ON THE EFFECT OF EXTERNAL ACTIVE CONFINEMENT ON SPIRALLY REINFORCED CONCRETE COLUMNS

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ABSTRACT :

External confinement has been adopted as an efficient technique of seismic upgrading of existing RC columns. This paper presents the experimental and analytical results of a research on strengthening small scale spirally reinforced columns. Experiments included axial compressive test of cylindrical concrete specimens with 12 cm diameter and 30 cm height. The specimens were internally confined with spiral reinforcements at two pitches of 4 and 6 cm. Post-tensioned high strength metal strips were wrapped around specimens. These strips had two different sizes of 16 and 32 mm with different strengths and ductilities. In addition to the area and material properties of confining strips, the effect of some other parameters on strength, peak strain and ultimate strain of columns were studied including spacing, number of layers and pretensioning force in the strips. The effect of mechanical confinement ratio on strength and toughness of columns was studied. Test specimens included "only internally reinforced specimens with spirals" and "doubly confined specimens with internal spirals and external strips". An equivalent volumetric ratio for internal and external confinements is defined. The observed stress-strain relations of columns with different levels of internal and external confinement were compared to those calculated based on Mander 1988 and Madas 1992 theoretical confinement models. It was found that although these models were capable to predict the behavior of specimens with either internal or external confinements, failed to forecast the response of doubly confined specimens. Based on the observed behavior of tested concrete specimens, a confinement model was proposed for doubly confined concrete which accounted for both internal and external confinements.

KEYWORDS: RC structure, Active confinement, seismic retrofitting, double confinement, column

1. INTRODUCTION

Observations of past earthquakes have proven the necessity of confining concrete columns to prevent structural collapse. Concrete Confinement increases strength, ductility and energy absorption of concrete. It can also prevent shear failure, longitudinal bar buckling and slippage failures, which are known as the brittle failure modes. [1] Confinement becomes more vital under the seismic actions. Ties, hoops and spirals can be designated to provide internal confinement of concrete columns. However, there are numerous seismically vulnerable reinforced concrete structures around the world, which require retrofitting by external confinement. Several techniques have been proposed and applied for external lateral confinement of concrete, such as jacketing with steel, reinforced concrete, FRP, ferrocement as well as wrapping external rods, cables.
High strength metal strips showed excellent capability in increasing both strength and ductility of plain concrete.[2,3] These strips are used in the packaging industries and can easily be pre-stressed and sealed around the columns. The available researches on axial behavior of confined concrete in the literature can be divided into two main categories. In the first type, several experimental studies have been performed on concrete cylindrical or prismatic specimens confined with various techniques of external lateral confinement. In addition, some theoretical models have been proposed for approximating this behavior. On the other hand, the second type of the available materials involve experimental and analytical works on the axial behavior of

large-scale reinforced concrete columns, which focus on the effect of internal confinement. [4] As a matter of fact, there are very few works on the effect of external lateral confinement on the axial behavior of internally confined concrete.

Among several theoretical models, two most famous models were selected to compare with the experimental results of this study, i.e. Mander 1988 [5] and Madas 1992 [6]. Mander et al. 1988 proposed a theoretical model to represent both the ascending and descending branches of the axial stress-strain curve for circular, square and wall type rectangular sections. Their model implicitly assumes that at the peak stress, the transverse reinforcement yields and applies the maximum confining pressure.

Madas and Elnashai (1992) developed a passive confinement model for reinforced concrete columns subjected to cyclic or transient loading. This paper presents the results of an experimental and analytical study on the effect of external confinement of concrete cylinders that are internally reinforced with spirals by means of strapping.

2. EXPERIMENTAL PROGRAM

Building and housing research center of Iran sponsored a fairly comprehensive study on the application of metal strips in retrofit of concrete. Experiments included axial compressive tests on small-scale columns with various sizes and shapes with or without internal reinforcement as well as cyclic lateral tests on large-scale RC beams and columns under constant axial loads. This paper only presents the results of external retrofit of spirally reinforced cylindrical small-scale concrete specimens by high-strength metal strips.

2.1. Specimen Layout

Experiments included axial compressive tests on 22 small-scale cylindrical concrete columns including 19 spirally reinforced and 3 plain concrete columns. The main objective of the experimental program was assessment of the stress-strain behavior of spirally reinforced concrete cylinders that were strengthened with various amounts of external metal strips. The spirally reinforced cylinders had a diameter of 12 cm and their height were 30 cm, while three plain concrete specimens had standard dimensions of 15*30 cm. The cover of the spiral was 1 cm. in order to prevent direct transfer of longitudinal load to the helicoids, it was deliberately made shorter than the column to have a 2 cm distance from top and bottom surfaces of the column specimens. Figure 1 shows details and dimensions of column specimens and the molds before casting concrete.

Figure 1 Molds of spirally reinforced specimens

The diameter of used spiral smooth bars was 4.9 mm and they showed average yield stress of 582.2 MPa and ultimate strength of 620.1 MPa. Their ultimate strain was 65000 microstrain. Two different pitches of 4 and 6 cm were taken for spirals of column specimens to study the effect of internal confinement level. Theses two pitches provide volumetric ratios of 0.019 and 0.013 for core concrete, respectively.

The concrete specimens were cast and tested in structure and concrete Laboratories of 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 concrete mixture. The mix proportions was 228:290:874:888 by weight for water:cement:gravel:sand.

The specimens were removed from the mold after 2 days and put into water to be continuously and uniformly moist cured.

2.2. Retrofit Description

Two different types and sizes of metal strips were used for strengthening specimens, named as S and T. Widths of these strips were 16 and 32 mm and thicknesses of 0.5 and 0.8 mm, respectively. They showed yield strengths of 101.2 and 857.1 MPa and ultimate strengths of 101.2 and 977.5 MPa, respectively. The main difference in the mechanical properties of the two strips was their ductility in terms of ultimate strain. The ultimate strain of S was 0.01, while T could experience strain values of 0.07 at rupture. The moduli of elasticity of all of the strips were about 200 GPa.

In order to compare the effects of active and passive external lateral confinements on concrete behavior, i.e. one of the main aims of the research, the retrofitted specimens were divided into two categories, named as actively and passively confined specimens. In passively confined specimens, the S and T confining strips were tensioned only to 40 and 140 kgf, while in actively confined specimens they were tensioned to 270 kgf and 750 kgf, respectively, which are about one third of their yield strain. Properties of the tested specimen are summarized in table 2.1. Considered parameters of specimens and their retrofit includes pitch of spiral, type of confining strip (material behavior and size), spacing of strips, tensioning force of strip and number of strip layers strapped around the column.

Table 2.1 Test matrix and results summary

Specimen	Spiral pitch (cm)	Confining strip (mm)	No. of strip layers	Strip spacing (mm)	Tensioning force (Kg)	f'cc/f'co♫	$\varepsilon_{cc}/\varepsilon_{co}$♫	$\varepsilon_{cu}/\varepsilon_{ou}$♫
C12-8-CONTROL	No spiral					1	1	1
C12-2-SPIRAL4-1	4	-	-	-	-	1.4	3.4	6.5
C12-9-T0(1)A-4	4	T	1	0	740	4.9	12.2	33.2
C12-10-T32(1)A-4	4	T	1	32	740	2.8	5.4	15.1
C12-11-T32(1)P-4	4	T	1	32	140	2.4	8.8	19.3
C12-4-SPIRAL4-2	4	-	-	-	-	1.5	3.8	6.4
C12-12-T64(1)A-4	4	T	1	64	740	2.3	8.2	17.1
C12-13-S16(1)P-4	4	S	1	16	40	2.7	2.7	9.3
C12-14-S16(1)A-4	4	S	1	16	240	2.7	4.8	9.7
C12-3-SPIRAL6-1	6	-	-	-	-	1.2	2.1	4.5
C12-15-T0(1)A-6	6	T	1	0	740	4.8	17.3	28.9
C12-16-T32(1)A-6	6	T	1	32	740	3.0	7.8	14.8
C12-17-T32(1)P-6	6	T	1	32	140	2.4	10.0	18.3
C12-5-SPIRAL6-2	6	-	-	-	-	1.2	2.1	4.5
C12-18-T64(1)A-6	6	T	1	64	740	2.0	6.1	18.5
C12-19-S0(2)A-6	6	S	2	0	240	4.2	4.9	10.0
C12-20-S0(1)A-6	6	S	1	0	240	3.4	3.8	6.2
C12-21-S16(1)A-6	6	S	1	16	240	2.5	2.7	6.9
C12-22-S32(1)A-6	6	S	1	32	240	2.2	1.5	5.7

♫f'_{cc},ε_{cc} ,ε_{cu}=strength, strain at peak stress and strain at 0.85 peak strength of unconfined concrete
f'_{co},ε_{co} ,ε_{ou}=strength, strain at peak stress and strain at 0.85 peak strength of unconfined concrete

2.3. Test set up and instrumentation

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 based on a displacement-controlled strategy until significant strength decay was recorded, which indicates failure of the specimens.

Six displacement transducers from TML Company were used to obtain the longitudinal and transverse strains. Three 50 mm CDP displacement transducers were used 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 DP 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.

FLA-5-11 Strain gages of TML Company were attached to spiral reinforcement at its midheight and to the external strips to obtain the strain of both internal and external confining elements 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.

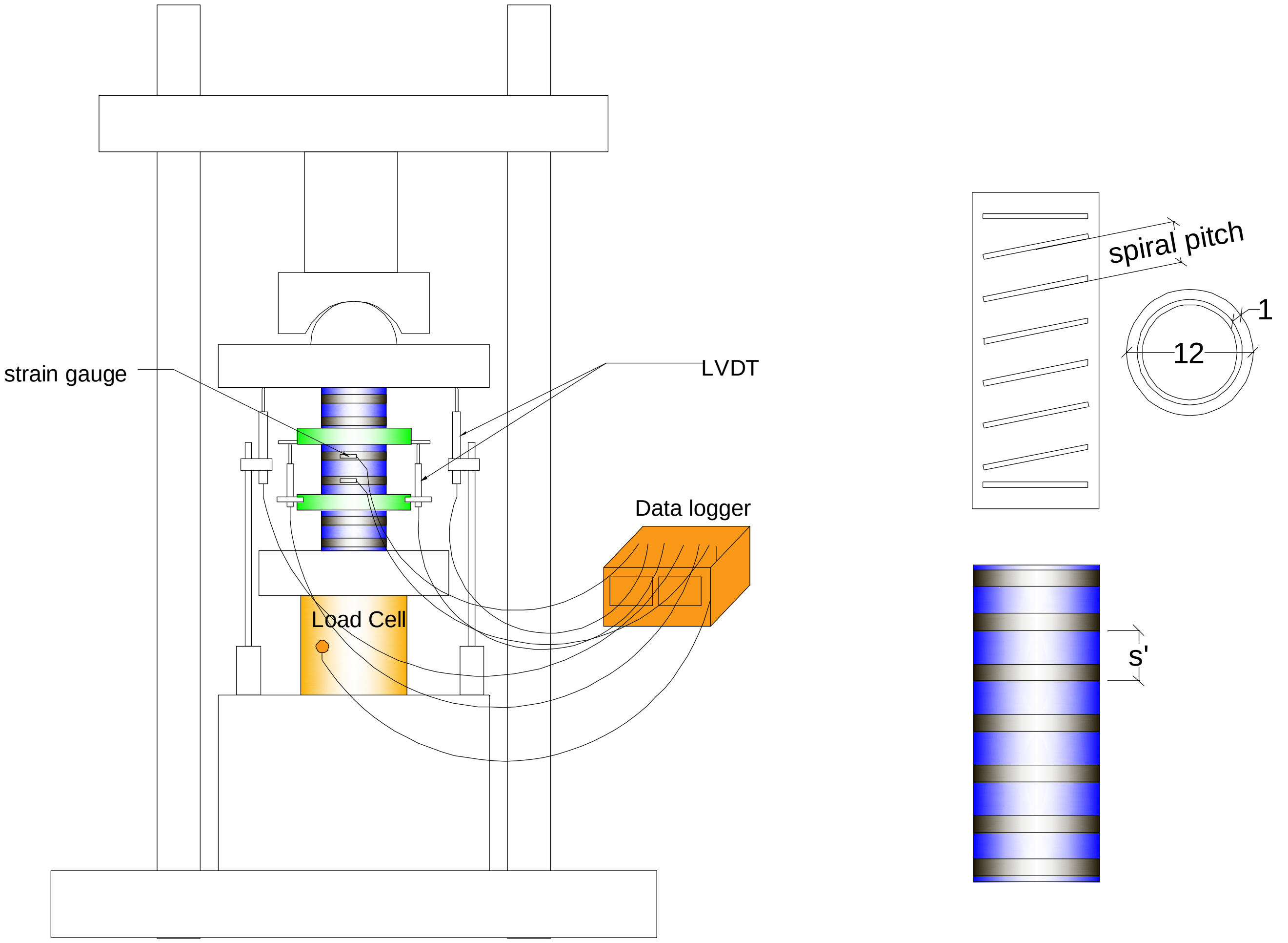

Figure 2 test set up and details of internal and external confinements

2.4. Observed behavior

Failure of the spirally reinforced columns mainly depended on the spacing and ductility of confining strips. In specimens with closely spaced strips, the failure is initiated by strip fracture and is followed by crack propagation in concrete and rupture of internal spirals. This failure mode was also observed in specimens retrofitted by widely spaced brittle S strips. In contrast, in specimens retrofitted with widely spaced ductile T strips, the concrete between two adjacent strips was crushed and fall without strip rupture. Since the area of the strip has been decreased inside the seal to form notches, most of the strips broke inside the seal. However, by simply injecting resin inside the seal in other specimens, the whole capacity of the strip is utilized and the strip rupture occurs outside the seal. Unlike the FRP confined concrete, failure mode of these specimens were not explosive or destructive. The main response improvement factors of confined specimens are summarized in table 2.1. In this table the increase factor in strength, strain at peak stress and ultimate strain of tested specimens are presented. It should be noted that the ultimate strain of these specimens is assumed to be the strain at 0.85 of the peak stress of unconfined specimen.

2.4.1. Axial Stress-strain behavior

In figures 3 to 6 the stress-strain curves of strengthened specimens are shown. Figures 3 and 4 correspond to column specimens with spiral pitch of 6 cm that have been strengthened with S and T strips, respectively. Each figure shows the stress-strain curves of column specimens with different spacing values. Similarly, in figures 5 and 6 the stress-strain behavior of columns with spiral pitch of 4 cm that have been strengthened with S or T strips at different spacing values are represented. The letters A and P are abbreviations for active and passive confinements, respectively.

Table 2.1 presents the improvements ratios that the technique provides to 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.

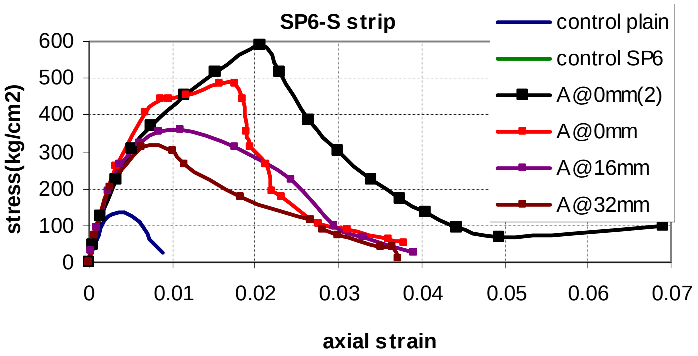

Figure 3 axial stress-strain of columns with 6 cm pitch internal spiral retrofitted by S strips

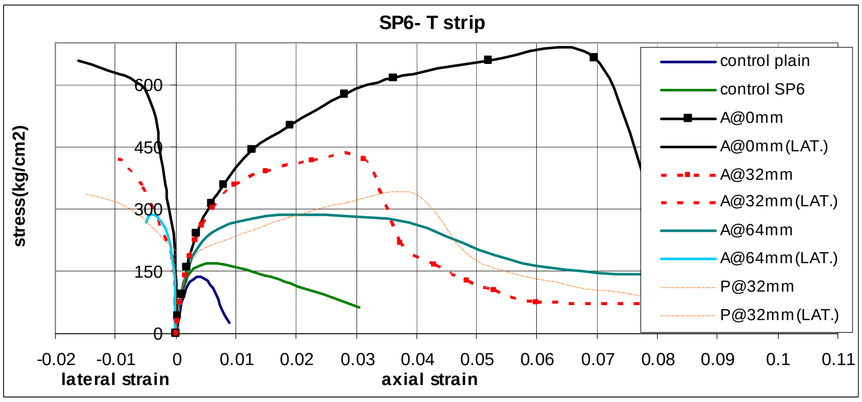

Figure 4 axial stress-strain of columns with 6 cm pitch internal spiral retrofitted by T strips

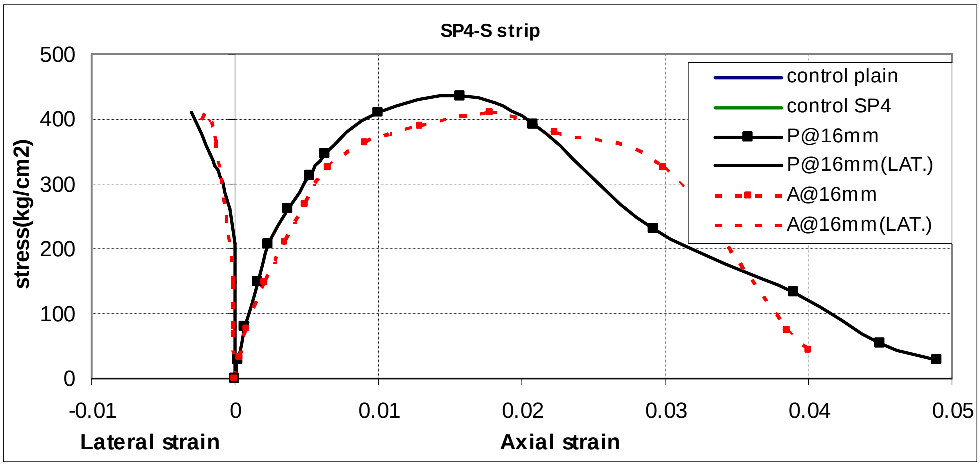

Figure 5 axial stress-strain of columns with 4 cm pitch internal spiral retrofitted by S strips

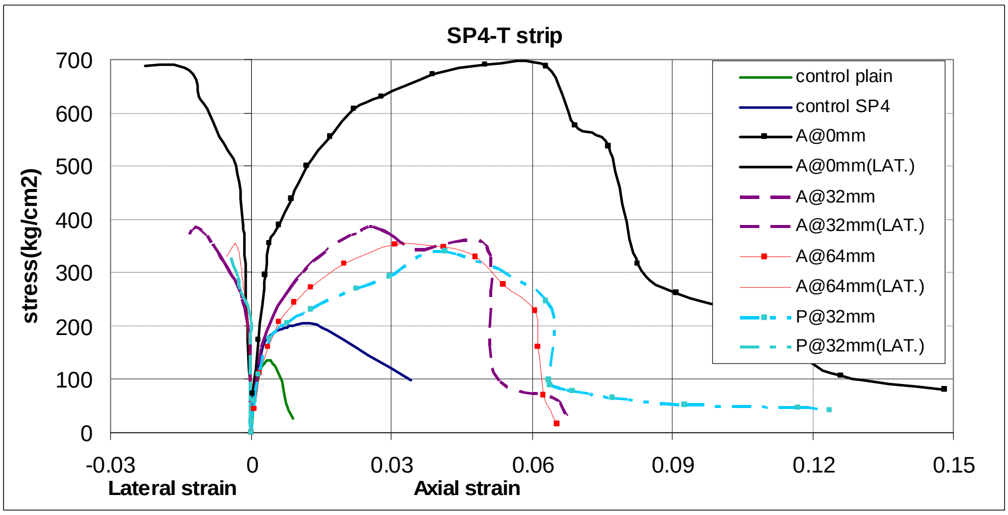

Figure 6 axial stress-strain of columns with 4 cm pitch internal spiral retrofitted by T strips

2.4.1.1. Effect of external confinement:

Following observations can be concluded from the curves:

1- External lateral confinement with metal strips could enhance the concrete behavior in terms of both strength and ductility more markedly than internal confinement. It should be noted that the volumetric ratios of external strips are in most cases less than those of internal spirals. As an example for specimen with 6 cm pitch and without external strips, i.e. specimen C12-3 in table 1 with a volumetric ratio of 0.0087, the strength increase ratio, f'cc/f'co , is only 1.18, while by strapping this spirally reinforced specimen with the same amount of volumetric ratio of S type, the strength increase ratio excesses value of 2.3.

2- Confinement does not have considerable effect on the initial stiffness of the specimens.

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 the most important role in ductility enhancement of concrete columns.

4- Fully jacketed specimens, that are specimens with zero clear spacing between strips, can increase strength and ductility of concrete much more markedly than spaced strips. Although this phenomenon has been known as the effect of more volumetric ratio or more confinement effectiveness so far, but there is really a meaningful difference between the results of fully jacketed specimens with others. This was mainly because fully jacketing does not allow small crushed particles to fall from the specimen. These particles, in extreme case, can be assumed as a material with no shear strength that can resist axial load by application of lateral pressure.

2.4.1.2. Effect of internal confinement

The two pitches of internal spirals provide two values of volumetric ratio of 0.0087 and 0.0131. So as to compare the effect of different amounts of internal confinement on behavior of doubly confined concrete, specimens with pitch values of 4 and 6 cm were strengthened with the same layout of retrofit with strips. In figure 7 responses of two pairs of these specimens are compared together. It can be realized that the influence of internal reinforcement is really insignificant. This can mainly be related to the benefit of strip width. In addition, strips postpone failure of the completely unconfined cover concrete and also confine the whole section.

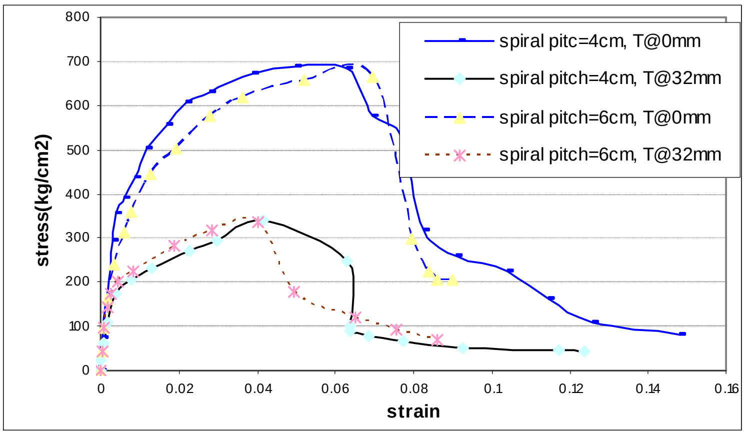

Figure 7 the effect of internal confinement on doubly confined concrete

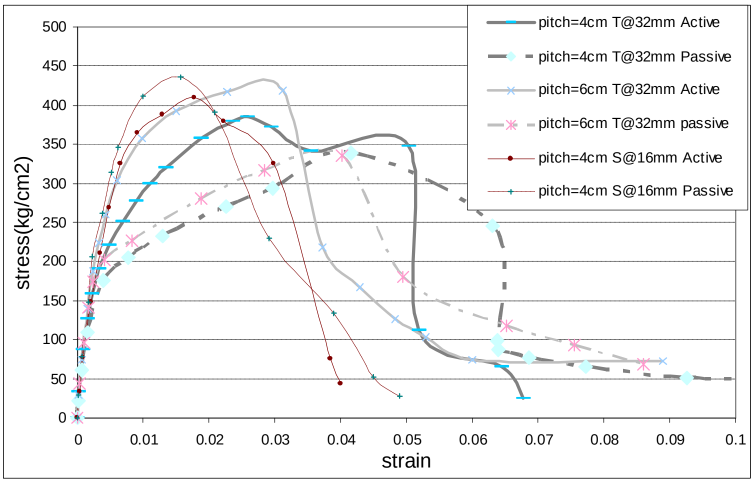

Figure 8 A comparison between active and passive confinement of concrete

2.4.1.3. Active Vs. passive confinement

In order to study the effect of prestressing confining strips on the behavior of concrete, while in most of specimens strips were tensioned to about one third of their yield strength, in a few of other specimens only a small tension was applied. In figure 8 the stress-strain behavior of three pairs of actively and passively confined similar specimens are compared. Actively confined specimens are shown with continuous lines and passive ones are drawn with dashed lines. It denotes that the active confinement results in small increase in strength and also a stiffer pre-peak behavior. However, although the ultimate strain of both actively and passively confined specimens, that is the strain at about a stress level of 75 kg/cm^2, are the same, but the area under the curve, that is a measure of energy absorption capacity, of passively confined column is more than that of actively confined one. As a matter of fact the main effect of active confinement is postponement of pre-peak degradation of concrete which comes from crack propagation and dilation.

3. ANALYTICAL WORK

Several analytical models have been proposed for approximation of the strength of confined concrete as well as its stress versus strain behavior. Most of these models obtain the lateral pressure provided by confining elements and then use available experimental active confinement models, e.g. Richart et al., to obtain strength of concrete under that level of lateral pressure. The main parameter of most of these models is mechanical volumetric ratio which determines lateral pressure.

3.1. gain in strength

From the following free body diagram, the relation between lateral pressure and mechanical volumetric ratio of confining steel can be obtained.

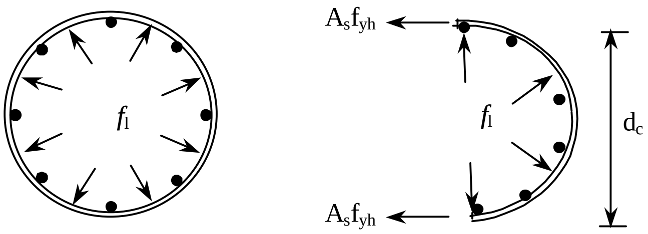

Figure 9 the relation between lateral pressure and confining force

By equating applied forced to a semicylinder with height equal with center to center spacing between lateral reinforcement, we obtain the following equation for applied lateral pressure to core concrete.

$$f_l \cong \frac{2A_s f_y}{D.S} \tag{3.1}$$

in which A_s and f_y are section area and yield strength of confining element, D is the diameter of confined core and S is the centre to centre spacing between two adjacent lateral reinforcements. The volumetric ratio can be defined by the following equation:

$$r = \frac{A_s.pD}{\frac{p}{4}D^2S} \tag{3.2}$$

if we substitute r in equation 3.1, we can find the following equation for lateral pressure:

$$f_l = \frac{r.f_y}{2} \tag{3.3}$$

Or in some cases it is normalized to the concrete strength and gives the confinement index:

$$\frac{1}{2} confinement\ \ index = \frac{r.f_y}{2f_c'} = \frac{f_l}{f_c'} \tag{3.4}$$

3.1.2. concept of equivalent volumetric ratio

In order to compute the confinement index of specimens that were confined with internal spirals and external strapping, a weighted some of confinement indices of these two regions are used. In figure 10 the section of columns is divided into two regions. Region 2 is only confined with external strips while region 1 is doubly confined with both spirals and strips.

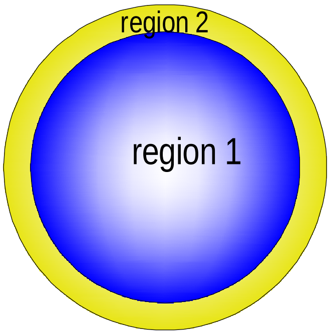

Figure 10 Divisions of column section to doubly confined and externally confined regions

$$\frac{1}{2}\text{Confinement index} = \frac{(r.f_y)_{spiral}}{2f'_c} * \frac{A_1}{A} + \frac{(r.f_y)_{strips}}{2f'_c} \qquad (3.5)$$

Where A_1 and A are area of region 1 and total are of section, respectively.
By using the abovementioned relationship, that can be named as the concept of weighted some of internal and external confinements, the confinement indices of confined specimens are computed and their corresponding values of strength increase ratios, i.e. the ratio of confined concrete strength to that of unconfined one, can be compared with the available steel-based confinement models.

$$r_{equivalent}.(f_y)_{strip} = (r.f_y)_{spiral} * \frac{A_1}{A} + (r.f_y)_{strips} \qquad (3.1)$$

3.1.3. fibre modelling approach

Among stress-strain models of confined concrete, two famous models for concrete confined with steel stirrups are applied in this study. The stress-strain behavior of concrete specimens were obtained from these models and 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. In this model, it has implicitly been assumed that the lateral reinforcements yield just when concrete reaches its strength. The second selected analytical model was the stress-strain model proposed by Madas and Elnashai (1992). They developed a passive confinement model for reinforced concrete columns subjected to cyclic or transient loading. In the procedure of this model, the lateral strain in concrete, $\varepsilon_{r,}$ was expressed as a cubic polynomial function of the longitudinal strain, ε_l. Then, for a certain axial strain ε_l, the corresponding value of ε_r, which is equal to the hoop strain in steel, is determined. Consequently, the stress in the steel (f_s) is determined and confining pressure σ_r is calculated using the hoop tension formula. For this value of confining pressure, the axial stress, $f_{l,}$ is calculated using the corresponding stress-strain curve, as described by any active confinement model such as that of Ahmad and Shah (1982).
In order to analyze the axial behavior of columns by the abovementioned theoretical models, a superposition based method was applied. The stress-strain state of columns was obtained through the integration of the nonlinear uniaxial stress-strain response of the individual fibres in which the section has been subdivided. The column section was divided into regions 1 and 2 as shown in figure 10. At the first step, region 1 was assumed to be confined by only spiral reinforcement and its analytical stress-strain behavior was obtained by using either of the two models. Then, confinement effect of external strapping on the whole of column section was calculated by assuming the obtained behavior of first step for stress-strain behavior of region 1 and the unconfined behavior for region 2.

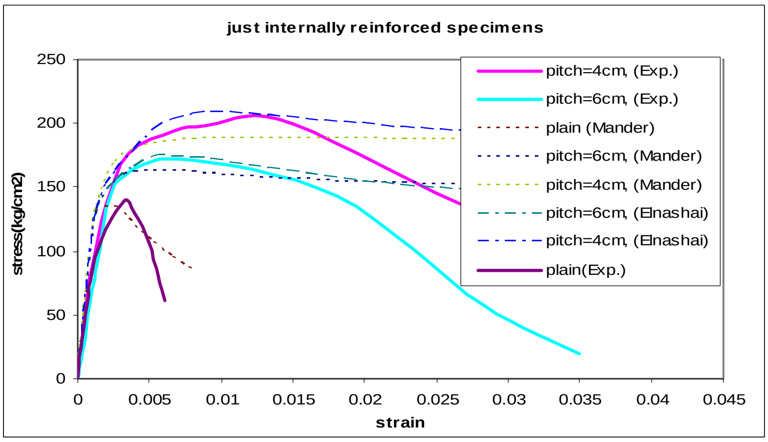

Figure 11 Results of analytical models with experimentally observed behavior of no retrofit specimens

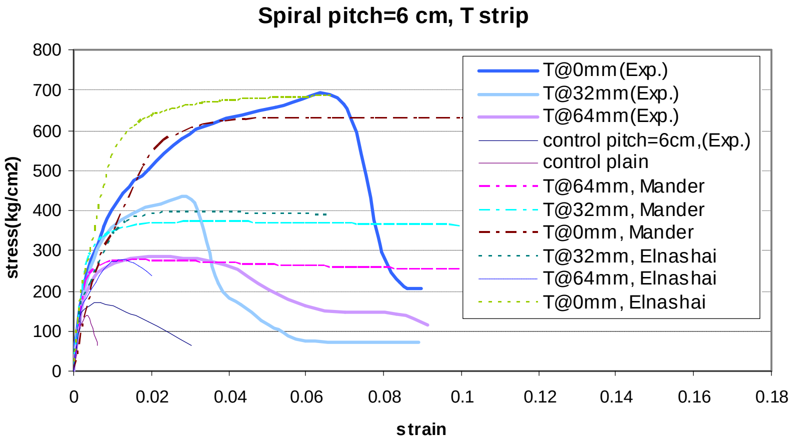

Figure 12 Results of analytical models with experimentally observed behavior of specimens with spiral pitch=6cm

In figures 11 and 12 the experimentally obtained stress-strain behavior of concrete specimens are compared with analytical models of Mander et al. 1988 and Madas and Elnashai 1992.

4. CONCLUSION

Axial compressive behaviors of Small-scale cylindrical specimens with internal spirals and external pretensioned strips were experimentally and analytically studied. It was observed that:

1- External confinement with metal strips considerably enhanced the strength and ductility of internally confined specimens.

2- For a constant amount of volumetric ratio, the external strips improve the strength and ductility more markedly than internal spirals.

3- Pretensioning the external confining material can improve the pre-peak response of column specimens.

4- The higher the ductility of the confining material, the higher the axial ductility of concrete columns.

5- The superposition-based combination of the analytical effects of external and internal confinements can reasonably approximate the experimentally obtained responses of doubly confined concrete.

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