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LATERAL POST-TENSIONED METAL STRIPS FOR STRENGTH AND DUCTILITY ENHANCEMENT OF CONCRETE COLUMNS: INVESTIGATION OF SIZE AND SHAPE EFFECTS

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ABSTRACT :

Recent earthquakes in urban areas have repeatedly demonstrated the vulnerability of inadequately designed or constructed reinforced concrete structures, with deficient shear strength, low flexural ductility, insufficient lap splice length of longitudinal bars and poor seismic detailing. This paper presents the results of a study on the application of strapping technique for seismic upgrade of existing concrete columns. In this method, high strength metal strips are applied to externally confine concrete by means of standard strapping machines. The axial behavior of confined small-scale columns is investigated experimentally and analytically. Experimental program included axial compressive tests on some cylindrical and prismatic small-scale columns which were confined by metal strips. The effects of various parameters on strength and ductility of confined concrete were studied including compressive strength of concrete core, mechanical volumetric ratio of confining strips, number of strip layers wrapped around the specimens and details of strip joint. The effects of strength and ductility of confining strips on behavior of columns were also studied. Longitudinal and lateral 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 by metal strips. It was also observed that ductility of confining material plays the most important role in ductility enhancement of concrete. The active and passive confinements were compared by studying the influence of amount of active lateral pressure on the strength and ultimate strain of specimens. Nonlinear finite element models of tested columns were also made and analyzed by using various failure surfaces. The axial stress-strain behaviors of columns were obtained from these NLFEA and are compared to the experimental results.

KEYWORDS: Metal strip, seismic retrofitting, RC structure, confinement, ductility

1. INTRODUCTION

Recent earthquakes have revealed an urgent need to develop retrofit techniques for the existing buildings and bridges designed in accordance with old seismic codes so as to meet the requirements of current seismic design standards. Some of the common problems revealed by earthquakes such as Kobe (Japan 1995), Athens (Greece 1999), Kocaeli (Turkey 1999) and Bam (Iran 2004) include inadequate confinement of concrete, leading to shear, anchorage and splice failures.

Confinement reinforcement is generally applied to compressive members as lateral reinforcement with the aim of increasing their strength and ductility. 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.

The development of easy and effective rehabilitation and strengthening techniques is required to retrofit many existing buildings and bridges. Several repair and strengthening techniques are currently in use for reinforced concrete structures that unfortunately, most 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 structures economically viable. (Frangou & Pilakoutas 1995)

In this paper, an easy technique of retrofit of concrete, which was firstly presented and used by professor Pilakoutas at the university of Sheffield, is presented. The main aim of this research was quantification of the enhancement of concrete strength and ductility by the application of the technique and improving the technique to achieve better performance. The results of experimental and analytical studies on application of this technique are discussed.

The technique used for strengthening concrete columns in this study, involves post-tensioning high-strength packaging straps around the column (by using standard strapping machines used in the packaging industry) and subsequently locking their ends in metal clip. Commercially available strapping tensioners and sealers make it easy to pretension the strip and fix the strip ends in the clamps. The available straps have widths of 10 to 50 mm and thicknesses of 0.5 to 1.12 mm. In terms of strength, high strength strips in excess of 10000 kg/cm^2 , are available in 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 and dilation. This has many benefits such as full utilization of the strip capacity and prevention from premature crushing of the confined concrete, as would be the case with not properly tightened strips.

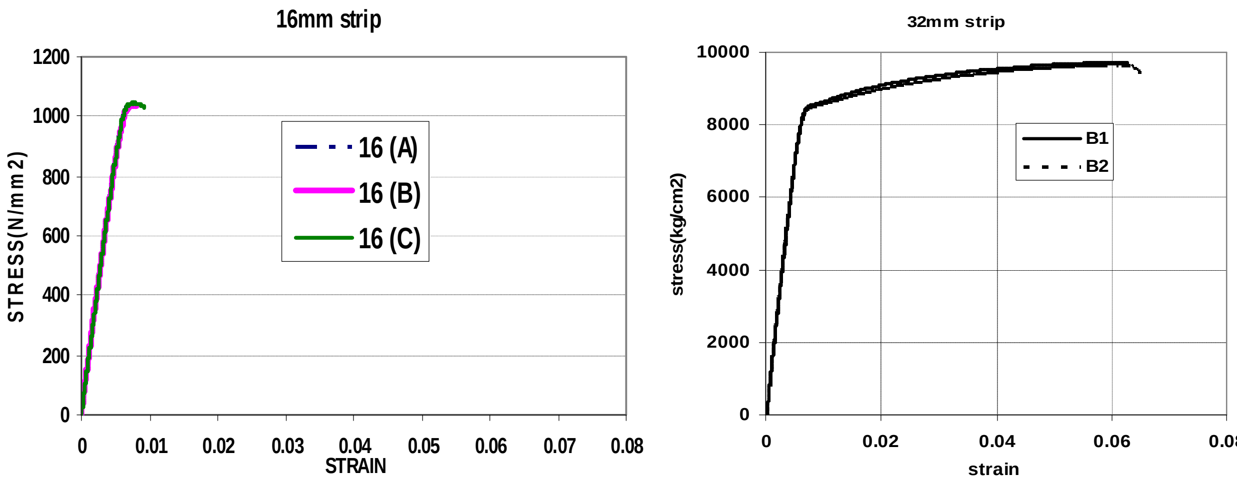
The low cost of strip and speed and ease of application of the strapping technique make this method efficient for use as a repair and strengthening technique for RC structural members. An RC column would normally require six man days' work to be jacketed whilst a maximum of two days' work is required for external strapping, which clearly demonstrates the cost saving when using the proposed technique. (Frangou & Pilakoutas 1995)

2. EXPERIMENTAL WORK

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 gravel. The maximum size of the gravel was 12 mm. No additive was used in any of the mixes. Experiments included axial compressive tests on small-scale columns with various sizes and shapes. Prismatic specimens had either of the two sizes of 10*20 and 15*30 as their section width*height. Similarly, cylindrical specimens were either 10*20 or 15*30. The strength of plain concrete was another parameter of this study.

Figure 1 A view of tested specimens

Two types of metal strips were used for strengthening of the specimens with different sizes. The width and thickness of the first type of applied strip, that is called S type hereafter, were 16 mm and 0.5 mm, respectively. The second type of strip, T type, had a width of 32 mm and thickness of 0.8 mm. In addition to the difference in width and thickness, the material behaviors of the strips were also dissimilar. In Figure 1, the stress-strain behavior of the used strips, which were obtained from standard tensile tests, are shown. As can be seen in these figures, although both strips have similar strengths, the elongation of the strips, that is an important characteristic of the confining elements, is quite different. The 32mm wide strip has larger ductility making it more suitable for application as a confining element for concrete.



(a) (b)

Figure 2: stress-strain behaviors of applied strips a) S type strip b) T type strip

The tensioning force in the strips was calibrated by means of special setups. Once the air pressure before the tensioner was set to a certain value, the tensioning force in the strip was monitored by using a tensile load cell and a data logger. The relationships between applied air pressure and the tensioning force were obtained for S and T strips separately. A linear relation was observed between these two parameters which was consequently used for measurement of the applied pre-tensioning to the strips.

The properties of the specimens and their main response improvements ratios are summerized in table 2.1 . the parameters include shape and size of specimens, type of confining strip, spacing of strips, pretensioning level in terms of strip yield strain and number of layers.

Table 2.1 Test matrix

Shape of specimen	Width or diameter (mm)	Height (mm)	Strength of plain Concrete (Mpa)	identification	Strip type	No. of strip layers	Clear spacing (mm)	Pretensioning level (* ε_y)	considerations	f'_{cc}/f'_{cu}	$\varepsilon_{cc}/\varepsilon_{cu}$	$\varepsilon_{uc}/\varepsilon_{uu}$
Cylindrical	100	200	50	C10-CNTRL	-	-	-	-		1.00	1.00	1.00
				C10-2-S0(1)P	S	1	0	0.05		1.48	1.54	3.28
				C10-3-S16(1)P	S	1	16	0.05		1.20	1.18	3.88
				C10-4-S32(1)P	S	1	32	0.05		1.28	0.78	2.84
				C10-5-S48(1)P	S	1	48	0.05		1.08	1.01	1.94
				C10-S0(2)P	S	2	0	0.05		2.06	3.89	5.97
				C10-7-S32(2)P	S	2	32	0.05		1.20	1.23	2.09
				C10-8-S0(1)	S	1	0	0.30		1.61	1.90	3.73
				C10-S16(1)	S	1	16	0.30		1.54	1.06	2.99
				C10-10-S32(1)	S	1	32	0.30		1.29	0.95	1.64
				C10-11-S48(1)	S	1	48	0.30		1.00	0.73	1.49
				C10-S0(2)	S	2	0	0.30		2.32	1.68	4.33

				C10-13-S32(2)	S	2	32	0.30		1.54	1.12	1.19
				C10-14-S32(1)2B	S	1	32	0.30	Double seal	1.31	1.57	1.49
				C10-15-S32(2)Glue	S	2	32	0.30	Glue inj. in seal	1.53	1.43	3.73
				C10-16-S16(1)AL	S	1	16	0.30	Add. strip in seal	1.37	1.43	2.39
				C10-17-S32(1)AL	S	1	32	0.30	Add. strip in seal	1.31	1.37	1.79
				C10-22-T0(1)	T	1	0	0.33		1.72	13.57	17.91
				C10-20-T32(1)	T	1	32	0.33		1.38	1.68	2.99
				P10-CNTRL						1.00	1.00	1.00
				P10-3-S0(1)	S	1	0	0.30		1.85	1.07	6.31
				P10-4-S16(1)	S	1	16	0.30		1.69	2.03	4.62
				P10-5-S32(1)	S	1	32	0.30		1.45	0.79	4.31
				P10-6-S48(1)	S	1	48	0.30		1.13	1.14	6.62
				P10-7-S0(2)	S	2	0	0.30		1.95	1.66	7.38
prismatic	100	200	50	P10-8-S16(2)	S	2	16	0.30		1.46	1.10	2.00
				P10-9-S32(2)	S	2	32	0.30		1.40	1.17	2.46
				P10-10-S48(2)	S	2	48	0.30		1.27	1.00	2.62
				P10-11-S16(1)SC	S	1	16	0.30	Chamfered corner	1.58	0.93	2.92
				P10-12-S16(1)WC	S	1	16	0.30	Sharp corner	1.42	1.17	4.00
				P10-13-T0(1)	T	1	0	0.33		1.80	1.14	15.08
				P10-14-T32(1)	32	1	32	0.33		1.51	0.93	7.85
				C15-CNTRL	-	-	-	-		1.00	1.00	1.00
Cylindrical	152	305	8	C15-5-T32(1)	T	1	32	0.33		3.33	7.63	5.12
				C15-6-T32(2)	T	2	32	0.33		5.93	12.54	4.64
				C15-11-S48(1)	S	1	48	0.30		2.11	3.28	2.40
				P15-1-CNTRLW	-	-	-	-		1.00	1.00	1.00
				P15-6-S16(1)W	S	1	16	0.30		1.31	1.28	3.46
Prismatic	150	300	22	P15-7-S0(2)W	S	2	0	0.30		2.30	2.50	7.56
				P15-9-T0(1)W	T	1	0	0.33		2.19	10.94	13.97
				P15-10-T32(1)W	T	1	32	0.33		1.67	6.28	12.31
				P15-3-CNTRLB	-	-	-	-		1.00	1.00	1.00
				P15-5-S0(1)B	S	1	0	0.30		1.85	1.68	9.34
Prismatic	150	300	32	P15-8-S16(2)B	S	2	16	0.30		1.81	1.73	1.28
				P15-2-T32(1)B	T	1	32	0.33		1.66	1.36	11.64
				P15-4-T0(1)B	T	1	0	0.33		2.24	3.95	14.92

2.3. Test set up

Concrete specimens were made and tested in concrete laboratory of building and housing research center. Axial compression tests were conducted on concrete specimens. The load was increased based on a displacement-controlled strategy until significant strength decay was recorded, which indicates failure of the specimens.

Recorded responses included load, relative displacements and strip strain. Six displacement transducers were used to obtain the longitudinal and transverse strains, including three 50 mm displacement transducers to measure the relative displacement of top and bottom plates of test machine and two 25 mm displacement transducers for measuring the relative displacement over the middle 2/3 height of columns. In addition, a tape measure type displacement transducer was used to measure the circumferential strain of the specimens. Figure 2 illustrates the test setup for a typical loaded column specimen.

Strain gages were attached to the external strips to obtain the strain of external confining elements during the test. All of the instruments were connected to a data logger to record the values of load, displacement and strain, simultaneously.

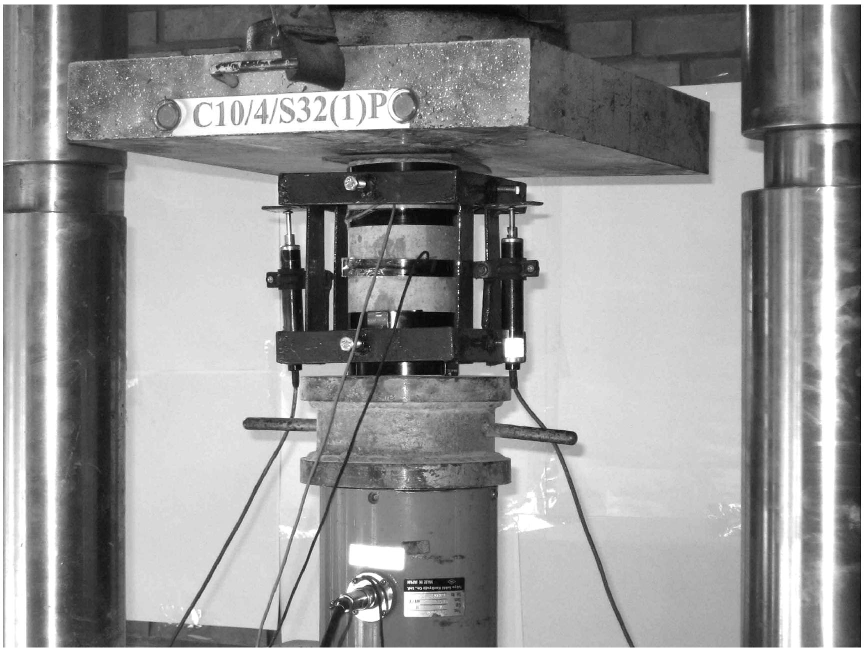


Figure 2 test set up

2.4. Observed behavior

At the end of test of all of the retrofitted columns, the strip rupture was observed. In fact, due to the type of used sealer, none of the strips slipped in the seal. Since the area of the strip has been decreased inside the seal to form notches, most of the strips broke inside the seal. However, the Failure mode of retrofitted columns mainly depended on the type of confining strip as well as the strength of plain concrete.

2.4.1. behavior of specimens confined with S strips

Most of the S strips in both circular and square sections ruptured in their weakened point in the seal, while a few of them failed in corners of square specimens, especially those who had sharp untreated corners. In High strength concrete specimens, the first rupture of confining strips is observed at the peak strength of the specimens which results in a sharp drop in stress-strain behavior.
On the contrary, in specimens with poor concretes, the crushing occurs too much sooner than strip failure. Even in some of the specimens with poor concrete and poor strengthening, strips do not fail until the end of test and the concrete crushes and falls between the strips.

2.4.2. behavior of specimens confined with T strips

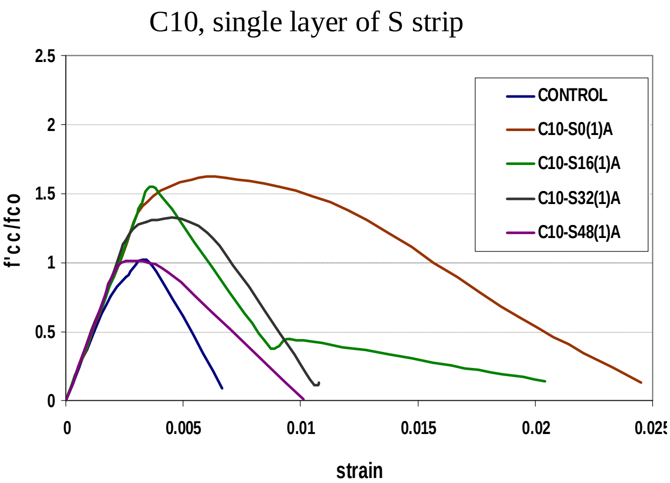
High strength concrete specimens that were strengthened with T type strips showed very ductile results. In prismatic specimens, the stress increases until failure of the first strip that leads to a drop in stress-strain curve but after this stage, the specimen continues load carrying and its stress increases again. In cylindrical specimens, which are more effectively confined than prismatic ones, ductility of strips provide a ductile compressive behavior for the concrete. In these specimens, when the first strip fails, the descending part of the curve starts.
In contrast, in poor concrete specimens, the strip failure almost always occurs after the peak.
In figures 4 and 5, results of T strip strengthened cylindrical and prismatic specimens are shown.

2.5. Axial Stress-strain behavior

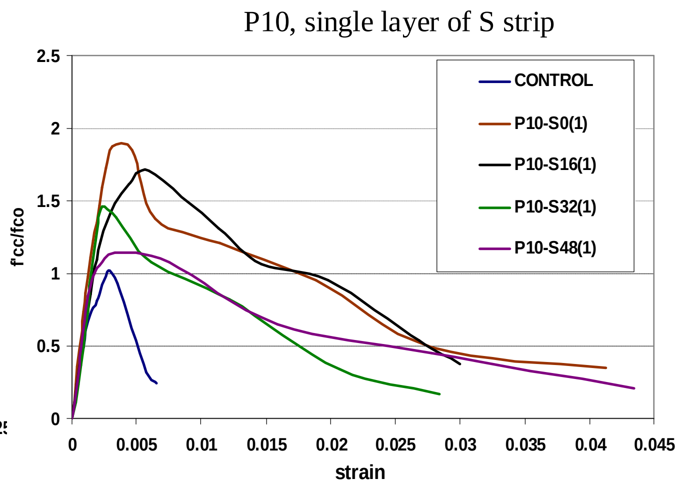
Recorded stress-strain behavior of tested columns and test observations showed that the axial stress and the confining pressure kept increasing until the value of lateral strain reached the yield strain of the strips in a circumferential direction. The specimens reached their maximum strengths when one 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. In figures 3 to 5 the normalized stress-strain curves of some of the strengthened specimens are shown. In these figures the stress has been normalized to the strength of plain concrete. The number after words S or T in the curves of these figures represents the clear spacing between strips. Figure 3a corresponds to cylindrical column specimens that have been actively strengthened with S strips. Each curve stands for a specific clear spacing between strips. Similarly in figure 3b curves of prismatic columns are shown.

In figures 4a and 4b the stress-strain behavior of 10*20 cylindrical and prismatic columns that were strengthened with T strips are shown. The great value of ultimate strain was obtained for T strip fully jacketed cylindrical specimen. Table 1 summarizes improvements of the technique over three main response characteristics of concrete. These properties are strength enhancement factor, the ratio of the concrete strain at peak and also the ratio of the strains of confined and unconfined concretes at a stress of 0.85 of peak strength of unconfined concrete.

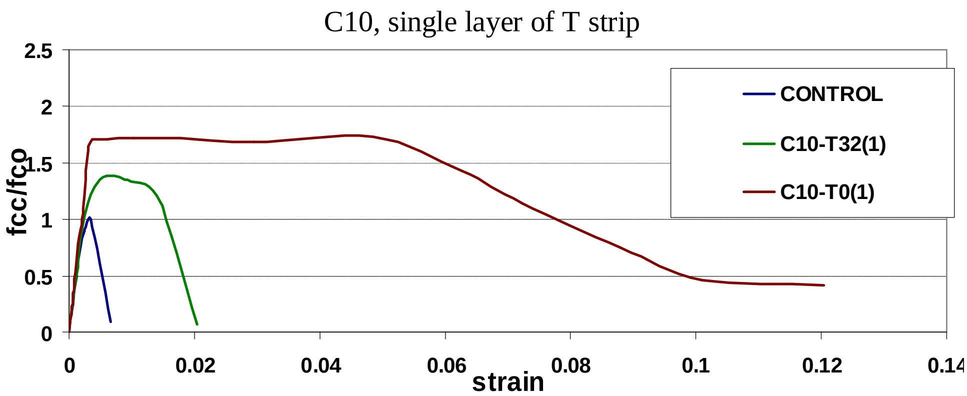


(a)



(b)

Figure 3 Axial stress-strain behavior of 10*20 specimens confined with S strips a)cylindrical b)prismatic



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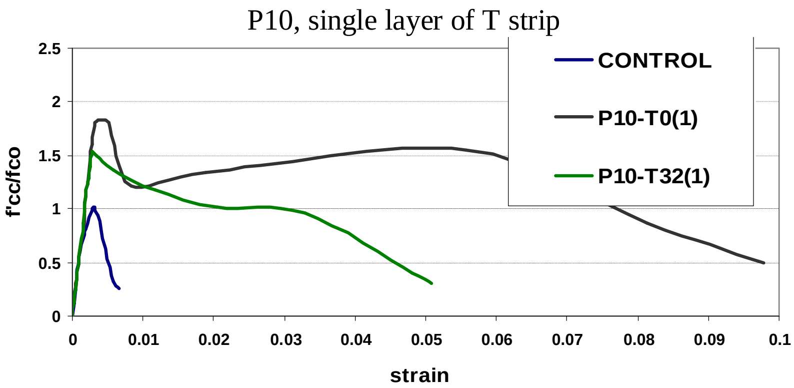
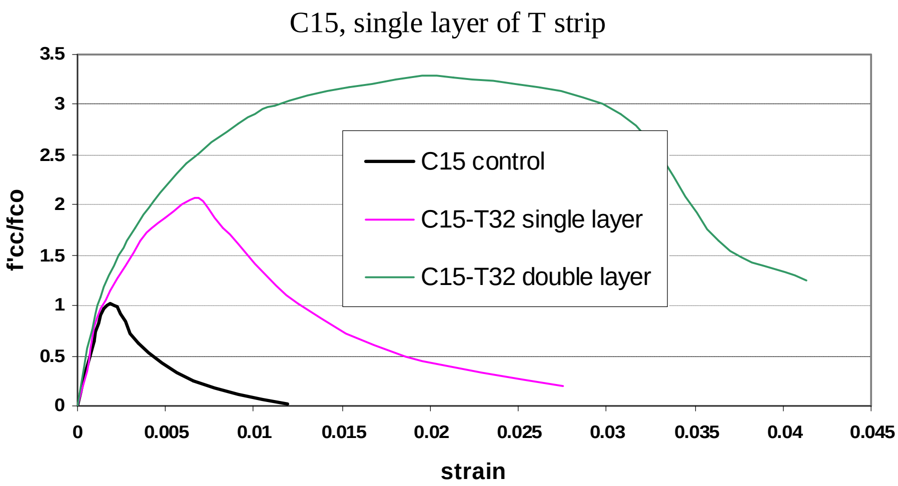
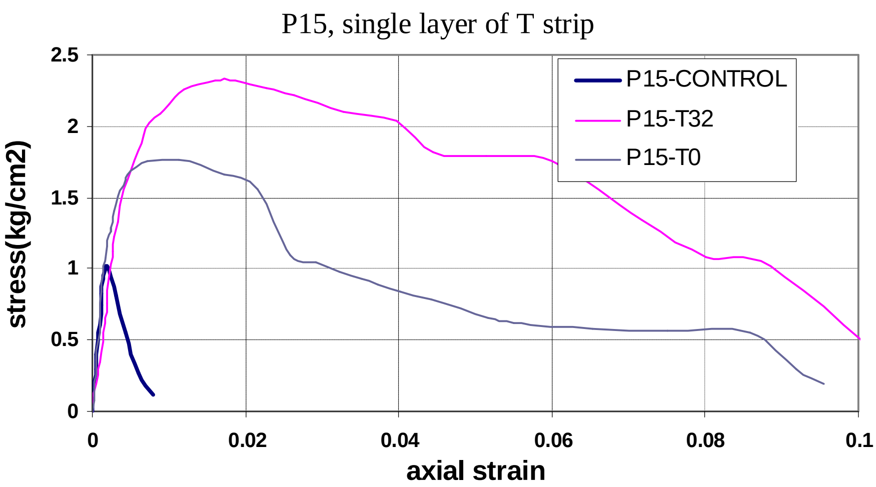


Figure 4 Axial stress-strain behavior of 10*20 specimens confined with T strips a)cylindrical b)prismatic



(a)



(b)

Figure 5 Axial stress-strain behavior of 15*30 specimens strengthened with T strips a)cylindrical b)prismatic

Some conclusions could be made from stress-strain curves that are described hereafter. Both strength and ductility of concrete is increased by confining with metal strips. The concrete confined with double layer metal strips has generally shown better enhancement in concrete strength than confinement with single layer. Decreasing the spacing between the strips always increases the strength of confined concrete.

2.6. improvement of axial compressive behavior

The main response improvement factors of confined specimens are summarized in table 1. In this table the increase factor in strength, strain at peak stress and ultimate strain of tested specimens are presented.

2.6.1. gain in strength

The strength of confined columns has been considerably increased for both S and T types of strips. The gain in strength mainly depended on volumetric ratio of confining strips. the higher the pretensioning force in the strips the higher concrete strength.

2.6.2. gain in ductility

Strain at peak strength of confined columns, i.e. a measure of ductility of concrete, showed a significant increase for all of the confined columns. The other and perhaps more important measure of concrete ductility , that is called ultimate strain in this paper, was assumed to be the strain at 0.85 of the peak stress of unconfined specimen. As can be seen in table 2.1, ultimate strain of concrete increased noticeably by strapping technique. Various parameters were found to affect the concrete ductility.

2.6.2.1. effect of strip ductility

In fact, the most important parameter affecting the concrete compressive ductility was ductility of confining strip. For a constant amount of volumetric ratio of S or T strips, Column specimens that were confined with ductile T type strips behaved much more ductile than those confined with S type strips.

2.6.2.2. effect of shape of column section

Test results showed that ductility of concrete was also dependent to shape of column cross section. For a constant amount of confining strips, specimens with circular sections showed more ductile behavior than those with square sections. This was observed for both ductile and brittle strips. It should be noted that although there is a stress concentration in strips at the corners of square section specimens, but most of these strips ruptured inside the seal where the strip section has been reduced by notches. The form of corner of square section columns plays an important role in behavior of confined concrete. In figure 6 three prismatic specimens with similar strengthening layout but with different shapes of their corners are compared. It can be seen that the specimen with sharp untreated corners shows a sharp drop in stress-strain behavior after peak strength, while rounding its corners improves the ductility.

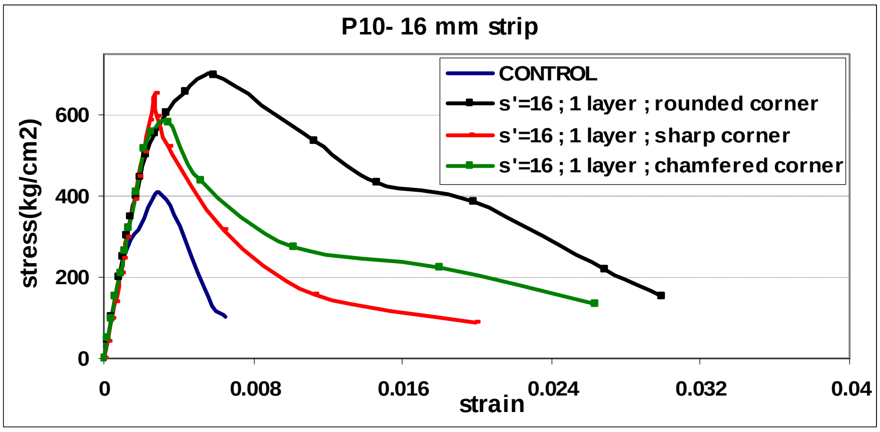


Figure 6 effect of form of corner of prismatic specimens on axial behavior of confined column

2.5.2.3. Effect of prestress force in strip

As can be seen in table 2.1, the level of pretensioning force in the strip was a parameter of this study. In some specimens, strips were tensioned to 30 percent of their yield strain, i.e. actively confined columns, while only a small pretensioning was applied to the others, i.e. passively confined specimens. It was observed that although application of higher pretensioning force to confining strips increases the concrete strength more markedly and provides stiffer pre-peak behavior, but at the same time it speeds up the post-peak degradation of concrete capacity. In other words, for both ductile and brittle strips, applying more pretensioning force to these strips reduces the ductility or ultimate strain. However, the strength of actively confined specimens 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.

3. NONLINEAR FINITE ELEMENT MODELING

Nonlinear Finite elemnt models of the tested specimens were made by using eight node solid elements in ABAQUS program. The concrete damaged plasticity model of the program was used for modeling the nonlinear behavior of concrete. This model uses concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete.
It consists of the combination of non-associated multi-hardening plasticity and scalar (isotropic) damaged elasticity to describe the irreversible damage that occurs during the fracturing process. Concrete damaged plasticity model requires that the elastic behavior of the material be isotropic and linear. The model is a continuum, plasticity-based, damage model for concrete. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. The evolution of the yield (or failure) surface is controlled by two hardening variables, $\tilde{e}_t^{pl}$ and $\tilde{e}_c^{pl}$, linked to failure mechanisms under tension and compression loading, respectively. $\tilde{e}_t^{pl}$ and $\tilde{e}_c^{pl}$ are tensile and compressive equivalent plastic strains, respectively.
The model assumes that the uniaxial tensile and compressive response of concrete is characterized by damaged plasticity.
Under uniaxial tension the stress-strain response follows a linear elastic relationship until the value of the failure stress, s_{t0} , is reached. The failure stress corresponds to the onset of micro-cracking in the concrete material. Beyond the failure stress the formation of micro-cracks is represented macroscopically with a softening stress-strain response, which induces strain localization in the concrete structure.

Under uniaxial compression the response is linear until the value of initial yield, s_{c0}. In the plastic regime the response is typically characterized by stress hardening followed by strain softening beyond the ultimate stress, s_{cu} .

The degradation of the elastic stiffness is characterized by two damage variables, d_c and d_t, which are assumed to be functions of the plastic strains, temperature, and field variables. The damage variables can take values from zero, representing the undamaged material, to one, which represents total loss of strength.

If E_0 is the initial (undamaged) elastic stiffness of the material, the stress-strain relations under uniaxial tension and compression loading are, respectively:

$$s_t = (1-d_t)E_0\left(e_t - \tilde{e}_t^{pl}\right) \qquad (3.1)$$
$$s_c = (1-d_c)E_0\left(e_c - \tilde{e}_c^{pl}\right)$$

The stress-strain relations for the general three-dimensional multiaxial condition are given by the scalar damage elasticity equation:

$$s = (1-d) D_0^{el} : (e - e^{pl}) \tag{3.2}$$

where D_0^{el} is the initial (undamaged) elasticity matrix.

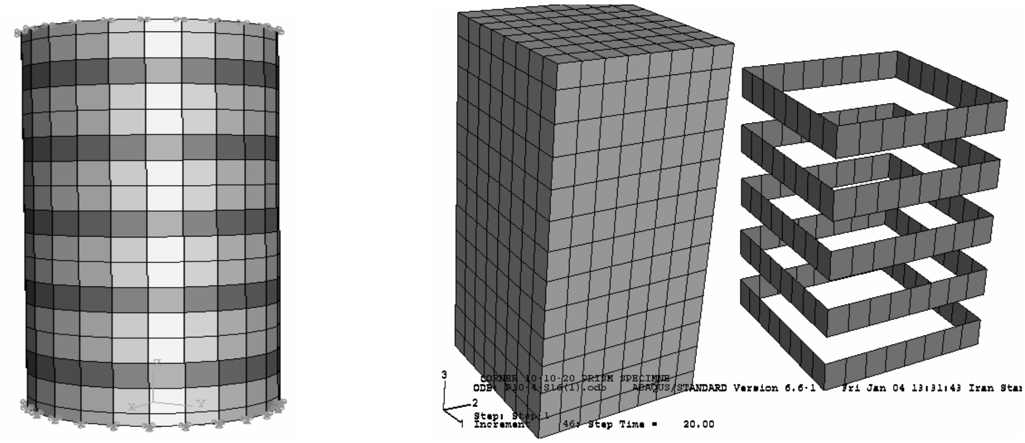
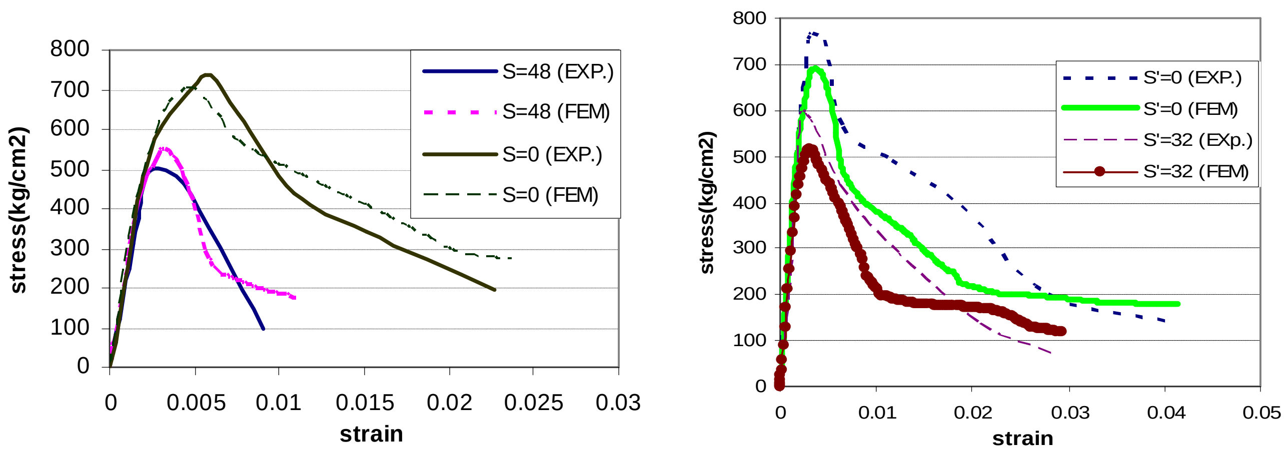


figure 7- mesh details of a cylindrical as well as a prismatic strengthened models

The concrete damaged plasticity model assumes nonassociated potential plastic flow. The flow potential G used for this model is the Drucker-Prager hyperbolic function. The model makes use of the yield function of Lubliner et. al. (1989), with the modifications proposed by Lee and Fenves (1998) to account for different evolution of strength under tension and compression.
The FE models of tested cylindrical as well as prismatic specimens were made in ABAQUS. These models consisted of solid and shell elements for modelling concrete and strips, respectively. The abovementioned plasticity model was defined and used for solid elements . The observed stress-strain behavior of strips in tensile tests were defined as the material behavior of shell elements. The bottom surface of models are restrained and the load was applied by incrementally increasing the displacement of nodes of the top surface. Figure 7 shows the mesh details and results of nonlinear finite element models of some of tested cylindrical specimens compared with observed stress-strain behavior.



(a) (b)

Figure 8 A comparison of FEM & experimental results for a)cylindrical b)prismatic specimens

In Figure 8a analytical and experimental results for two columns with strips spacings of 48 and 0 mm are compared. As can be seen in this figure, there is relatively good agreement between analytical and experimental results. However, the NFEM has underestimated the experimental results. It should be mentioned that the pretensioning force in the strips in actively confined specimens have been applied in the model before application

of the incremental displacement.
Similarly in figure 8b, the results of nonlinear finite element models of some of the prismatic specimens are shown. A comparison between analytical and experimental results show that the nonlinear finite element method has underestimated the post-peak part of stress-strain behavior of confined specimens.

4. CONCLUSION

Axial compressive tests were conducted on prismatic and cylindrical specimens with two different sizes that were retrofitted by metal strips. Following conclusions can be made:
1- Lateral confinement with metal strips improves strength and ductility of concrete.
2- Fully jacketed specimens, that is specimens with zero clear spacing between strips, increase strength and ductility of concrete more markedly than spaced strips.
3- Specimens that were strengthened with T type strips behaved more ductile than those retrofitted by S type strips. This implies that ductility of confining material plays an important role in ductility enhancement of concrete columns.
4- Columns with circular sections are more effectively confined than those with square section. Ductility is more sensitive to the shape of column. Form of corners in prismatic specimens also affects ductility of confined columns.
5- Confinement does not have considerable effect on the initial stiffness of the specimens.
6- Nonlinear finite element analysis by application of damaged plasticity model can estimate the axial behavior of confined concrete reasonably.

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