrete, a number of cylinders from the same batch were exposed to the same conditions as with pull-out specimens. Similarly, five CFRP coupons were exposed to each of the exposure series stated above.

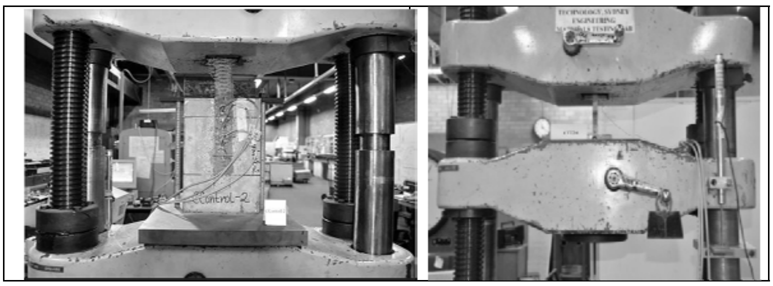
The rationale for the selected temperature cycles and humidity cycles in this study was mainly two separate two variables, namely, temperature and humidity. The highest temperature in the cyclic temperature exposure was chosen to simulate the usual maximum temperature in Sydney. Moreover, the temperature was kept below the glass transition temperature (47 $^{o}$ C) of epoxy resin used in this study. The lowest temperature below 30 $^{o}$ C was not achievable due to the limitations of the drying oven used for the conditioning. Similarly, the humidity cycles were also separated from the temperature by keeping the temperature close to the ambient temperature and eliminating the effect of high temperature on the humidity specimens.

Table 1. Mechanical properties of concrete, CFRP and epoxy

| Material name | Mechanical properties | | | |
|---|---|---|---|---|
| Concrete | Characteristic compressive strength MPa | | Measured compressive strength MPa | |
| | 32 | | 36.6 | |
| CFRP | Thickness per ply mm | Measured tensile strength MPa | Measured tensile modulus of elasticity GPa | |
| | 0.117 | 2758.4 | 221.9 | |
| Epoxy | Tensile strength after 7 days of curing at + 23 $^{o}$ C MPa | Tensile modulus of elasticity after 7 days of curing at + 23 $^{o}$ C GPa | Coefficient of thermal expansion between - 10$^{o}$ C to + 40 $^{o}$ C /$^{o}$C | Heat distortion/ glass transition temperature ($T_g$) after 7 days of curing at + 23 $^{o}$ C $^{o}$C |
| | 30 | 4.5 | $4.5 \times 10^{-5}$ | + 47 |

**Test performed**

Pull-out tests (single-lap-joint shear test) were performed with a loading rate of 2 mm/min of cross-head travel of the universal testing machine with a 500kN capacity. Specimens were placed vertically using a steel rig such that the concrete prism was fully restrained and tensile force was applied to the FRP strip (Figure 2a). Three strain gauges were glued to FRP surface to obtain strain values at different levels of loads. Compressive strength of concrete on the day of the pull-out tests were identified using compressive strength tests on 100 mm diameter concrete cylinders, subjected to the same conditions as the pull-out specimens, as per AS 1012.9 (1999). Tensile strength and tensile modulus of elasticity of CFRP coupons subjected to identical exposure conditions were also determined using tensile tests as per ASTM D3039/D3039M (2008) (Figure 2b).



(a) Pull-out test set-up (b) Tensile test of CFRP coupons

Figure 2. CFRP pull-out and tensile test set-up

## RESULTS AND DISCUSSIONS

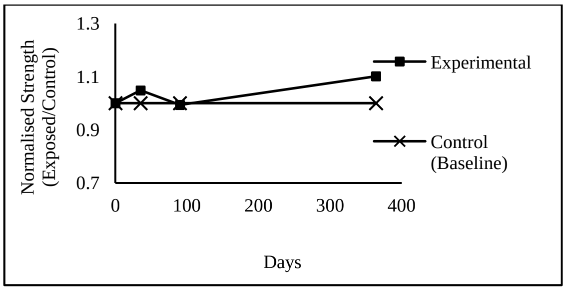
Test results for pull-out specimens were analysed in terms of maximum stress developed in FRP, failure modes and strain profiles. The maximum stress developed in FRP was calculated by dividing the load by the cross sectional area according to Eq. 1.

$$\boldsymbol{\sigma_{db}} = {\boldsymbol{P_u}}/{(\boldsymbol{b_f} \times \boldsymbol{t_f})}$$
(1)

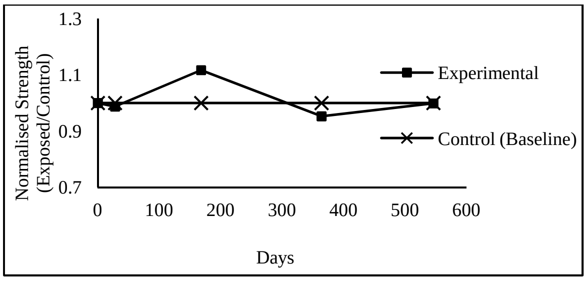
Where, $\sigma_{db}$ = maximum stress developed in FRP in MPa, $P_u$ = maximum load in Newtons, $b_f$ = width of FRP sheet in mm and $t_f$= thickness of FRP sheet in mm.

Figure 3 shows the normalised bond strengths (the ratio of exposed to control strength) of exposed CFRP pull-out specimens with days of exposure for three different exposure conditions Also, normalised concrete compressive strengths (Figure 4) and normalised tesnile moduli of elasticity of CFRP (Figure 5) have been plotted against the time of exposure to explain the changes of material properties due to environmental conditions. In addition, the typical failure modes observed for the control specimens and exposed specimens have been illustrated in Figure 6 to understand the dependence of pull-out strength on the material properties.

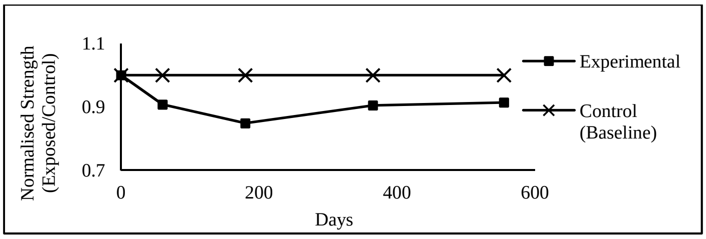
The behaviour of CFRP-concrete bond for three different conditions has been explained seperately in the following sections in terms of pull-out strength, failure modes and material properties.




(a) Temperature cycles




(b) Humidity cycles




(c) Outdoor environment

Figure 3. Normalised bond strengths with exposure durations

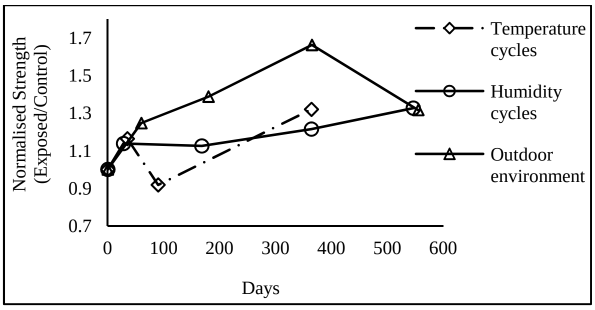



Figure 4. Normalised concrete compressive strengths with time of exposure

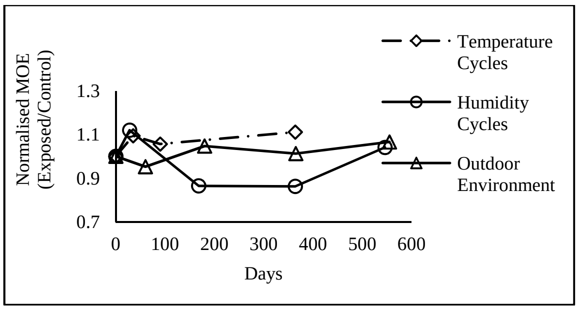
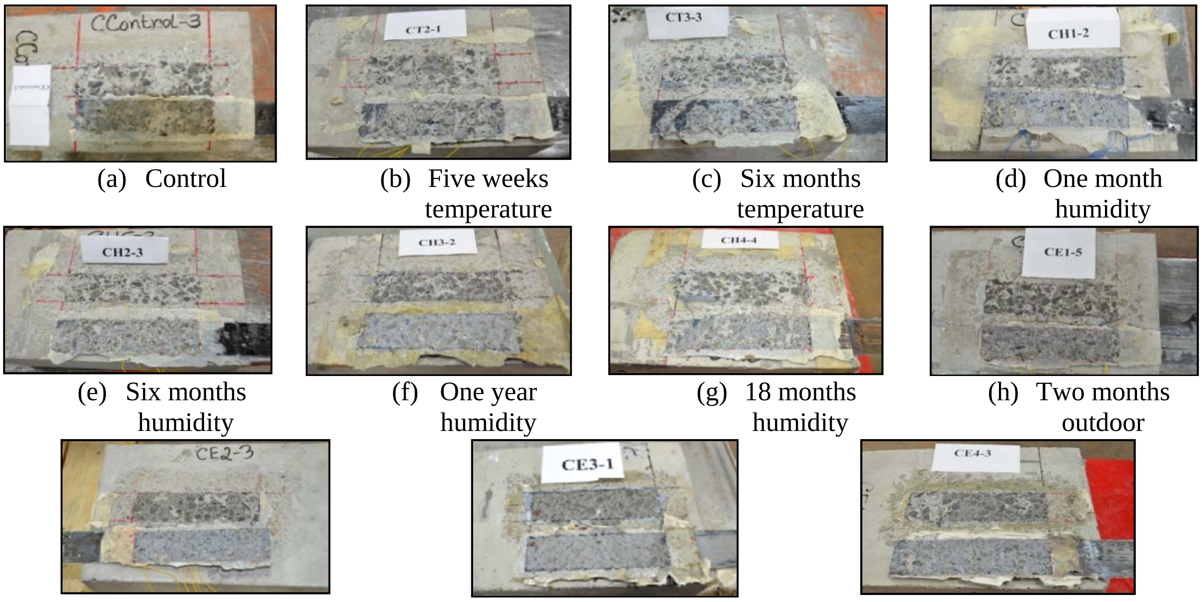



Figure 5. Normalised tensile modulus of elasticity of CFRP with time of exposure

**Temperature cycles**

It can be observed from Figure 3a that temperature cycles did not cause any negative effects on the FRP-concrete bond. Although, the bond strength showed a descending  trend after initial increase of 5% at 5 weeks, the strength value was still close enough to the control value at 3 months. After 1 year, bond strength increased by 10% compared to that of control specimens. This behaviour can be attributed to the change of concrete strength due to exposure conditions (Figure 4) as the failure of the cyclic temperature specimens were always with the concrete layer attached to the debonded FRP (Figure 6b and c).



(a) Control
(b) Five weeks temperature
(c) Six months temperature
(d) One month humidity
(e) Six months humidity
(f) One year humidity
(g) 18 months humidity
(h) Two months outdoor
(i) Six months outdoor
(j) One year outdoor
(k) 18 months outdoor

Figure 6 Failure modes of control and exposed specimens

**Humidity cycles**

Humidity cycles also showed initial positive effects (Figure 3b) on the CFRP-concrete bond behaviour with the exception of 5% decrease in bond strength after 12 months of exposure. The positive effect of humidity cycles on the pull-out strength (12% increase from the control series) after six months was mainly due to the imporved concrete compressive strength and can be correlated with the thick concrete layer attached to the debonded CFRP (Figure 6e). As humid environment is the most suitable condition for concrete curing, especially in the initial stage, concrete strength was found to increase continuously up to 18 months in this study (Figure 4). The bond degradation of 5% in terms of strength after 12 months can be correlated with the change of failure mode - from thicker concrete layer to almost no concrete attached to debonded FRP (Figure 6f). The reason can be the approaching of concrete strength to the epoxy strength and the degradation of epoxy properties due to humidity cycles. Although the mechanical properties of epoxy resin due to exposed conditions were not determined in this study, the failure pattern after 12 months suggests the dependence of bond strength more on the epoxy property than that of concrete.

**Outdoor Environment**

Exposure to outdoor environment had the most prominent effect on the CFRP-concrete bond and led to deterioration of bond strength by 15% after six months of exposure compared to control value (Figure 3c). Then an improvement of bond strength was observed and it reached equilibrium after one year and no further change of bond strength occurred. The tensile moduli of exposed CFRP coupons showed values always close enough to the control ones except initial degradation of 5% (Figure 5). And concrete compressive strengths for exposed specimens were always higher than those of control specimens (Figure 4). But the evolution of failure locations of the exposed specimens from concrete substrate to concrete-adhesive interface or adhesive layer confirms that the bond deterioration occurred mainly because of the degradation of adhesive properties.

## CONCLUSIONS

The aim of this research was to investigate the durability of CFRP and GFRP -concrete bond subjected to three environmental conditions up to 18 months. This paper only included parts of the results of CFRP-concrete bond. Based on the results presented in this paper, the following conclusions can be drawn:

Temperature cycles had negligible effect on the deterioration of CFRP-concrete bond provided that the temperature was below the glass transition temperature of epoxy resin. Humidity cycles also showed very small amount of degradation (5%) after one year but the nature of bond strength with time of exposure suggests the cyclic nature of bond behaviour. Consequently, studies of longer period should be conducted for better understanding. The most degradation of CFRP-concrete bond was due to outdoor environment and the maximum degradation of 15% after six months of exposure was noticed. But the plateau reached after one year suggests no further deterioration of bond. As the change of failure modes from thicker concrete layer to very thin concrete layer attached to debonded CFRP was observed in this study, the investigation on the epoxy properties due to same environmental conditions is necessary to confirm whether the change of epoxy properties is more responsible for the bond deterioration.

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