



Strength and Ductility of Concrete Members Confined by External Post-Tensioned Strips

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Abstract

This paper presents the results of experimental and analytical study on a new technique of seismic retrofitting of concrete columns. In this technique, standard strapping machines, which are used in the packaging industry, are used to post-tension metal strips around concrete columns. The two ends of the strip are tightened in sealed clamps to maintain the pre-stress force in the strip. Experimental program included axial compressive tests on 30 cylindrical as well as 30 prismatic small-scale columns which were actively confined by pre-stressed metal strips. Longitudinal strain of concrete and strain in the strips were monitored. Test Results showed significant increase in strength and ductility of columns due to active confinement with metal strips. The effect of various parameters such as pretensioning force in the strip, number of strip layers wrapped around the specimens, details of strip joint and the mechanical volumetric ratio of confining strip on strength of concrete is studied. The observed stress-strain relations of columns with different levels of confinement are compared to those calculated based on Mander's and Madas's confinement models.

Keywords: Metal strip, seismic retrofitting, RC structure, confinement, ductility.

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. It is well known and proven that lateral confinement improves the strength and ductility of concrete (Dilger et al., 1989). Confinement reinforcement is generally applied to compressive members as lateral reinforcement with the aim of increasing their load carrying capacity and their ductility in case of seismic upgrading. In addition, lateral confinement prevents slippage and buckling of the longitudinal reinforcement (Saadatmanesh et al., 1994). Lateral reinforcement can be provided by using circular hoops, rectangular ties, jacketing by steel, FRP, ferrocement, etc.

Because the total cost of replacement of the vulnerable structures is so overwhelming, the development of innovative rehabilitation and strengthening techniques is requested to extend the life expectancy of many existing buildings and bridges. A number of repair and strengthening techniques are currently in use for reinforced concrete structures. Unfortunately, majority of them are very expensive, time consuming and require the interruption of use of the structure whilst works are carried out. Hence, there is a pressing need for the development of improved, low cost, less disruptive techniques, which will make necessary interventions in many

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structures economically viable. It should be borne in mind that the cost of retrofitting buildings is the primary factor which deters many private owners from executing essential works.

In this paper, an easy and innovative technique of retrofit of concrete is presented. The main aim of this research was quantification of the enhancement of concrete strength and ductility by the application of the technique. The results of experimental and analytical studies on the performance of the technique are discussed.

Description of the technique

The technique under investigation for the repair/strengthening of columns, involves post-tensioning metal strips around the column (by using standard strapping machines used in the packaging industry) and subsequently securing them in place by metal clips, as shown in Figure 1.

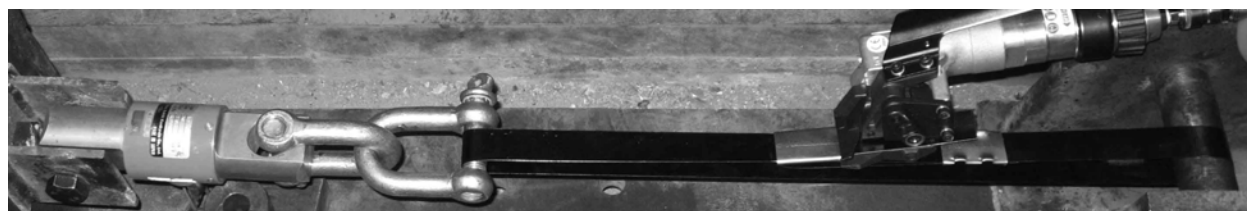


Figure 1- Metal strips and tensioner machine in calibration test

Commercially available strapping equipment enables the operator not only to apply stress on strip but also to link the stressed strip by the pressing of special clips. Even though there is a limit to the maximum thickness and width of a strip which can be bent easily around corners, in terms of strength, high strength strips in excess of 10000 kg/cm², are available on the market. The strips are tensioned to 30 percent of their yield stress. Hence, an effective lateral stress is applied on the column prior to loading, thus firstly ensuring the utilization of the capacity of the strip and secondly avoiding early crushing of the confined concrete, as would be the case with not properly tightened strips.

The low cost of strip and speed and ease of application of the strapping technique make this method efficient for use as a repair and strengthening technique for certain structural members. An RC column would normally require six man days' work to be jacketed whilst a maximum of two days' work is required for external strapping, which clearly demonstrates the cost saving when using the proposed technique.

Experimental program

Two distinctive concrete batches were made and casted in cylindrical and prismatic molds. The inner dimensions of the prismatic molds were 10*10*20 cm and the diameter and height of the cylindrical molds were 10 cm and 20 cm, respectively. The column models were made of a normal strength concrete with no air-entrainment. This concrete reached an average uniaxial compressive strength f_c of about 40 MPa. The specimens were removed from the forms after 2 or 3 days and put into water to continue the wet curing. One series of the cylindrical and prismatic specimens were tested after 35 days and the other was tested after 428 days.

Two sizes of metal strips were used for strengthening of the specimens. The first series of specimens were strengthened by using 12.7 * 0.5 mm strips and the second series were retrofitted by 16 * 0.5 mm strips. One of the important parameters in this study was to compare the active and passive external lateral confinements by this technique. In order to do so, some of the cylindrical specimens were tensioned only to 40 kg (which will be called passively confined specimens hereafter) while a tensioning force of 250 kg was applied in pretensioning the other specimens (which will be called actively confined specimens hereafter). In fact, the metal strips of the latter specimens are tensioned to 0.36 of their yield strain. The following table shows the mechanical characteristics of the strips. The modulus of elasticity of all the strips is 200 GPa.

Table 1- Mechanical characteristics of strips used

Strip	Ultimate stress (kg/ cm ²)	Ultimate strain
Bryten 12.5 * 0.5 mm	4900	0.0081
Signode 16 * 0.5 mm	8500	0.01
Signode 32 * 0.8 mm	10000	0.07

Test setup and instrumentation

The concrete specimens were fabricated in the structure and concrete Laboratory at the building and housing research center. The material used for the concrete specimens included type I Portland cement, local sand, and



crusted lime stone gravel. The maximum size of the gravel was 10 mm. No additive was used in any of the mixes.

Most of the concrete prismatic columns were made to have round corners with a radius of 10 mm to improve the confinement effectiveness and to avoid stress concentration at sharp edges. In order to investigate the effect of shape of corners, some of the specimens had sharp corners with a 90 degree angle between the orthogonal sides and some of the other specimens had chamfer corners forming a 135 degree angle at the corners.



Figure 2- Setup of axially test of a prismatic specimen

No internal reinforcement was used for the specimens. After the concrete column models had been cured, the metal strips were strapped around the specimens. Axial compression tests were conducted using a Tinius Olson testing machine with a capacity of 1,780 KN (400 kips) in the Concrete Laboratory of building and housing research center. The load was increased until significant strength decay was recorded, which indicates failure of the specimens.

At the bottom of the column specimens, a steel end plate and a V-block were used the pin support. Three 12.7 mm (0.5 in.) linear variable differential transducers (LVDT) were mounted on steel rods between top and bottom plates to measure the axial deflection of the column specimen top surface. In addition a special setup was made to measure the relative displacement over the middle $\frac{3}{4}$ height of the specimens. Also a wire LVDT was used to measure the circumferential strain of the specimens. Fig. 2 illustrates the test setup for a typical loaded column specimen.

FLA-5-11 Strain gages of TML CO. were attached to the strips to obtain the strain of strips during the test. A 200 ton load cell was located at the end of the specimen to measure the load at desired intervals together with other data.

Observed Behavior and Test Results

The column specimens were tested. The axial load, with a load rate of 178 KN/min (40 kip/min), was increased monotonically until the column specimens failed. This loading rate is equivalent to 0.25 MPa/s (37 psi/s). The ASTM standard loading rate for compressive strength of cylindrical concrete specimens is within the range of 0.14–0.34 MPa/s (20–50 psi/s). Therefore, selected loading rate falls within the range of the ASTM standard.

The observed failure surfaces of the column specimens can be divided into four major categories as shown in the following figure.

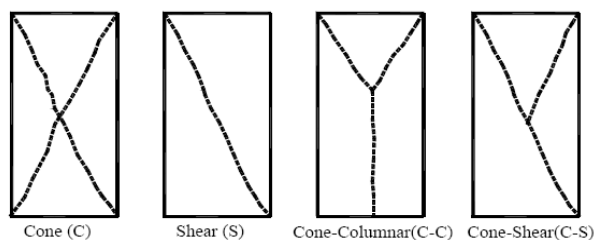


Figure 3- Compression test failure modes for specimens



The axial stress and the confining pressure kept increasing until the value of lateral strain reached the yield strain of the strips in a circumferential direction. The specimens reached their maximum strengths when one or more of the strips yielded. After the peak stress, the strips ruptured one by one resulting in the loss of axial stress. Column specimens with two layers of the metal strips gained larger strengths as well as a larger ultimate axial strain as compared with column specimens with one layer of the metal strip. The strength enhancements of cylindrical as well as prismatic specimens are drawn in the following figures versus the ratio of strips spacing to diameter of the specimen.

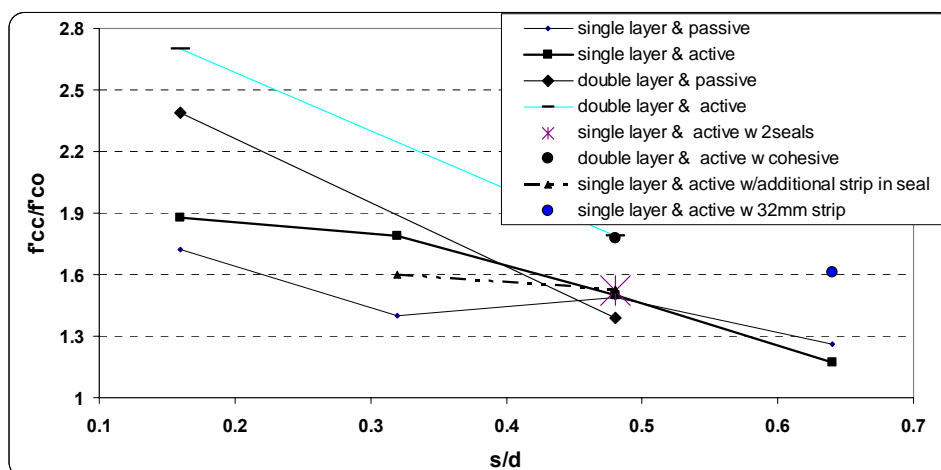


Figure 4- Strength enhancement of cylinder specimens

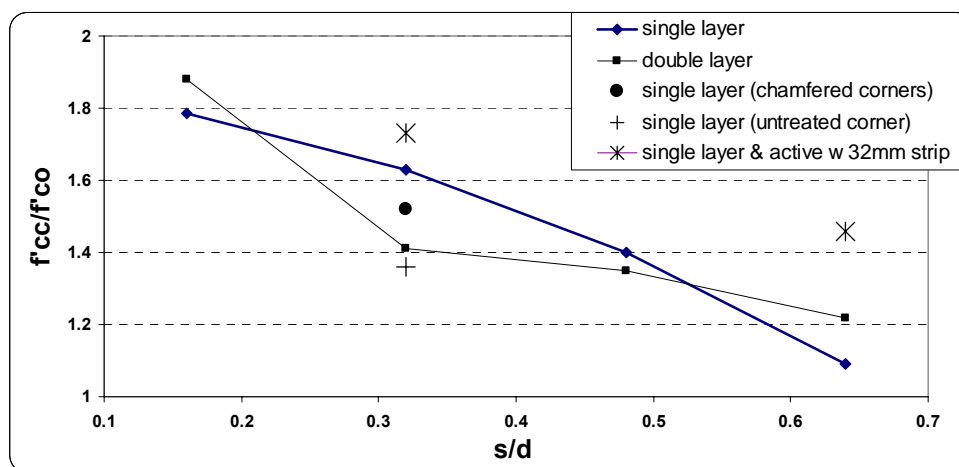


Figure 5- Strength enhancement of prismatic specimens

It can be concluded from the figures that:

- 1) This technique has been able to increase the strength of concrete up to 2.7.
 - 2) An increase in the spacing between the strips, has always led to increase in strength of confined concrete.
 - 3) Active confinement resulted in more increase in concrete strength than the passive one this is mainly because whilst the ordinary passive confinement is mainly utilized after the core concrete has dilated (which means that some cracks have occurred in it), the active confinement influences the core concrete even before load application.
 - 4) The strapping of concrete with double layer metal strips has generally shown better enhancement in concrete strength than confinement with single layer.
 - 5) Among prismatic columns with the same detail of strengthening, the round corner specimen showed better performance than the specimen with chamfered corners which in turn was better than sharp edge specimen.
- The above results have also been drawn versus mechanical volumetric ratio of confining strips in figure 6. it should be noted that α_{ω_w} in this figure is the effective mechanical volumetric ratio (EMVR) of confining steel as defined in EC8 code.

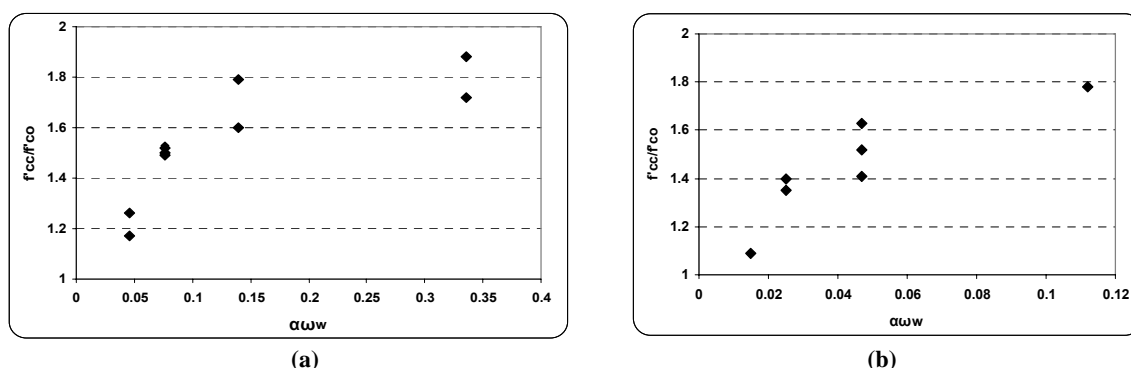


Figure 6- strength enhancement factor for single layer strapping versus EMVR a)Cylindrical b)Prismatic specimens

Analytical assessment of the experimental results

There are lots of analytical models for the stress-strain behavior of confined concrete. Among these models, two famous models for concrete confined with steel stirrups are selected in this study. The stress-strain behavior of the concrete specimens from these models is compared to experimental results.

The first selected model in this study is the model proposed by Mander, Priestley and Park 1988. They proposed an expression to represent both the ascending and descending branches of the stress-strain curve for circular, square and wall type rectangular sections. The longitudinal compression stress-strain curve for monotonic loading is as shown in Fig. 7. The equations presented in the following are only valid for static slow strain rate monotonic loading.

$$f_c = \frac{f_{ccl} x^r}{r - 1 + x^r} \quad (1)$$

where: $x = \frac{\epsilon_c}{\epsilon_{ccl}}$ in which, ϵ_c is the longitudinal compressive concrete strain.

The maximum longitudinal strain was calculated by Mander using the following Equation as suggested by Richart et al. (1928).

$$\epsilon_{ccl} = \epsilon_{co} \left[1 + 5 \left(\frac{f_{ccl}}{f_{co}} - 1 \right) \right] \quad (2)$$

and $r = \frac{E_c}{E_c - E_{sec}}$ where: $E_c = 5100\sqrt{f_{co}}$ (Mpa) and $E_{sec} = \frac{f_{ccl}}{\epsilon_{ccl}}$

In which; E_c is the tangent modulus of elasticity of concrete and E_{sec} is the secant modulus of confined concrete. The peak compressive strength of confined concrete, f_{ccl} , for circular or spiral reinforcement is given by:

$$f_{ccl} = f_{co} \left(-1.254 + 2.254 \sqrt{1 + \frac{7.94 f_l'}{f_{co}}} - 2 \frac{f_l'}{f_{co}} \right) \quad (3)$$

where:

- f_l' is the effective lateral confining stress on the concrete
- f_{co} is the unconfined concrete compressive strength
- ϵ_{ccl} is the peak longitudinal strain corresponding to f_{cc}
- ϵ_{co} is the peak longitudinal strain corresponding to f_{co}

The second selected analytical model was the stress-strain model proposed by Madas and Elnashai (1992) . They developed a passive confinement model (Fig. 7) for reinforced concrete columns subjected to cyclic or transient loading. Their model was an improvement over the model of Mander et al. (1988) and at the same time, a simplification of the Ahmad and Shah's model (1982). In their procedure, the lateral strain in concrete, ϵ_r , was expressed as a cubic polynomial function of the longitudinal strain, ϵ_l . The derivative ($d\epsilon_{ry} / d\epsilon_{ly}$) is based on the relationship proposed by Elwi and Murray (1979) between the Poisson's ratio ν and ϵ_l (Eq. 4).



$$\frac{\epsilon_r}{\epsilon_l} = v = v_o \left[1.0 + 1.3763 \left(\frac{\epsilon_l}{\epsilon_{co}} \right) - 5.36 \left(\frac{\epsilon_l}{\epsilon_{co}} \right)^2 + 8.586 \left(\frac{\epsilon_l}{\epsilon_{co}} \right)^3 \right] \quad (4)$$

where: v_o is the initial value of v and ϵ_{co} is the axial strain at f_{co}

Thus, for a certain axial strain ϵ_l , the corresponding value of ϵ_r is equal to the hoop strain in steel by strain compatibility is determined. Consequently, the stress in the steel (f_s) is determined and σ_r is calculated using the hoop tension formula. The axial stress, f_l is then calculated using the corresponding stress-strain curve, as described by any active confinement model such as that of Ahmad and Shah (1982).

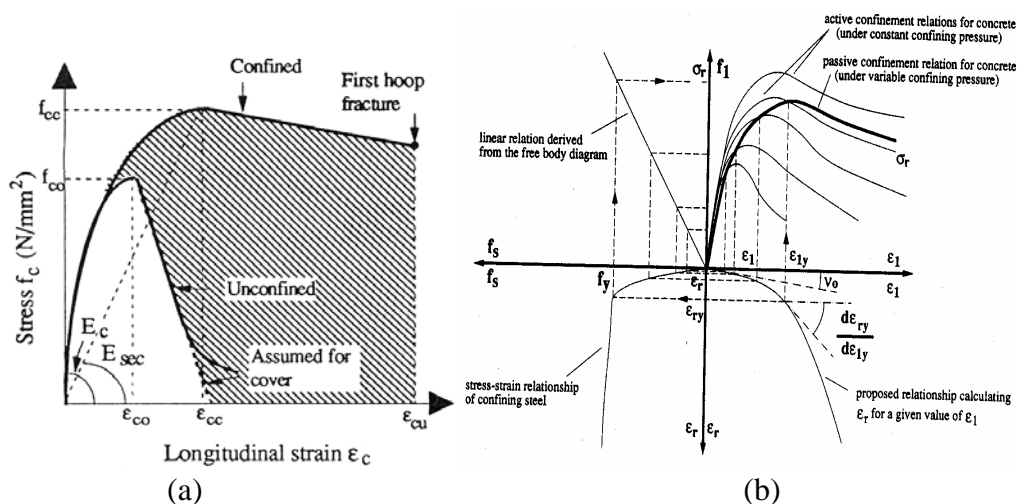


Figure 7- Schematic presentation of the proposed concrete model by a) Mander (1988) b) Madas & Elnashai (1992)

These two models were utilized for obtaining the stress-strain behaviour of concrete specimens of the experiments. It should be noted that these models have mainly been calibrated and proposed for round bar confined concrete. So, in order to get able to use these models it was necessary to obtain the equivalent diameter of the used steel strips. This was done by equating the area of the strip with the equivalent round bar. In the following figures, the observed stress-strain behaviour of the concrete specimens is compared to those obtained from these models. Figure 8 shows the observed stress-strain behaviour of the cylindrical specimens and also compared that to the results obtained by means of Mander and Elnashai models. All of these figures correspond to specimens confined by single layer strips that have passively strapped around the specimens. These figures show that the confining strips could be able to considerably enhance both strength and ductility of the concrete.

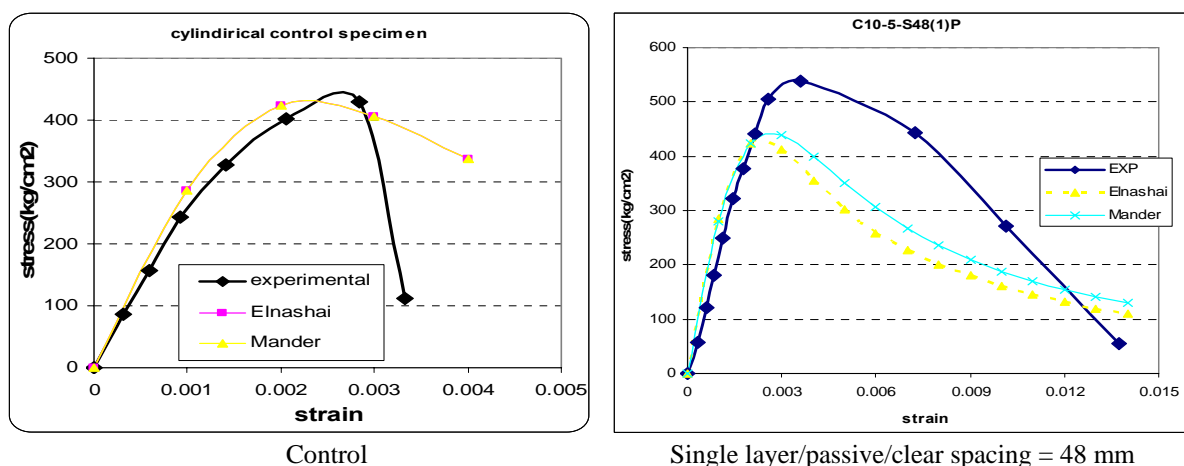
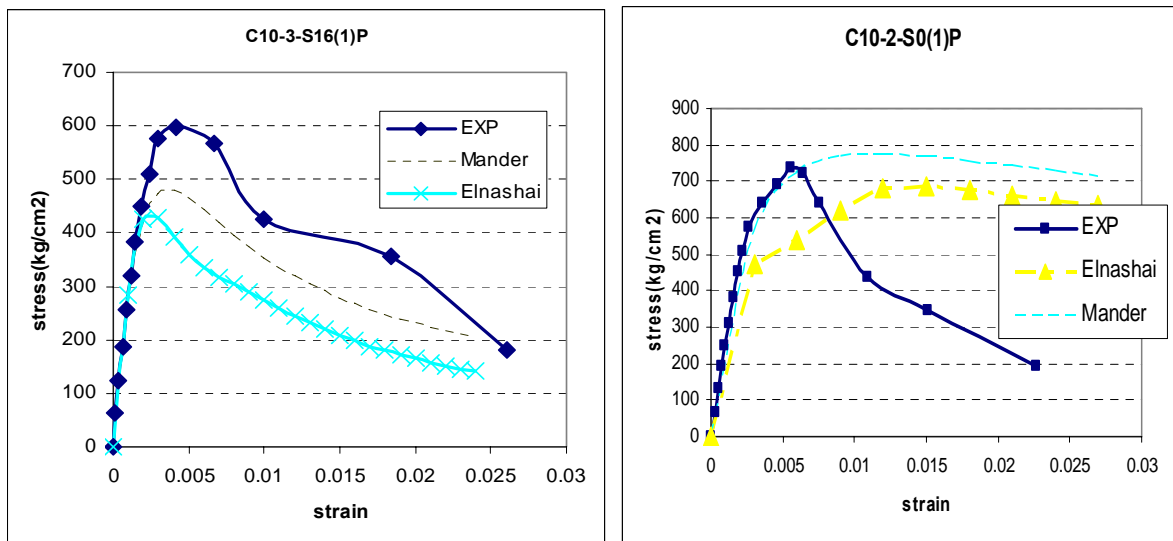
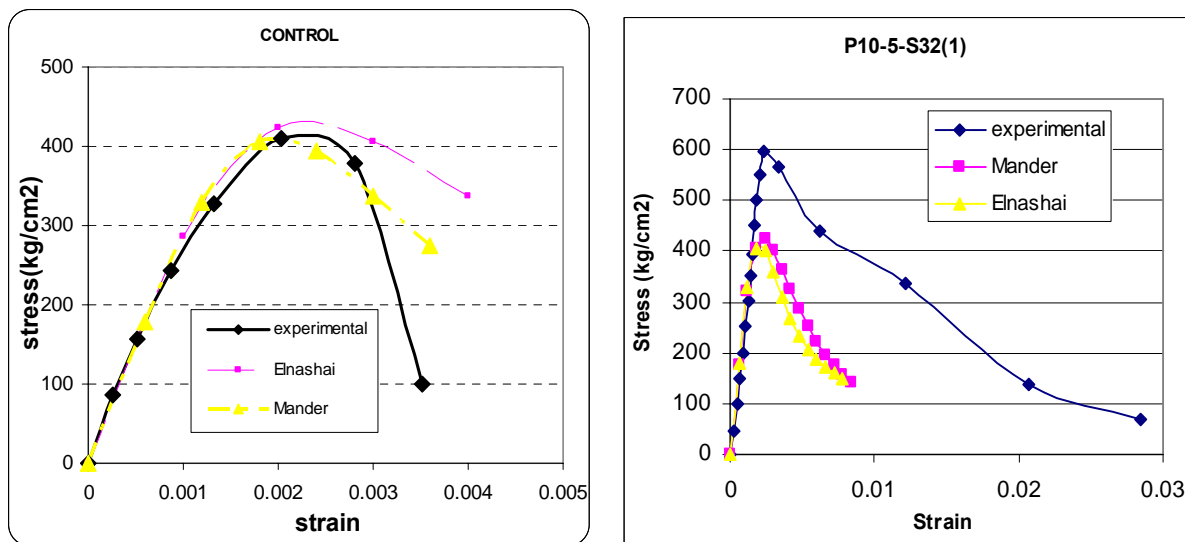


Figure 8(a) - Experimental stress-strain behaviour of cylindrical specimens compared to Mander et al. 1988 and Madas & Elnashai 1992 theoretical models



Single layer/passive/clear spacing = 16 mm
Single layer/passive/clear spacing = 0
Figure 8(b) - Experimental stress-strain behaviour of cylindrical specimens compared to Mander et al. 1988 and Madas&Elnashai1992 theoretical models

It can be seen from the figures that although the theoretical models are able to forecast the behaviour of unconfined concrete with good accuracy, the equivalent diameter strategy for analyses failed to predict the response of concrete confined by metal strips. As was predictable, the use of equivalent round bar (with the same area as the strip) leads to underestimation of the confinement effect in almost all of the cases. Similarly, Figure 9 shows the observed stress-strain behaviour of prismatic concrete column. In addition the results of analytical models are compared to the experimental ones.



Control
Single layer/passive/clear spacing = 32 mm
Figure 9(a) - Experimental stress-strain behaviour of prismatic specimens compared to Mander et al. 1988 and Madas&Elnashai1992 theoretical models

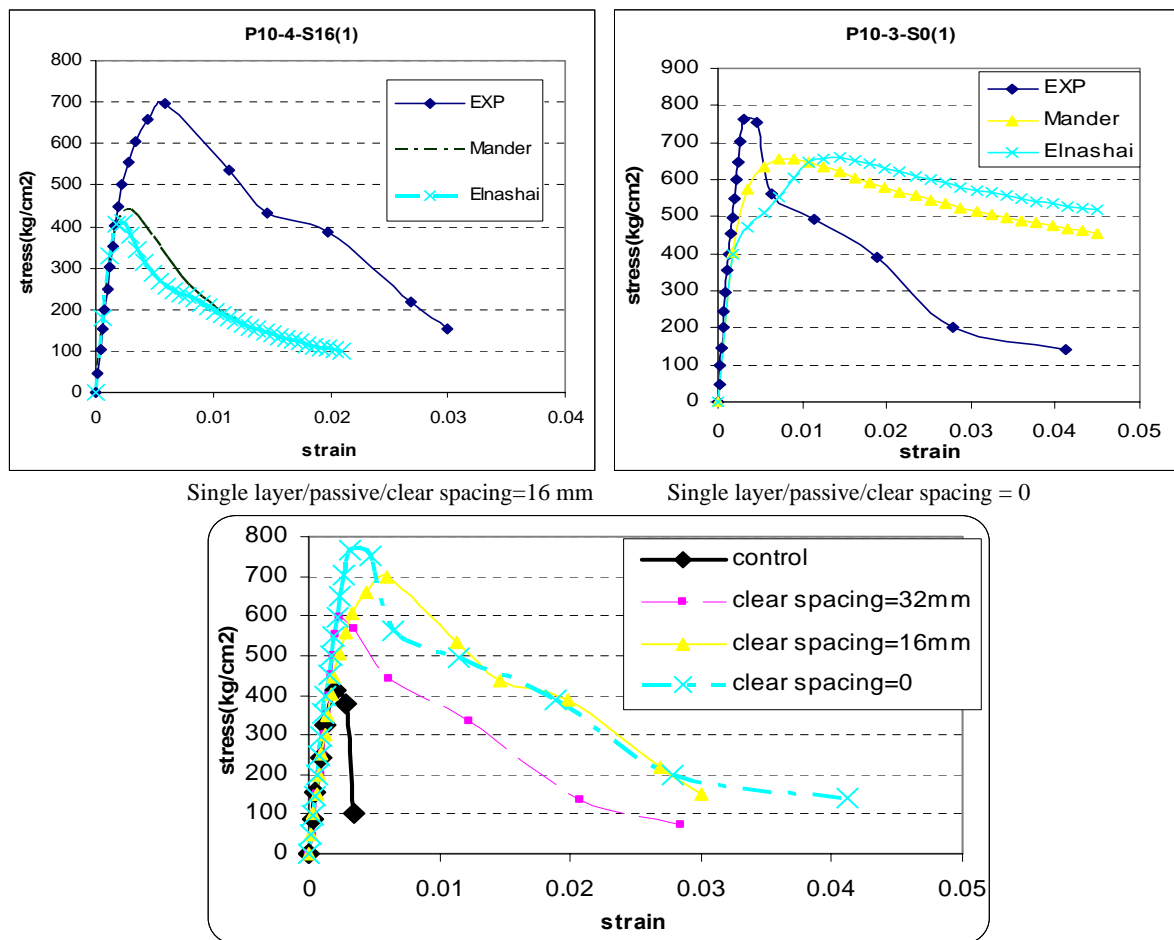


Figure 9(b) - Experimental stress-strain behaviour of prismatic specimens compared to Mander et al. 1988 and Madas&Elnashai1992 theoretical models

Conclusion

The proposed technique was capable to provide considerable increase in both strength and ductility of concrete. The increase in strength could even exceeded 2.7. Active confinement resulted in better enhancement (up to 25 percent) of strength and ductility of confined concrete than passive confinement. Rounding the corners of the prismatic specimens increases the effectiveness of confinement. There is a close relationship between the mechanical volumetric ratio of confining strips and the strength as well as ductility of columns. Since the conventional steel based concrete models are mainly for round bad confined concrete, underestimate the confining effect of wide strips.

Acknowledgement

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