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Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

RC column strengthening by lateral pre-tensioning of FRP

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Abstract: This paper presents a unique strengthening technique for existing concrete columns that uses expansive materials to apply lateral pre-tensioning. The technique increases the capacity and ductility of a column as well as achieving better utilisation of the confining FRP (Fibre Reinforced Polymer) material. The confinement material properties and the confined cylinder performance are investigated experimentally. From the results it is shown that it is possible to control the degree of applied pre-tension by controlling the amount of expansive material used. In addition, it is confirmed that jacketing columns by pre-tensioned FRP materials can increase the load bearing capacity up to 35% compared with no pre-tensioning and up to more than 4 times compared with unconfined concrete. The paper presents details of experimental work undertaken for the development of the confinement pressure with different confining materials (Carbon-CFRP, Glass-GFRP and Steel) and makes comparisons with predictive models.

Keywords: Lateral pre-tensioning, expansive agent, CFRP, GFRP, ductility, expansive grout, confinement stiffness

INTRODUCTION

Earthquakes can cause severe damage to reinforced concrete structures, which are not designed or detailed properly. Some of the common problems revealed by earthquakes such as Kobe (Japan 1995) and Athens (Greece 1999) include inadequate confinement of concrete, leading to shear, anchorage and splice failures. Since the 1995 Kobe earthquake, composites have started being used for the repair and strengthening of columns against seismic actions and seismic codes are being re-examined. Extensive research has been undertaken in the field of FRP confined concrete columns [1,2,3,4,5] and recently, the fib task group 9.3 has published a bulletin on 'Externally bonded FRP reinforcement for RC structures' [6].

One of the problems with FRP confinement of concrete is that the strength of the FRP jacket is not utilised until the lateral strain in the confined concrete is very high. In some cases, the concrete will crush before the FRP jacket is fully utilised. The existing design equations for steel confined concrete, such as the ones proposed by Eurocode 8 [7] (see below) assume that the confining steel strength is fully utilised.

$$f_{cc}= f_{co}\,(1+2.5\,\alpha\omega_w) \qquad \text{for } \alpha\omega_w <0.1 \qquad 1(a)$$

$$f_{cc}= f_{co}\,(1.125+1.25\,\alpha\omega_w) \qquad \text{for } \alpha\omega_w >0.1 \qquad 1(b)$$

where;

f_{cc} and f_{co} are the maximum axial strength of confined and unconfined concrete core, respectively

α is the confinement effectiveness coefficient equal to one (for FRP cylindrical jacketing)

ω_w is a confinement index based on the volumetric mechanical ratio and is calculated as shown below:

$$\omega_w = \frac{\text{volume of lateral confinement materials}}{\text{volume of concrete core}} \times \frac{\text{strength of lateral confinement}}{f_{co}} \qquad (2)$$

Figure 1 shows the above relationships by using the normalised concrete strength f_{cc}/f_{co} versus the effective confinement index $\alpha\omega_w$. These equations cannot be used for FRP confined concrete, since the FRP strength may not be fully utilised when concrete begins to fail. For example, as shown in Figure 1, the strength of concrete confined with 2 and 3 layers of glass FRP [10] is below the predictions of Eurocode 8. In these two cases, the concrete failure took place when the strength in the glass confinement was 50% and 40% of the material strength.

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

One way of overcoming this problem is to reduce the lateral strain of the concrete at failure through pre-tensioning of the confinement materials [8]. This method is particularly useful for low modulus materials (like glass) or when relatively low amounts of confinement are applied, such as in full-scale structures [9]. In addition, existing structures may already have very large strains due to existing loading. Adding pre-tensioned FRP wraps can help reduce the stress from the internal links and provides active confinement to the structure in its service condition [10].

Lateral pre-tensioning of composites is not easy to achieve unless the fibres are stretched before the resin hardens. Resin injections under pressure were adopted by some researchers [11, 12] when trying to address the problem of inadequate starter bar lap length in columns. However, the active pressure created by this method (resin injection) is generally quite small in comparison with the passive pressure generated by concrete dilation [13]. The method proposed by the authors adopts a different approach, since it uses an expansive grout (EG) to apply pressure on the jacket reacting against the concrete. In the experimental work, an expansive agent (EA) is mixed with cement grout in different proportions to achieve different levels of confinement. The EA employed in the experiments is normally used as a non-explosive concrete cracking agent [14]. In this paper, the parametric tests on the behaviour of EA are presented and the results are discussed.

PRE-TENSIONING METHOD

The specimens prior to the introduction of the EA are shown in Figure 2. In this method, a pre-formed confining tube (jacket) is placed around an existing concrete cylinder and then a mix comprising cement, sand and EA is inserted between the concrete cylinder and the CFRP/GFRP jacket. The jacket confines the expansion of the grout during the hardening period (3-4 days) and thus the chemical pre-tensioning occurs in the jacket reacting against the concrete core.

Once the grout sets, the jacket and grout becomes an integral part of the column and this naturally increases the cross sectional area by a small amount. However, the strength and ductility enhancement come primarily from the confinement action. This action is already central to the design equations of Eurocode 8 [7] and is taken into account when detailing the links of beams and columns. Experimental work on properties of expansive grout (EG).

The expansive pressure of the grout is believed to be a function of the allowable lateral displacement. If a large displacement is allowed, then the pressure can reduce to zero. Hence, an understanding needs to be developed regarding the mechanical properties of the EG so as to enable appropriate design.

As the chemical pre-tensioning depends on the degree of expansion of the grout and the stiffness of the lateral confinement, experimental work was conducted with the following objectives:

- Examination of the relationship between the stiffness of the jacket and the amount of expansive pressure.
- Determination of the relationship between the ratios of expansive agent (EA) used per unit volume of mortar and expansive pressure.
- Investigation of the effect of the amount of EA in cylinders with the same confining stiffness.

First series

In the first series of experiments the EG was confined directly by metal tubes. The tubes were selected to apply different confinement stiffness levels through the use of different material (steel or copper), thickness and diameter, as shown in Figure 3. The ratio between length (L) and inner diameter (D) of the tubes was set as 10, as shown in Table 1. It is obvious that choosing different thickness of confinement material (t), elastic modulus of the jacket (E) and radius of tube or jacket (r) can change the confining stiffness (CS), which is defined as (E t / r).

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

Different ratios of EA to EG were used to achieve different expansion pressures. To measure the amount of expansion, three strain gauges measuring longitudinal and circumferential strain were applied in the middle of the pipes, as seen in Figure 3. Figures 4 and 5 show the initial lateral strain on the tubes versus time. It is seen that the initial rapid expansion takes place within 12-36 hours. Figure 4 shows that different confining stiffnesses, either due to the use of different material or diameter, result in different lateral strains. Figure 5 shows that increasing EA ratios result in larger lateral strains. Figure 6 shows the relationship of maximum expansive pressure MEP (calculated from measurements by strain gauges), and the confining stiffness (CS) for two different ratios of EA. It is clear that, as the CS and EA increases, the expansive pressure increases as well.

Second series

The second series of experiments was designed in accordance to the third objective of this work and examined the effect of the amount of EA in cylinders with the same confining stiffness. For this propose, three steel tubes with the same diameter and thickness were used. One sample (S1) was filled with expansive material without any core in the middle, the second sample (S2) was made with a concrete core 50mm diameter and the third sample (S3) with a concrete core 66mm diameter as shown in Figure 7. Strain gauges were placed on the outside of the steel jacket and the arrangement of the strain gauges was the same as for the tube samples, but with additional strain gauges placed on the concrete core. To avoid any leaking from the top and bottom of the cylinders, two steel plates (with rubber washers) were used as shown in Figure 8.

Figure 9, shows the strain developed in the confinement jacket versus time both for the radial (lateral) and axial (longitudinal) directions. It can be seen that although the confinement stiffness and the EA ratio are constant for all these specimens (S1, S2, S3), the lateral and longitudinal strains increase as the volume of EG increases (from S3 to S1). This figure also

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

indicates that due to the lateral expansion, the confining material shrinks in the longitudinal direction, as illustrated by the axial strains.

Figure 10 shows the relationship between the maximum expansive pressure (MEP) and the ratio of the volume of EG to the volume of the cylinder (EG/V) with a constant EA ratio (20%). It appears that the MEP increases linearly with increasing volume of EA.

PRETENSIONING OF GFRP AND CFRP CONFINEMENT

Glass and carbon fibres have been introduced as wrapping materials for RC strengthening only in recent years. As shown in Table 2, the glass fibre used is a material with low elasticity and stiffness and high elongation whilst carbon fibre has much higher strength and elasticity. However, as carbon is a much more expensive material, it is possible to achieve a similar stress by using more glass fibre having a similar overall cost. The main problem for both types of fibre when used as confinement is that, to mobilise their strength, larger deformations are required, up to ten times higher than those of steel.

Unconfined concrete crushes in compression when the lateral strains are relatively low (~0.1%) but this value increases with increased confinement. However, for moderate amounts of confinement, as used in practice, the concrete will start crushing when the lateral strain is well below 0.25% (steel yield strain) which means that, the fibre strength is not fully utilised. Only by pre-tensioning the fibres will the confined concrete delay crushing until the strength of the fibres is reached.

In this investigation, a total of 68 concrete cylinders (100mm diameter, f_{co}= 32 MPa) were tested to find out how the pre-tensioning can generate lateral confining strain and affect the strength and ductility of concrete. Some of the specimens were pre-tensioned and some were not. To create different degrees of confining pressure, different layers of CFRP and GFRP were applied. Furthermore, to show the effect of the EA ratio, different percentages of EA were used.

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

SPECIMEN PREPARATION

For the wrapping of concrete cylinders without pre-tensioning, after applying the epoxy primer on the concrete surface, epoxy adhesive was applied and Carbon/Glass sheets were wrapped around the concrete cylinder until one wrapping layer was completed (with one third of the perimeter as overlap). At the same time, a special roller was used to help impregnate the fibre with resin and hardener and give a smooth finish. After curing, the strain gauges were glued directly onto the body of the jacket.

For the pre-tensioned specimens, a gap is needed between the concrete and FRP for the insertion of the EG. For these experiments, the FRP jacket was pre-manufactured with a diameter 14mm larger than the concrete cylinder. After curing, the jacket was placed around the concrete and the ends were capped to seal the EG inside. Strain measurements were taken during the expansion phase of the EG for up to four days.

EXPERIMENTAL RESULTS

Failure mode

Because of the massive amount of experimental information collected only the experimental results of the monotonic compression tests carried out on two layers of a uni-directional carbon wrapping and three layers of a bi-directional glass wrapping are presented here (Figures 11-14). Failure was always explosive due to the high strain energy stored by the FRP material and it took place around the middle of the cylinder height. This was not the type of failure observed when steel jackets were used, due to the gradual yielding of the confining steel jacket.

Figures 11 and 12 show the catastrophic failure of the concrete specimens wrapped with two layers carbon (WC2-2) and three layers glass (WG3-1), respectively. As shown in these figures, the mode of failure of the glass fibre wrapping is completely different from that of

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

carbon. This is probably due to the bi-directional nature of the glass fibre wrapping, which has the effect of redistributing lateral strains over the full height of the specimen.

Stress-strain behaviour

Figures 13 and 14 show the stress-strain diagrams for the specimen tested with two layers of carbon fibre (WC2-1/PC2-20-1) and three layers of glass fibre (WG3-1/PG3-20-1), respectively. Each graph shows the results for the unconfined cylinders as well as for the confined samples with pre-tensioning (PC2-20-1, PG3-20-1) and without pre-tensioning (WC2-1, WG3-1). Strain measurements shown, are the average values from two longitudinal and three lateral strain gauges. The confining pressure was developed with 20% of EA. The graphs also show the pre-strain that was developed by the EG.

Figure 14 shows the amount of initial pre-tensioning achieved in the three layers of glass fibre wrapping. The strength of the pre-tensioned cylinder is increased by about 20% and the lateral strain about 50%. The behaviour of lateral and longitudinal strains is more complicated compared with carbon wrapping, because the glass wrapping contains longitudinal fibres. From the figures it can be seen that the pre-tensioned wrapped fibres failed at a higher lateral strain (almost 100% higher), which means that the fibre was better utilised. Due to eccentric deformations and slip of the jacket, it is not always clear if the pre-tensioning had a beneficial effect on the longitudinal strain other than showing a higher initial stiffness. This aspect of behaviour is being further investigated.

GENERAL COMPARISONS

Figure 15 shows a general comparison of results for glass and carbon FRP confined concrete and confinement models by Eurocode 8, Mander et al. [16], Fardis et al. [17] and Karbhari et. al. [18]. It is clear that pre-tensioning led to an enhancement in strength and this strength is conservatively predicted by the Eurocode 8 equations. The equations of Mander et al., developed for steel reinforcement, give slightly better predictions at higher values of $\alpha\omega_w$, however, they are unconservative for $\alpha\omega_w$ less than 0.7. The Fardis et al. model, developed for composite confinement, is better at the lower ratios of confinement, but it is unconservative after $\alpha\omega_w$ 0.7. The Karbhari et al. model also developed for composite confinement seems to be the most conservative of all models.

Further research will aim to develop new constitutive models and to demonstrate the effect of pre-tensioning on the cyclic behaviour of concrete. The later is of particular interest since the degradation of concrete is expected to be less when lateral confinement is pre-tensioned.

CONCLUSIONS

It is shown that pre-tensioning can be achieved by using an expansive grout. Results presented show that the expansive pressure can be controlled by the ratio of expansive agent employed and the level of the confining stiffness.

This paper has demonstrated that pre-tensioning of confined concrete can enhance the utilisation of the fibres used for wrapping and the behaviour of the concrete. In the case of GFRP, for conventional non pre-tensioned wrapping with three layers, the wrapping failed at half the lateral strain achieved for the pre-tensioned jacket. This represents a 100% increase in the utilisation of the fibre. For the CFRP specimens, lateral and longitudinal strains were about 10 times greater than those for unconfined concrete. Existing models for concrete confinement does not represent the behaviour of FRP confined concrete accurately since they assume that the FRP strength is fully utilised.

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Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

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Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

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Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

LIST OF TABLES AND FIGURES

TABLE 1

METAL TUBES AND THEIR PROPERTIES

Material	D (mm)	T (mm)	L (mm)	E kN/mm^2	CS kN/mm^2
Black steel					
Bl.S.	21.53	1.40	220	180	46.82
Bl.L.	41.26	1.85	420	180	32.02
Annealed steel					
An.S.	34.82	1.60	350	195	17.92
An.L	47.5	1.65	475	195	13.55
Copper					
Cop.S.	25	1.50	255	124	14.88
Cop.L.	38.2	2.00	380	124	12.4

TABLE 2

TYPICAL GLASS AND CARBON PROPERTIES [15]

Fibre	E_{frp} GPa	f_{frpu} MPa	ε_{frpu} %	t mm	Density gr/cm^3
Glass AR	65	1700	2.88	0.135*	2.6
Carbon 240	240	3900	1.55	0.117	1.7

* Design thickness is equal 0.0675 (the glass sheet is woven bi-directional-90^o)

E_{frp} Young’s modulus of elasticity

f_{frpu} Ultimate tensile strength

ε_{frpu} Elongation of pultruded laminate

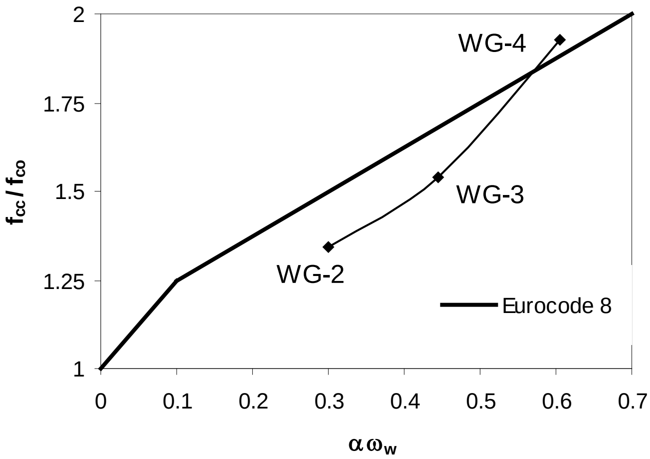

Figure 1: Eurocode 8 predictions and experimental results for GFRP wrapped concrete

Figure 2: Specimens prior to grouting

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

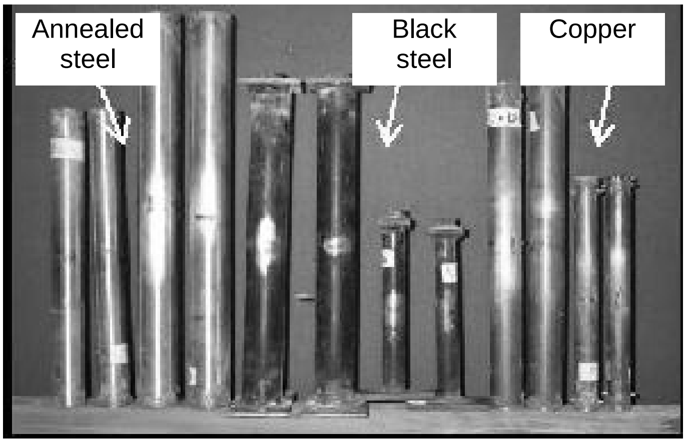

Figure3: Metal tubes filled with expansive grouts

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

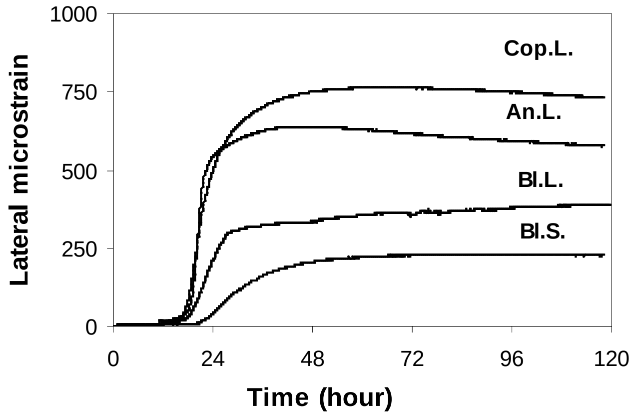

Figure 4: The effect of confinement stiffness on lateral strain (20% EA)

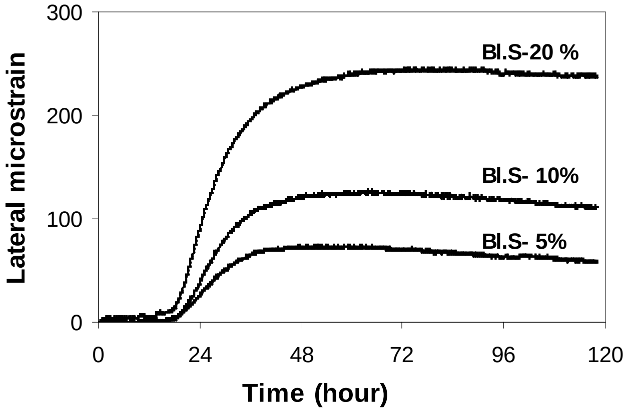

Figure 5: The effect of EA ratio on lateral strain when CS is constant

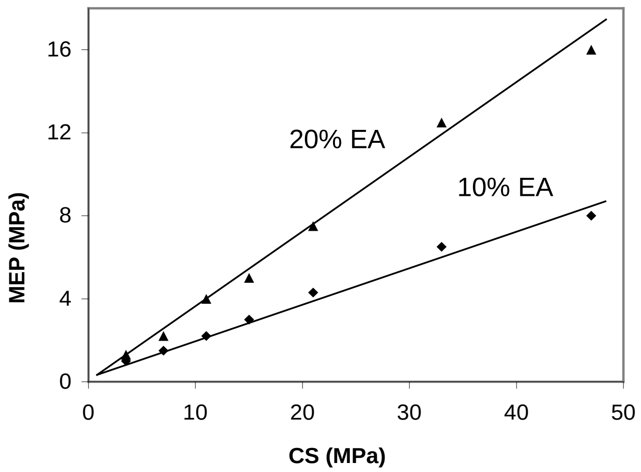

Figure 6: MEP versus CS for two values of EA

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

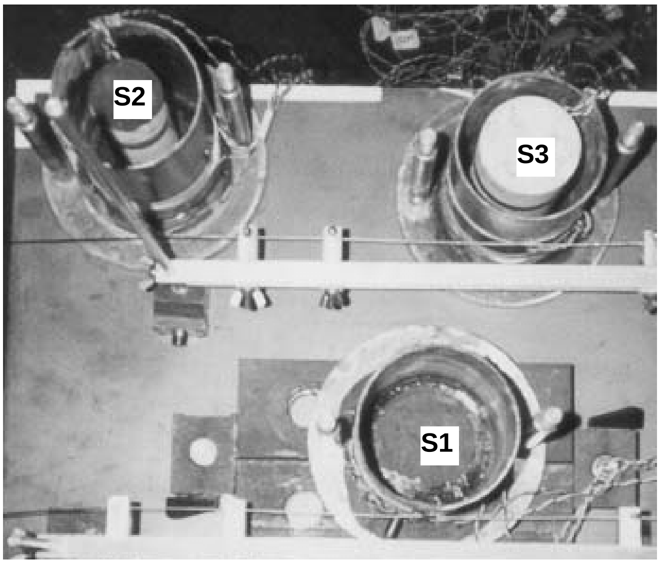

Figure 7: Three cylinders with different volumes of EA

Figure 8: Confined cast and sealed cylinders

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

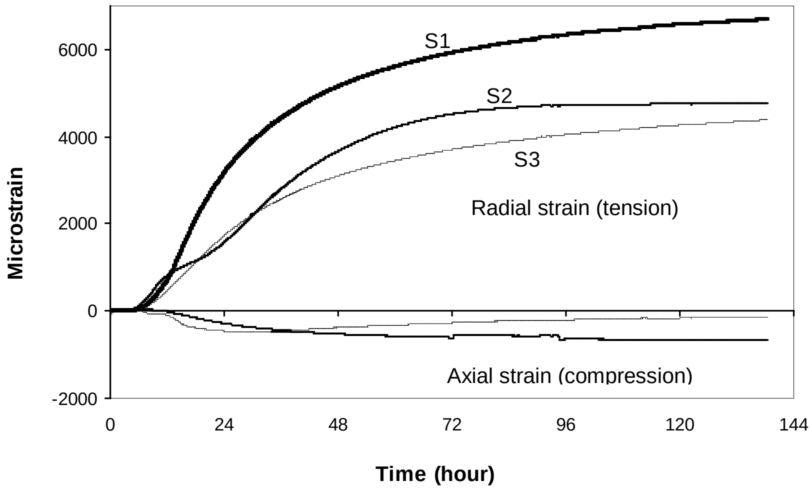

Figure 9: The effect of EG volume on axial and radial strains

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

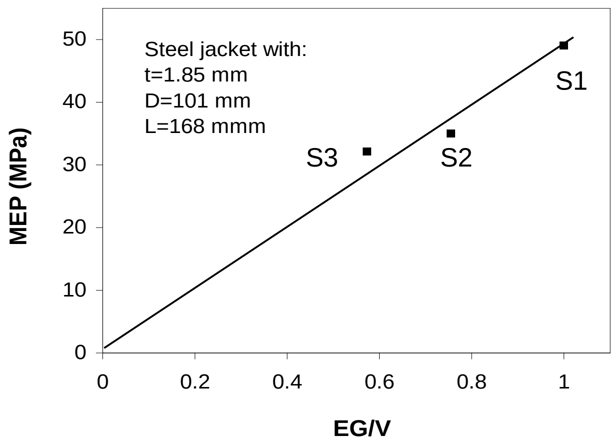

Figure 10: MEP versus EG/V for 20% EA

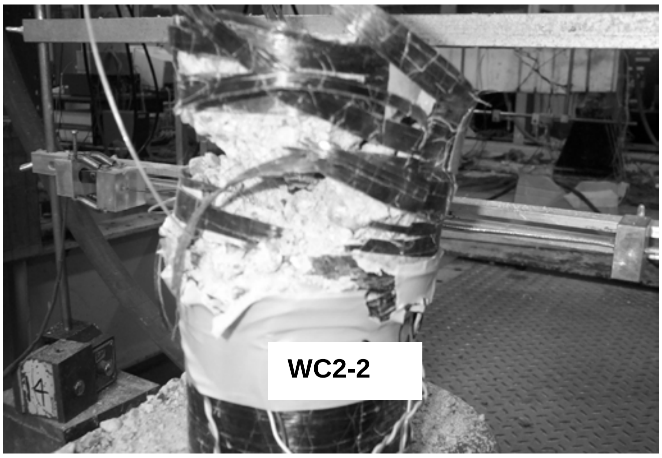

Figure 11: Carbon wrapping after failure

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

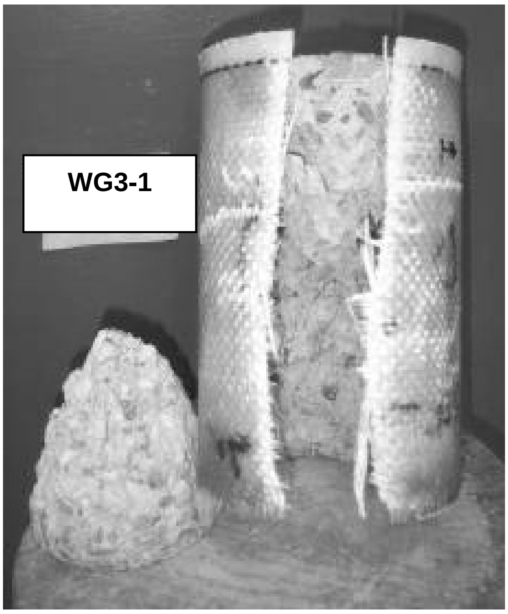

Figure 12: Glass wrapping after failure

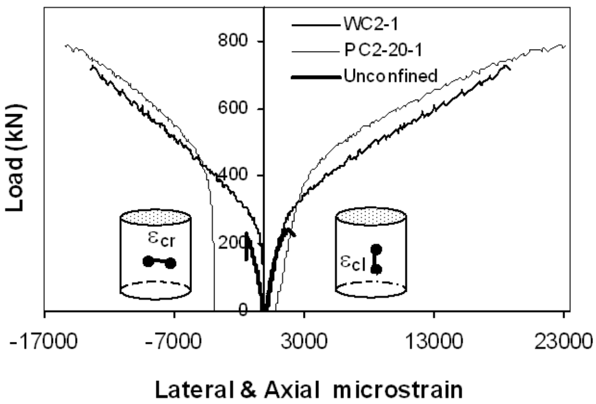

Figure 13: Load versus average radial and axial microstrain (2 layers Carbon)

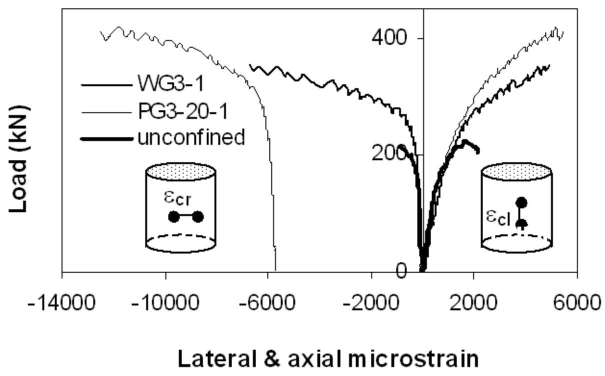

Figure 14: Load versus average radial & axial microstrain (3 layers Glass)

Journal of Construction and Building Materials, Volume 17, Issues 6-7, September - October 2003, pp 363-518

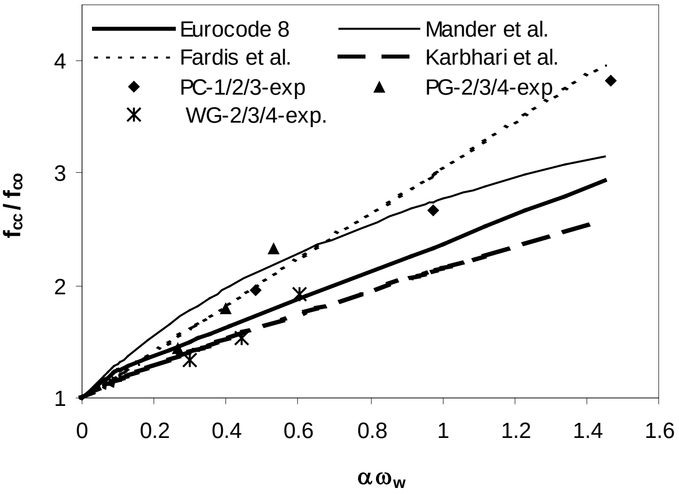

Figure 15: Comparisons between experimental and theoretical predictions