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Title: Utilisation of fibre reinforced polymer (FRP) composites in the confinement of concrete

Year of publication: 2007

Citation: Ciupala, M.A., Pilakoutas, K., Mortazavi, A.A. (2007) 'Utilisation of fibre reinforced polymer (FRP) composites in the confinement of concrete' Proceedings of Advances in Computing and Technology, (AC&T) The School of Computing and Technology 2nd Annual Conference, University of East London, pp.145-150

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UTILISATION OF FIBRE REINFORCED POLYMER (FRP) COMPOSITES IN THE CONFINEMENT OF CONCRETE

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Abstract: This paper presents an experimental investigation carried out on concrete cylinders confined with fibre reinforced polymers (FRP), subjected to monotonic and cyclic loading. Carbon fibres (CFRP) were used as confining material for the concrete specimens. The failure mode, reinforcement ratio based on jacket thickness and type of loading are examined. The study shows that external confinement of concrete can enhance its strength and ductility as well as result in large energy absorption capacity. This has important safety implications, especially in regions with seismic activity.

1. Introduction:

FRP materials have been extensively used in the last ten years to improve the performance of reinforced concrete members in terms of strength and ductility. The civil engineering community, faced with the increased problem of premature deterioration of traditional construction materials, has sought high performance materials to enhance the safety and to extend service life of the infrastructure applications.

FRP materials offer several advantages with respect to the traditional concrete structures, such as lightness, high stiffness, high strength-to-weight ratios and ease of application (Hollaway, 1999).

Several composite jacketing systems have been developed and validated in laboratory or field conditions (Seible, 1997), (Teng et al., 2003), (Karantzikis et al., 2005). One of these systems uses unidirectional carbon fibre sheets wrapped longitudinally and/or transversely in the region which needs retrofitting or strengthening.

This paper presents an experimental investigation carried out on CFRP confined concrete cylinders, subjected to

monotonic and cyclic loading. The carbon fibre sheets are wrapped transversely around concrete cylinders to increase their strength and ductility.

2. Experimental investigation:

2.1. Specimen details, instrumentation and test procedure:

Though the research investigated a large number of cylinders, for brevity this paper will deal with only six FRP confined concrete cylinders (Mortazavi, 2002). Carbon fibres (CFRP) were used for the construction of the FRP jackets. The mechanical properties of the fibres are shown in Table 1.

Mechanical properties	CFRP
Nominal Thickness t_j (mm)	0.117
Young's modulus E_j (MPa)	240000
Ultimate tensile strength f_u (MPa)	3900

Table 1 Mechanical properties of fibres used in the FRP jackets

Three jacket thicknesses were considered comprising 1,2,3 layers of CFRP material. The diameter of cylinders was 100 mm and the height of cylinders was 200 mm.

A number of five concrete cylinder control specimens with a diameter of 100 mm and a height of 200 mm were cast and cured under the same conditions as the FRP confined concrete specimens. Based on the cylinder test results at the time of testing, the average concrete strength (f_{co}) was found to be 33 MPa.

All the specimens were instrumented with five 15 mm strain gauges: three strain gauges were attached horizontally at mid-height of each specimen, 120° apart, to measure lateral strain and two strain gauges were attached vertically at mid-height, to measure axial strain. In addition to the strain gauges, two other displacement measuring devices were employed to measure the lateral and axial strain, respectively.

The tests were carried out using a servo-controlled hydraulic actuator with a capacity of 1000 kN. The specimens were labelled as follows: WCL-n, where W stands for wrapping, C denotes the confinement material - Carbon, L is the number of layers of the FRP jacket and n represents the sample number.

Some of the specimens were tested under uniaxial monotonic compression loading and some of them were tested under uniaxial cyclic loading, as shown in Table 2.

2.2. Failure mode:

The failure of all the specimens confined with CFRP jackets was sudden and occurred in an explosive manner.

Almost all of the CFRP jackets failed at different locations and a small rupture in the jackets induced complete failure of the

specimen, as shown in Fig.1. In vast majority of cases, the top and bottom part of the samples remained undamaged and hence did not deteriorate during failure. In general, the specimens tested under cyclic load experienced more damage than those tested under monotonic load.

Specimens /Loading	CFRP
Monotonic	WC1-1, WC1-2 WC2-1, WC3-1
Cyclic	WC2-2, WC3-2

Table 2 Testing program

2.3. Stress-strain behaviour:

In the case of specimens WC1-1 and WC1-2, the ultimate compressive strength of the confined concrete increased by about 75% of that of the plain (unconfined) concrete, f_{co} , as shown in Fig.2. The normalised axial stress is defined as the ratio of f_{cl} / f_{co} , where f_{cl} is the axial compressive strength of the confined concrete.



Fig. 1 Failure of concrete-filled CFRP tubes

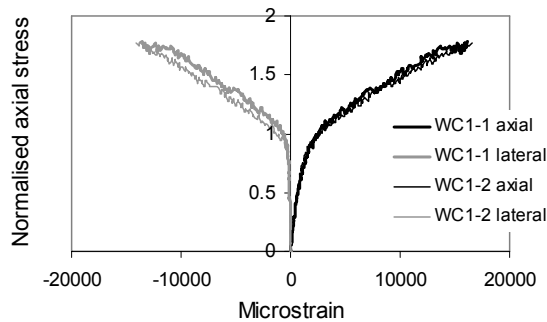


Fig. 2 Stress-strain curves for WC1 specimens
The axial strains have positive values whilst the lateral strains have negative values. At failure, the jacket strength was well mobilised in both specimens. The lateral strain in both cases was around $14000 \mu\epsilon$.

Specimens WC2-1 and WC2-2 appeared to have developed the full capacity of the CFRP jacket and both of them exhibited an ultimate compressive strength of about $2.7 f_{co}$. Fig.3 shows the normalised axial stress versus the lateral and axial strain for the WC2 specimens.

Samples WC3-1 and WC3-2 showed an ultimate compressive strength of about $3.5 f_{co}$. At failure, in the cyclic test, the full capacity of the jacket was mobilised whilst in the monotonic test the specimen failed at around $14500 \mu\epsilon$, as presented in Fig.4.

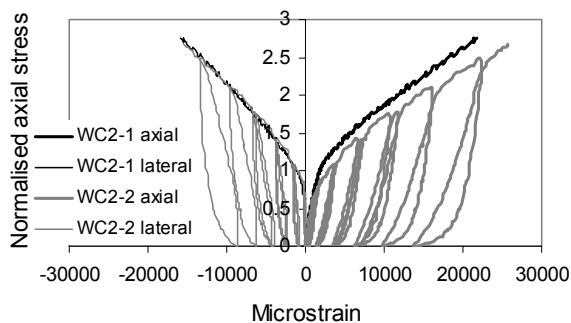


Fig. 3 Stress-strain curves for WC2 specimens

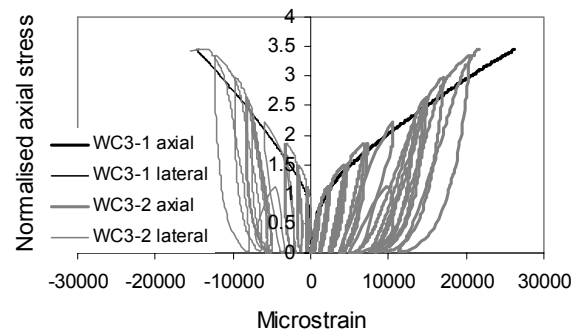


Fig. 4 Stress-strain curves for WC3 specimens

2.4. Volumetric strain:

The normalised axial stress and normalised axial/lateral strain were plotted versus the volumetric strain. The normalised axial strain is expressed as $\epsilon_{cl} / \epsilon_{co}$ and the normalised lateral strain is defined as $\epsilon_{cr} / \epsilon_{cor}$, where ϵ_{cl} and ϵ_{cr} are the average axial and lateral strains in the confined concrete and ϵ_{co} and ϵ_{cor} are the average axial and lateral strains in the unconfined concrete ($\epsilon_{co} = 0.002$ and $\epsilon_{cor} = 0.001$).

The volumetric strain is defined as $(V - V_o) / V_o$, where V_o and V are the initial and final volume of concrete, respectively. Fig.5 shows the relationship between the normalised axial stress and the volumetric strain for WC1-1 and WC1-2 specimens. It can be noted that WC1-1 appears to be less damaged than WC1-2, at similar levels of axial load. Both samples show a similar behaviour as they developed more or less the same volumetric strain at failure. The maximum contraction of the concrete core for WC1-1 and WC1-2 was reached at about f_{co} and $0.8 f_{co}$, respectively. The relationship between the axial and lateral strain and the volumetric strain for these two specimens after the initiation of expansion

due to cracking is almost linear, as shown in Fig.6.

In the case of the WC2-1 and WC2-2 specimens, the volumetric expansion of the concrete core started when the compressive strength of the unconfined concrete, f_{co} , was reached, as shown in Fig.7. Although both specimens showed a ductile behaviour, WC2-2 exhibited a larger amount of contraction at the initial stages and a larger amount of expansion in the area of unstable crack propagation.

As presented in Fig.8, the relationship between the axial and lateral strain and the volumetric strain for the monotonic loading is almost quasi-linear.

At failure, specimen WC3-1 had an expansion much less than that of specimen WC3-2, as presented in Fig.9.

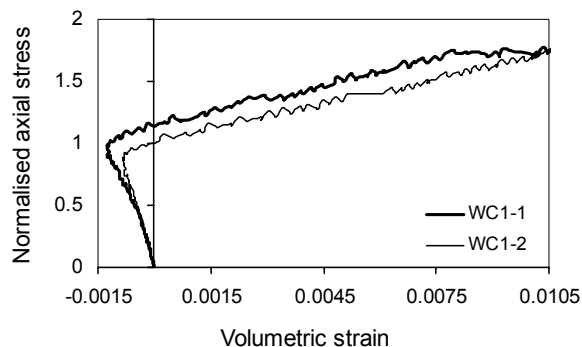


Fig. 5 Normalised axial stress versus volumetric strain for WC1 specimens

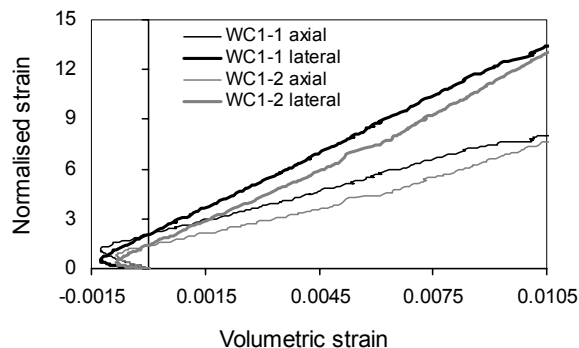


Fig. 6 Normalised strain versus volumetric strain for WC1 specimens

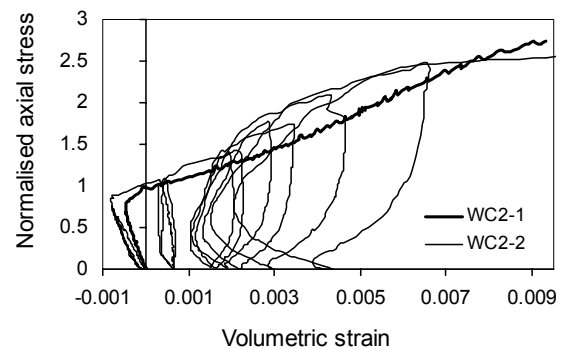


Fig. 7 Normalised axial stress versus volumetric strain for WC2 specimens

The contraction point of concrete reached its maximum value at f_{co} and $0.8 f_{co}$ for WC3-2 and WC3-1, respectively. As shown in Fig.10, although the normalised axial strain values are higher for WC3-2 than WC3-1, the values of the normalised lateral strains seem to be similar for both samples. Unlike the WC2 specimens, the normalised axial strain in WC3-1 throughout loading is lower than the normalised lateral strain in the contraction area. This is not the case with specimen WC3-2, as it was noted in Fig.10.

3. Discussion of results

The results of the experimental work are summarised in Figs. 11 and 12.

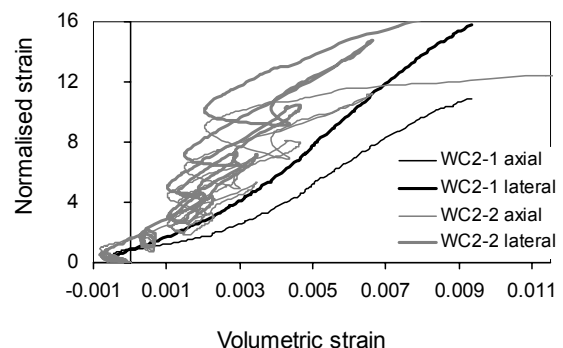


Fig. 8 Normalised strain versus volumetric strain for WC2 specimens

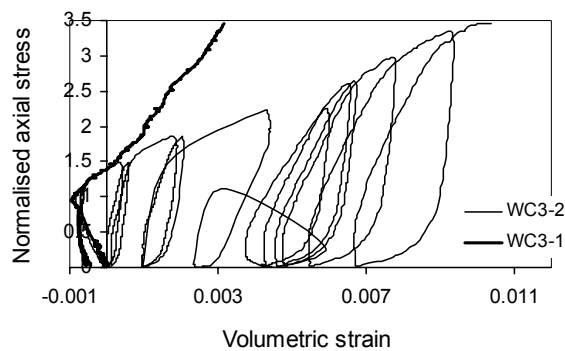


Fig. 9 Normalised axial stress versus volumetric strain for WC3 specimens

Fig.11 shows the normalised axial stress for the CFRP confined specimens under monotonic loading and Fig.12 shows the normalised axial stress for the CFRP confined specimens under cyclic loading.

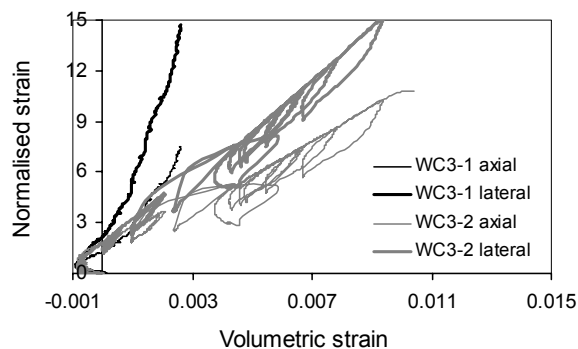


Fig. 10 Normalised strain versus volumetric strain for WC3 specimens

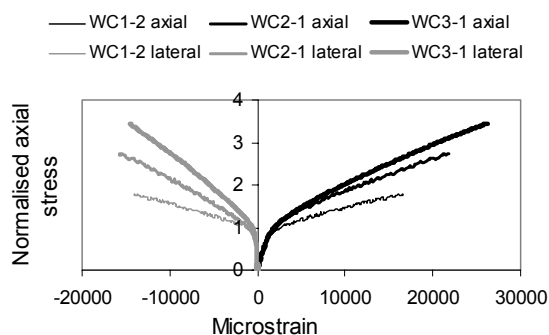


Fig. 11 Normalised axial stress for CFRP confined specimens under monotonic loading

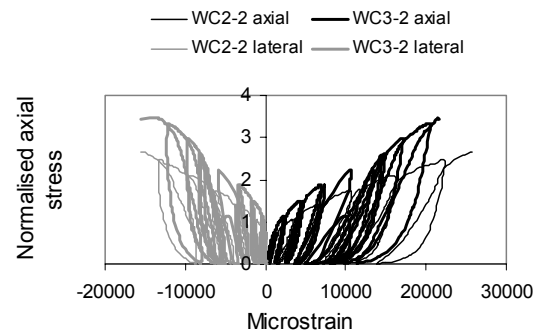


Fig. 12 Normalised axial stress for CFRP confined specimens under cyclic loading

An enhancement of the concrete strength of $3.5 f_{co}$ is noted for both the monotonic and cyclic loading.

The stress-strain response of all specimens under cyclic loading is nonlinear, with a parabolic shape, up to failure.

The energy dissipation during the unloading and reloading cycles is considerable for all the FRP confined concrete specimens. Significant plastic strains after unloading are also noticeable. No stiffness degradation upon reloading was observed.

The stress-strain relationship for the monotonic loading may serve as an envelope for cyclic loading.

4. Conclusions:

An experimental investigation was carried out on the monotonic and cyclic response of concrete cylinders confined with CFRP jackets. The study shows that concrete confined with FRP material has increased strength and deformability. Under monotonic loading, the FRP materials exhibit a more or less bi-linear relationship between strain and stress, while under cyclic loading, this relationship becomes more non-linear, but with a similar envelope as for monotonic loading.

Depending on the stiffness and strength of the confining material, both the ductility and the concrete strength could increase under cyclic loading. This has important safety implications, especially in regions with seismic activity.

5. References:

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