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DEFORMATIONAL BEHAVIOUR OF FRP CONFINED CONCRETE UNDER SUSTAINED COMPRESSION

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ABSTRACT
Confining concrete is an effective method to enhance the strength and ductility of reinforced concrete columns. Fibre reinforced polymer (FRP) composites are emerging as a suitable confining material to replace conventional materials such as steel and fibre-reinforced cement composites. Past research on the behaviour of FRP confined concrete in compression is considerable; however, limited research has been reported on the behaviour of confined concrete under sustained compressive loading. This paper reports the preliminary results of an experimental investigation on the deformational behaviour of carbon FRP (CFRP) confined concrete columns under sustained compressive stress levels, corresponding to 40% and 60% of the unconfined concrete compressive strength for up to 150 days. The results show that the creep of confined concrete columns is marginally influenced under moderate sustained stress/strength ratios.

KEYWORDS
Carbon fibre reinforced polymer, CFRP, concrete, confinement, time dependent behaviour, creep

1. INTRODUCTION

Fibre reinforced polymer (FRP) composites have significantly high tensile strength, stiffness and strain capacity compared to concrete. These qualities contribute to the acceptance of FRP as a viable material for strengthening and rehabilitating of concrete structures. In addition, FRP is a durable material in normal exposure conditions and is capable of wrapping any shaped concrete sections. Based on considerable research on the performance of FRP strengthened concrete members under short-term loadings, design recommendations (fib 2001, ACI 2002, Teng et al. 2002) have been published. However, a lack of research on the time-dependent effectiveness of FRP deters a wide-spread usage of FRP (Karbhari et al. 2003). Creep of FRP confined concrete under sustained loading is an important durability parameter in the design of FRP strengthened concrete columns (Smith et. al. 2005), and in some early applications, creep rupture of FRP in strengthened concrete columns has been reported (Naguib and Mirmiran 2002). This paper presents preliminary results of an experimental investigation on the creep behaviour of carbon FRP (CFRP) confined concrete columns, under moderate sustained stress/strength levels.

2. FRP CONFINEMENT TO CONCRETE COLUMNS

Fibre reinforced polymer (FRP) confinement improves the strength and ductility of concrete columns in compression. The strength Improvement depends upon the fibre type, thickness and wrapping orientation (Lam and Teng 2003, Matthys et. al. 2005). The FRP, which confines the lateral expansion of concrete, is in tension in the hoop direction and fails in a brittle explosive manner when the concrete is excessively compressed. Research has shown that the tensile strength of FRP in the hoop direction is 10 to 20% lower than that in direct tension (Xiao and Wu 2000), where the ratio of failure hoop strain to that in direct tension is termed as the reduction factor. In FRP confined concrete under sustained compression, concrete experiences compressive creep whereas the FRP is under sustained tension. As the concrete creeps with time, time-dependent increase in confinement stress in FRP will occur due to load transfer from the low modulus concrete to the relatively high modulus FRP. The interfacial bond stress between FRP and concrete will also experience time-dependent changes. Creep of FRP composite is a combined response of fibres, resin and interfacial behaviour of fibre and the matrix under sustained tension. In addition, the temperature will have a significant influence on the instantaneous and time-dependent deformation of FRP. Naguib and Mirmiran (2002) experimentally investigated the behaviour of glass FRP (GFRP) confined concrete under sustained compression and showed that the effect of confinement on creep of the concrete core is not significant. They also found the ACI 209R-92 (1992) model overestimates the creep of FRP confined concrete and the creep coefficients for the FRP tubes. The difference in the case of FRP wrapped confinement was not however significant. Analytical studies indicated that the creep of FRP wrapped columns is similar to that of sealed concrete.

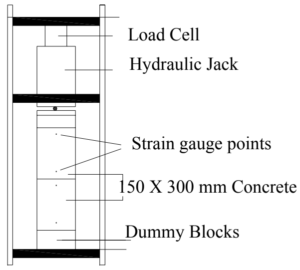


Figure 1: FRP confined concrete cylinders under sustained compression.

3. EXPERIMENTAL SET-UP AND INSTRUMENTATION

Normal weight medium strength concrete (28-day cylinder strength of 37 MPa) was used in this study. A number of 150 x 300 mm concrete cylinders were cast in standard steel moulds and cured in water at 20°C for 28 days prior to testing. The cylinders were then either confined by wrapping with two layers of unidirectional CFRP formed in a wet lay-up procedure in the hoop direction or unconfined but sealed by coating with epoxy resin used in the formation of the CFRP. The confined and unconfined cylinders were subjected to either short-term uniaxial compressive loading until failure at specified ages or sustained uniaxial compression (up to 150 days) in self-reacting creep rigs, as shown in Figure 1. Each creep rig had a pair of either CFRP confined or unconfined cylinders. The sustained stress intensity corresponded to 40 and 60% of the cylinder strength of the unconfined concrete at the ages of loading (Table 1). The confined compressive strength of the cylinders at the ages of loading is also given in Table 1 (last column in brackets) as well as the sustained stress intensity expressed as a percentage of the cylinder strength of confined concrete. Loads were applied via hand-operated for 40% stress level and electrically-operated hydraulic jacks for 60% stress level and the loads were monitored through calibrated load cells. Periodic load adjustments were made to ensure that appropriate sustained stresses are maintained on the creep cylinders. The confined cylinders loaded were air stored at the uncontrolled laboratory environment for 14 and 32 days respectively after the removal of the cylinders from water curing prior to application of the CFRP.

Table 1: Details of concrete specimens under sustained compressive loading

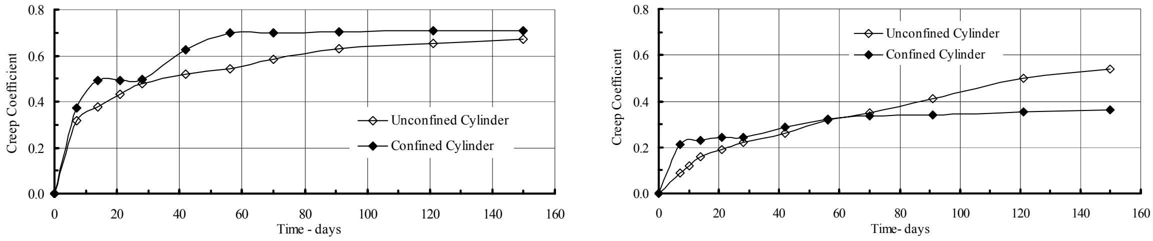
Creep Rig	Specimen #	Age of concrete at loading	Duration of load	Applied stress level with respect to strength of	
				Unconfined concrete	Confined concrete
No. 3	P3, P4	60 days	150 days	40% (of 42.5 MPa%)	26% (of 65.0 MPa%%)
No. 4	F3, F4	60 days	150 days		
No. 5	P5, P6	100 days	150 days	60% (of 47.5 MPa%)	43% (of 65.1 MPa%%)
No. 6	F5, F6	100 days	150 days		

P = Plain unconfined cylinder coated with epoxy resin: F = CFRP confined cylinder
% = unconfined compressive strength at age of loading: %% = confined compressive strength at age of loading

The axial (longitudinal) deformations on both the concrete and CFRP surfaces were measured using a demountable mechanical strain gauge (DEMEC) over a 200mm gauge length. The DEMEC points were mounted on diametrically opposite sides of each cylinder on (i) the concrete surface in unconfined cylinders, or in confined specimens after small holes were drilled through the CFRP, and (ii) on the surface of the CFRP in confined cylinders at a quarter of the circumferential distance from the concrete DEMEC points. The hoop strain on the CFRP was measured using electrical resistance strain gauges over 67 mm gauge length. Drying shrinkage of companion non-loaded, non-wrapped and non-epoxy coated cylinders, stored in the same room and environment as the creep rigs, was measured throughout the whole duration of the experiment. The creep test was conducted in uncontrolled laboratory environment having the mean temperature and relative humidity of 23°C and 60% respectively. Tension tests were conducted on eight identical two layered, 15 mm wide, 252 mm long and 0.234 mm thick (2 layers of 0.117 mm CFRP nominal thickness sheet) coupons to determine the tensile strength, rupture strain and modulus of elasticity of the CFRP.

4. RESULTS AND DISCUSSION

The mean tensile strength, rupture strain, and modulus of elasticity of the CFRP coupons was 3030 MPa, 1.10 % and 246 GPa with standard deviations of 91 MPa, 0.05 % and 11 GPa, respectively. The mean confined compressive strength of concrete at 28 days was 65.0 MPa compared to 37.0 MPa for the unconfined concrete at the same age. Thus, CFRP confinement increased the cylinder strength by approximately 75%. The sustained stress/strength ratios of the confined cylinders were 26% (at 60 days of age) and 43% (at 100 days of age) which corresponded to 40% and 60% of the unconfined cylinders as given in Table 1. The stress-strain relationships for confined and unconfined concrete in compression indicate that the modulus of elasticity of concrete was not significantly affected by the confinement. The values for the modulus of elasticity, calculated by dividing the applied stress by the instantaneous strain on loading (AS 1012.16 1996) of the creep rigs for the unconfined and confined cylinders were 26.3 GPa and 27.8 GPa at the 40% stress level and 28.9 GPa and 29.4 GPa at the 60% stress level, respectively. Even though the strength of the concrete changes with time (fifth column in Table 1), the strength of the confined concrete cylinder is virtually identical (sixth column in Table 1) as the failure is primarily dependent on the confinement of the CFRP.



(a) 40% stress level (b) 60% stress level

Figure 2: Creep of confined and unconfined concrete: up to 150 days of loading

The time dependent behaviour of loaded concrete is evaluated via its creep behaviour with time. Creep intensity is expressed in terms of creep coefficient which ratio of creep strain to the instantaneous strain on loading. The creep strain is equal to the total strain on the loaded cylinders minus the drying shrinkage strain from non-loaded companion cylinder. Figure 2 shows the development of creep coefficient with time for both confined and unconfined concrete up to 150 days, under both sustained stress levels.

Table 2: Creep coefficient for FRP confined and unconfined concrete

Time (Days)	Creep Coefficient @ 40% Stress Level			Creep Coefficient @ 60% Stress Level		
	Unconfined (Φ1)	Confined (Φ2)	Φ2/ Φ1	Unconfined (Φ1)	Confined (Φ2)	Φ2/Φ1
28	0.47	0.49	1.04	0.22	0.24	1.09
90	0.62	0.70	1.12	0.41	0.34	0.84
150	0.67	0.70	1.04	0.54	0.36	0.67

The creep coefficient at 150 days for unconfined concrete at the 40% stress level was 0.67 compared to 0.54 for that under 60% stress level. This is partly due to the increase in the age at loading from 60 to 100 days.. With the confined concrete more significant drop from 0.70 to 0.36 was observed after 150 days. Also evident in Figures 2a and 2b is the creep in confined cylinders stabilised earlier than the unconfined cylinders. This is a consequence of the latter having lower concrete stress levels. The rate of creep for the unconfined cylinders increased as the applied stress is increased. This is particularly evident in the unconfined cylinder at 60% loading in which a high stress level has led to more significant microcracking which may have increased the rate of creep in concrete (Sri Ravindrarajah and Swamy 1989). At both stress levels, the minimally activated FRP is mainly acting as a moisture barrier to the concrete. This was confirmed by small FRP hoop strain measurements. However, when the sustained stress level is greater than the unconfined strength of concrete, the creep response of confined concrete may be influenced by the creep properties of the FRP. Research is in progress to study the creep of confined concrete under high sustained stress levels.

Table 2 summarises the creep coefficients after 28, 90 and 150 days of loading. The ratio of creep coefficient for confined to unconfined concrete was 1.04, 1.12 and 1.04 after 28, 90 and 150 days, respectively at the 40% stress level compared to a more decreasing trend with the ratios at 1.09, 0.84, and 0.67 at 60% stress levels. The increasing creep coefficient of the unconfined cylinder as opposed to the stabilised creep coefficient for the confined cylinders from 90 to 150 days results in a reduction of the ratios in Table 1.

5. CONCLUSION

Compressive strength, modulus of elasticity and creep of concrete confined with 2 layers of CFRP were studied. Concrete cylinders were subjected to constant sustained stress levels, corresponding to 40% and 60% of the unconfined concrete strength at the age of loading of 60 and 100 days, for up to 150 days. The confinement increased the concrete 28-day cylinder strength by 75%. At the stress to strength level of 40%, no significant effect of CFRP on the creep of concrete was noted, however the rate of creep slowed quicker in the confined than the unconfined specimens. Current research is undertaken to investigate the creep of confined concrete under high sustained stress levels. Creep tests on CFRP coupons subjected to different conditions are also being conducted in order to give a better understanding of variations in moisture and temperature in the uncontrolled laboratory conditions, and stress distribution and creep effects in a CFRP confined system. Time-dependent tests will also be conducted on GFRP confined cylinders in the future, where GFRP has been traditionally observed to creep more than CFRP.

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