CHAPTER I

INTRODUCTION

The launching of an innovative and unique area for structural research in prestressed concrete is presented in this thesis. To the author's knowledge, this area of research which was initiated at Chulalongkorn University had not been previously investigated. The initial purpose of this research was to investigate the utilization of confinement for strengthening a concrete member.

1.1 Research Background

The concept of using lateral force to increase the axial strength and ductility of concrete was first introduced by Richart[1] in 1928 where it was reported that the axial strength and ductility of concrete increased with an increase in lateral fluid pressure. The following equation was presented to predict the axial compressive strength f'_{cc} of a cylinder of unconfined strength f'_c, under a lateral pressure f_l :

$$f'_{cc} = f'_c + 4.1f_l \tag{1.1}$$

In 1899, Considere[2] used spiral reinforcement in concrete columns and the idea was explored by many engineers as the concept of passive confinement. Currently, circular and rectangular reinforcing spirals have been commonly used in many kinds of concrete members. Consequently, there have been many research innovations including confinement of concrete members using steel pipes filled with

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[1] Richart, F. E.; Brandtzaeg, A.; and Brown, R L., "A study of the Failure of Concrete under Combined Compressive Stresses," University of Illinois Engineering Experiment Station *Bulletin* No. 185, Urbana, Nov. 1928.

[2] Considere, A., "Resistance a la Compression du Beton Arme et du Beton Frette," Genie Civil, 1903. Also, translation "Experimental Researches on Reinforced Concrete," Moisseiff, L. S., McGraw-Hill Book Company, 1906.

concrete as columns, and using fiber reinforcement polymers (FRP) wrapped around concrete columns or beams as a structural restoration or upgrading technique.

Most confinement in RC structures tends to be of a passive nature wherein the confining element remains inactive until its confining ability is mobilized by a change in lateral strains. Thus, the effect of passive confinement is effective only after the concrete expands or yields to induce lateral strain and then spiral reinforced steel will develop confining forces. This implies that the concrete is approaching failure or has already failed when passive confinement takes an effect. In this respect, passive confinement is used to enhance ductile behavior.

A few researchers have proposed methods to create active confinement that can act in service stage. For example, Saatcioglu and Murat (1999) invented hardware devices to grip and prestress circular wire hoops to produce active confining forces. This technique is illustrated in Figure 1.1.
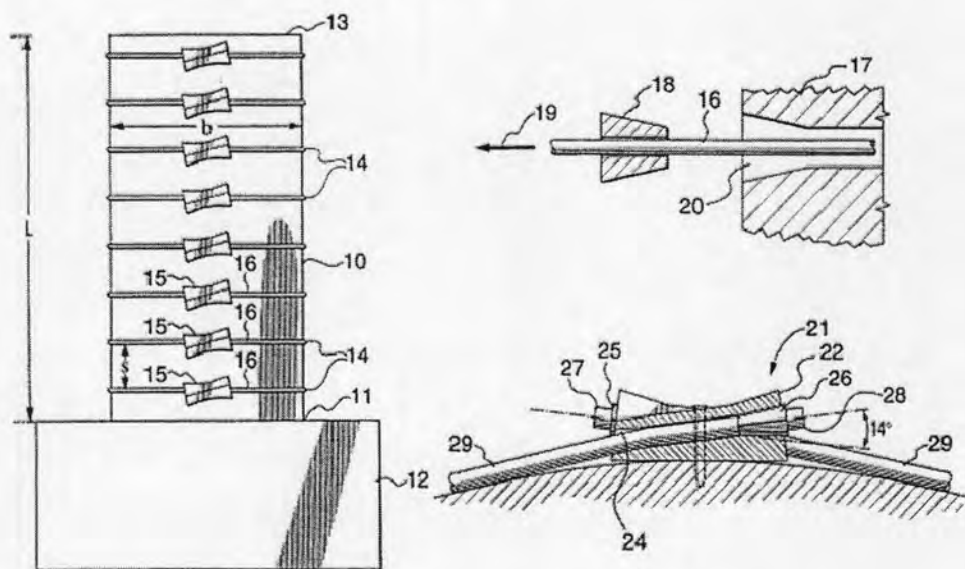

Figure 1.1 Gripping and prestressing devices

In this manner, lateral hoop prestressing provides active confining pressure around a concrete column. However, providing lateral pressure causes tensile stress in the axial direction which may cause the column to crack. This is a limiting concern when using the lateral hoop prestressing technic. While the method may strengthen

a concrete column the tensile cracking is of concern and the benefits of adding ductility must be weighed against such disadvantages.

The research developed herein describes a new technique whereby lateral prestressing and axial compressive prestressing are applied simultaneously by utilizing a newly developed spiral post-tensioning technology. The spiral post-tensioning system significantly increases the strength and ductility of circular concrete cylinders. The spiral configuration of the prestressing strands provides both active lateral confinement as well as axial longitudinal stresses to compensate for possible adverse effects of tensile cracking that would result from lateral active confinement. This technique also permits the ability to control the strength and ductility by varying prestress levels. A typical spiral configuration is shown in Figure 1.2.
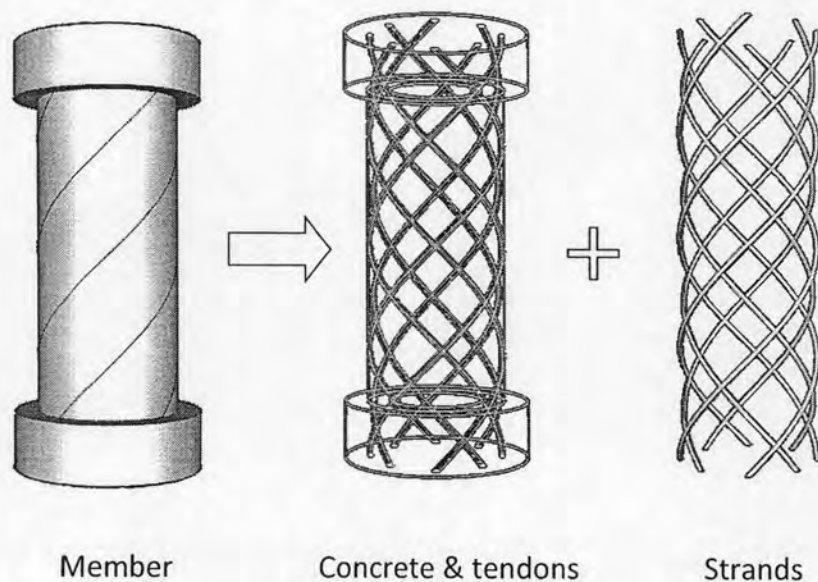

Member   Concrete & tendons   Strands

Figure 1.2 Spirally prestressing system configuration

1.2 Revision of Confinement Models

The basic philosophy of confining concrete for structural design are: (1) to increase strength of the core due to confinement which must be sufficient to offset the loss of the unconfined cover, and; (2) to apply the confinement so as to enable

the column to sustain large deformations without loss of the load-carrying capacity. As provided by the ACI code of practice:

$$\rho_s \geq 0.45 \left(\frac{A_g}{A_c} - 1\right)\frac{f_c'}{f_y} \qquad (2.1)$$

and

$$\rho_s \geq 0.12\frac{f_c'}{f_y} \qquad (2.2)$$

where

ρ_s =   percentage of steel

A_g =   gross area of section

A_c =   core area inside steel stirrup

f_c' =   compressive strength of concrete

f_y =   yield strength of steel stirrup

The effect of passive confinement in concrete columns is that the confining force will be mobilized only after the concrete expands or yields to induce lateral strain. Only then will the spiral confining steel exert confinement forces. Thus in the service stage, passive spiral confining steel is inactive. This observation has lead to the proposed technique of applying active spiral confinement and subsequent research as described herein.

The historical development of various proposed mathematical models for confined concrete columns and cylinders is described in the following subsections.

1.2.1 Active Confinement (Triaxial tests)

The initial idea of confinement started from triaxial principles as recognized several decades ago. More recently, engineers have come to realize the beneficial aspects of active confinement as it becomes feasible in actual construction

applications by using new material and modern technology. Table 1.1 summarizes the different models proposed for tri-axially stressed concrete.

Table 1.1 Proposed model for triaxially stressed concrete

Authors	Models	Comments
Considere (1903)	$f'_{cc} = k_1 f'_c + 4.8 f_l$	$1.0 \leq k_1 \leq 1.5$
Richart et al. (1928) Chinn and Zimmerman (1965) Newman & Newman (1972) Ahmad and Shah (1982) Saatcioglu and Razvi (1992)	$f'_{cc} = f'_c + k_c f_l$ $k_c = 4.1$ $k_c = 3.65 f_l^{-0.117} (f_l \ in \ ksi)$ $k_c = 3.7 \left(\frac{f_l}{f'_c}\right)^{-0.14}$ $f'_{cc} = f'_c + 4.256 f_l \ (\text{for } f_l \leq 0.679 f'_c)$ $f'_{cc} = 1.776 f'_c + 3.117 f_l \ (\text{for } f_l \geq 0.679 f'_c)$ $k_c = 4.825 f_l^{-0.17} (f_l \ in \ ksi)$	

1.2.2 Passive Confinement Using Lateral Steel Reinforcement

Since the 1980's, numerous research studies have dealt with the behavior of concrete columns of various strength levels and passively confined using different configurations of steel reinforcing cages. The general formulae proposed for relating the axial compressive stress at failure f'_{cc}, to effective confining pressure f_l are presented in Table 2.2.

Table 1.2 Models for passive confinement by lateral steel reinforcement

Authors	Models	Comments
General formula Richart et al. (1929)	$f'_{cc} = f'_c + 4.1 f_l$ $f_l = \dfrac{2 f_{sy} d_s}{D}$	Same as active confinement f_{sy} = steel yield stress d_s = diameter of confining spirals D = inside diameter of column
Kent and Park (1971)	$\varepsilon_c \leq \varepsilon_o;\ f_c = K f'_c \left[\dfrac{2\varepsilon_c}{\varepsilon_o} - \left(\dfrac{\varepsilon_c}{\varepsilon_o} \right)^2 \right]$ $\varepsilon_c > \varepsilon_o;\ f_c = K f'_c [1 - Z_m (\varepsilon_c - \varepsilon_o)] \geq 0.2 K f'_c$ $K = 1 + \dfrac{\rho_s f_{yh}}{f'_c}$ $\varepsilon_o = 0.002 K$ $\varepsilon_{50u} = \dfrac{3 + 0.002 f'_c}{f'_c - 1000}$; (stress in psi) $\varepsilon_{50h} = 0.75 \rho_s \sqrt{\dfrac{b''}{s_h}}$ $Z = \dfrac{0.5}{\varepsilon_{50u} + \varepsilon_{50h} - \varepsilon_o}$	The original Kent and Park model was modified by Scot et al. (1982) to include the strength and ductility enhancement due to confinement effect and the effect of strain rate.

Authors	Models	Comments
Iyengar et al. (1982)	$$f_l = \frac{2f_{sy}A_{sp}}{DS_{sp}}$$	A_{sp}, S_{sp} = cross section and pitch of spiral
Sheikh et al. (1986)	$$\varepsilon_c \leq \varepsilon_{s1}; \; f_c = f'_{cc}\left[\frac{2\varepsilon_c}{\varepsilon_{s1}} - \left(\frac{\varepsilon_c}{\varepsilon_{s1}}\right)^2\right]$$ $$\varepsilon_{s1} \leq \varepsilon_c \leq \varepsilon_{s2}; \; f_c = f'_{cc}$$ $$\varepsilon_c > \varepsilon_{s2}; \; f_c = K_s f_{cp}[1 - Z(\varepsilon_c - \varepsilon_{s2})] \geq 0.3 f'_{cc}$$ $$f'_{cc} = K_s f_{cp}$$ $$K_s = 1.0 + \frac{2.73B^2}{P_{occ}}\left[\left(1 - \frac{nC^2}{5.5B^2}\right)\left(1 - \frac{s}{2B}\right)^2\right]\sqrt{\rho_s f'_s}$$ (unit in ksi, kips) $$P_{occ} = f_{cp}A_{cc}$$ $$\varepsilon_{s1} = 0.55K_s f'_c \times 10^{-6} \text{ (stress in psi)}$$ $$\frac{\varepsilon_{s2}}{\varepsilon_{oo}} = 1 + \left[\frac{0.81}{C}\left(1 - 5\left(\frac{s}{B}\right)^2\right) + 0.25\sqrt{\frac{B}{c}}\right]\frac{f'_s \rho_s}{\sqrt{f'_c}}$$ $$Z = \frac{0.5}{\frac{3}{4}\rho_s\sqrt{\frac{B}{s}}}$$	Model for concrete confinement in tied columns A_{cc} = area of concrete in the core f_{cp} = strength of plain concrete C = the distance between the laterally supported longitudinal bars c = the depth of the neutral axis

Authors	Models	Comments
Mander et al. (1988)	$$f_c = \frac{f'_{cc}xr}{r - 1 + x}$$ $$x = \frac{\varepsilon_c}{\varepsilon_{cc}}$$ $$\varepsilon_c = \varepsilon_{co}\left[1 + 5\left(\frac{f'_{cc}}{f'_{co}} - 1\right)\right]$$ $$r = \frac{E_c}{E_c - E_{cc}}$$ $$E_{sec} = \frac{f'_{cc}}{\varepsilon_{cc}}$$ $$f'_{cc} = f'_{co}(1.254 - 2.254)\sqrt{1 + \frac{7.94f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}}$$ $$f'_l = f_l k_e$$ $$k_e = \frac{A_e}{A_{cc}}$$	Based on work of several other research works (Popovics 1973, Richart et al. 1928, Scott et al. 1982, etc.) The model assumes a constant confining pressure throughout the loading history and is insensitive to variation of the ratio of concrete.

Authors	Models	Comments
Saatcioglu et al. (1992)	$$\varepsilon_c \leq \varepsilon_1;\ f_c = f_{cc}'\left[\frac{2\varepsilon_c}{\varepsilon_1} - \left(\frac{\varepsilon_c}{\varepsilon_1}\right)^2\right]^{\frac{1}{1+2K}}$$ $$\varepsilon_c > \varepsilon_{s2};\ f_c = f_{cc}'\left[1 - \frac{0.15}{\varepsilon_{85} - \varepsilon_1}(\varepsilon_c - \varepsilon_1)\right]$$ $$\geq 0.2 f_{cc}'$$ $$K = \frac{k_1 f_{le}}{f_{co}'}$$ $$k_1 = 6.7 f_{le}^{-0.17}$$ $$f_{le} = k_2 f_l$$ $$k_2 = 1.0\ ;\ \text{for closely spaced circular spirals}$$ $$k_2 = 0.15\sqrt{\frac{b_c^2}{ss_l}} \leq 1.0\ ;\ \text{for rectilinear}$$ reinforcement $$f_l = \frac{\sum A_{sh} f_s \sin\alpha}{b_c s}$$ $$f_s = E_s\left[0.0025 + 0.04\left(\frac{k_2 \rho}{f_{co}'}\right)^{1/3}\right]$$	The model is based on the computation of confinement pressures starting from the material and geometric properties of columns. s_l = spacing of laterally supported longitudinal reinforcement f_{le} = the equivalent uniform pressure f_l = average pressure f_s = stress in transverse steel at peak concrete stress

Authors	Models	Comments
Cusson and Paultre (1995)	$\varepsilon_c \leq \varepsilon_{cc}; \ f_c = f'_{cc}\left[\dfrac{k(\varepsilon_c - \varepsilon_{cc})}{k - 1 + (\varepsilon_c/\varepsilon_{cc})^k}\right]$ $\varepsilon_c > \varepsilon_{cc}; \ f_c = f'_{cc}e^{k_1(\varepsilon_c - \varepsilon_{cc})^{k_2}}$ $k = \dfrac{E_c}{E_c - (f'_{cc}/\varepsilon_{cc})}$ $k_1 = \dfrac{\ln 0.5}{(\varepsilon_{C50C} - \varepsilon_{cc})^{k_2}}$ $k_2 = 0.58 + 16(f_{le}/f_{co})^{1.4}$ $f'_{cc}/f_{co} = 1.0 + 2.1(f_{le}/f_{co})^{0.7}$ $\varepsilon_{cc} = \varepsilon_{co} + 2.1(f_{le}/f_{co})^{1.7}$ $\varepsilon_{C50C} = \varepsilon_{C50U} + 0.15(f_{le}/f_{co})^{1.1}$ $f_{le} = f_l K_e$ $K_e = \dfrac{\left(1 - \dfrac{\sum w_i^2}{6c_x c_y}\right)\left(1 - \dfrac{s'}{c_x}\right)\left(1 - \dfrac{s'}{c_y}\right)}{1 - \rho_c}$ $f_l = \dfrac{f_{hcc}}{s}\left(\dfrac{A_{shx} - A_{shy}}{c_x + c_y}\right)$	A stress-strain for confined high-strength concrete has been developed and calibrated against the test results from 50 large-scale high-strength concrete tied columns tested under concentric loading f_{le} = the equivalent uniform pressure f_l = average pressure f_{hcc} = stress in the transverse reinforcement at the maximum strength of confined concrete c_x, c_y = widths of the concrete core

1.2.3 Passive Confinement Using Steel Tubes

In parallel to these studies on the confinement using steel cages, other studies were carried out where the confinement was provided by thin walled steel

tubes. These studies have been conveniently summarized by Knowles and Park (1969) who suggested the following design formulae that were adopted by many modern codes and standards for the compressive strength of concrete filled steel tubes. The compressive strength of a concrete filled steel tube is made up of the strengths of concrete and of the steel tube modified by correction factors i and i'. These factors reflect the effects of the slenderness of the columns as well as the steel tube thickness compared to the column diameter. That is:

$$Crc = \tau C_r + \tau' C_r' \qquad (2.3)$$

$$C_r' = 0.85\phi_c f_c' A_c \lambda_c^{-2} \left[\sqrt{1 + 0.25\lambda_c^{-4}} - 0.5\lambda_c^{-2}\right] \qquad (2.4)$$

$$\lambda_c = \frac{kl}{r_c} \sqrt{\frac{f_c'}{\pi^2 E_c}} \qquad (2.5)$$

where r_c = radius of gyration of concrete; E_c = modulus of elasticity of concrete including long-term effects; k = factor reflecting column-end conditions; l = length of column; f_c' = compression strength of concrete; ϕ_c, ϕ_s = resistance factors for concrete and steel, respectively; A_c, A_s = section area of concrete and steel, respectively.

The correction factors τ and τ' can be assumed equal to 1.0 (no confinement) if the section of the steel tube is rectangular or if the length of the column l is greater than 25 times its diameter D (i.e., $L/D > 25$). Note that confinement enhances the compressive strength of concrete but decreases that of the steel envelope due to the biaxial state of loading. Therefore, $\tau' \geq 1.0$ and $\tau \leq 1.0$. These correction factors can be derived from:

$$\tau = \frac{1}{\sqrt{1+\rho+\rho^2}} \leq 1 \qquad (2.6)$$

$$\tau' = \left(\frac{25\rho^2\tau}{D/t}\right)\left(\frac{F_y}{0.85f_c'}\right) \geq 1 \qquad (2.7)$$

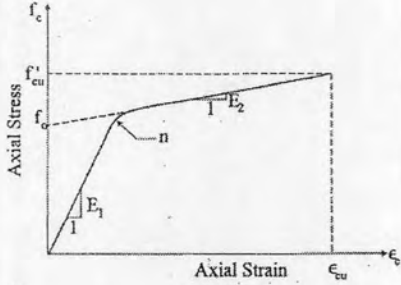$$\rho = 0.02 \left(25 - \frac{t}{D} \right) \tag{2.8}$$

where D = diameter of the column, and t = thickness of steel tube.

1.2.4 Available Models for FRP Wrapped Columns

It is observed that most existing empirical models were developed for concrete confined with steel tubes. These models are based on an elastic perfectly plastic behavior of the steel tube and consider, therefore, the confining pressure constant after concrete has reached its compressive strength. While this may be true for steel tube confined concrete, it may not hold for FRP confined concrete where the confining pressure increases with loading up to failure since FRP composites behave linearly up to rupture. Table 2.3 summarizes the confinement models for FRP wrapped circular columns.

Table 1.3 Confinement models for FRP wrapped columns

Authors	Models	Comments
Fardis and Khalili (1981)	$f_c = \dfrac{E_c \varepsilon_c}{1 + \varepsilon_c \left(\dfrac{E_c}{f'_{cc}} - \dfrac{1}{\varepsilon_{cc}} \right)}$ $\varepsilon_{cc} = 0.002 + 0.001 \dfrac{E_j t_j}{D f'_c}$	E_j, t_j = modulus of elasticity and thickness of FRP jacket E_c = initial tangent modulus of concrete
Ahmad et al. (1991)	$f'_{cc} = f'_c \left(1 + \dfrac{k}{4^n Ssp} \right)$ $\varepsilon_{cc} = \varepsilon_{co} \left(1 + \dfrac{k}{4^n Ssp} \right)$	k and n are functions of f_c Ssp = spacing of FRP spirals

Authors	Models	Comments
Monti and Spoe Istra (1997)	$\varepsilon_r = 0.5\beta \dfrac{E_c - E_{sec}}{E_{sec}}$ $E_{sec} = f_c/\varepsilon_c$ $\beta = -\dfrac{V_p^3 v_c}{3}$ $v_c = 3.22 \dfrac{W_o - 0.364\alpha_x}{1 + 3.22W_o}$ $\alpha_x = \dfrac{1.031W_o}{0.194 + W_o}$	Essentially the same as the model by Ahmad and Shah (1982) V_p = volume fraction of paste in concrete v_c = natural capillary porosity of paste W_o = water-cement ratio α_x = degree of hydration
Samaan, Mirmiran and Shahawy (1998)	(a) Model for the axial strains $v_c = \dfrac{(E_1 - E_2)\varepsilon_c}{\left[1 + \left(\dfrac{(E_1 - E_2)\varepsilon_c}{f_o}\right)^n\right]^{\frac{1}{n}}} + E_2\varepsilon_c$ $f'_{cu} = f'_c + 3.38f_r^{0.7}$ $f_r = \dfrac{2f_j t_j}{D}$ $E_1 = 47.586\sqrt{f'_c}$ $E_2 = 10.482f'_c + 1.3456\dfrac{E_j t_j}{D}$ $f_o = 0.872f'_c + 0.371f_r + 0.908$ $\varepsilon_{cu} = \dfrac{f'_{ju} - f_o}{E_2}$ (b) Model for lateral strains	 f'_{ju}, E_j and t_j = tensile strength, modulus of elasticity and thickness of FRP wrap D = diameter of column n = curve shape parameter (n = 1.5 for circular) r = denotes lateral (radial) direction v = Poisson's ratio

Authors	Models	Comments
	$$f_c = \dfrac{(E_{1r} - E_{2r})\varepsilon_r}{\left[1 + \left(\dfrac{(E_{1r} - E_{2r})\varepsilon_r}{f_{or}}\right)^{n_r}\right]^{\frac{1}{n_r}}} + E_{2r}\varepsilon_r$$ $$E_{1r} = \frac{E_1}{v}$$ $$\mu = -\frac{d\varepsilon_r}{d\varepsilon_c}$$ $$\mu_u = -0.187 \ln\left(\frac{2E_j t_j}{f_c' D}\right) + 0.881$$ $$E_{2r} = \frac{E_2}{\mu_u}$$ $$n_r = \frac{n}{\mu_u}$$ $$f_o = 0.636 f_c' + 0.233 f_r + 0.661$$ $$\varepsilon_{ru} = \frac{f_{ju}' - f_{or}}{E_{2r}}$$	μ = dilation rate ε_{ru} = ultimate radial strain

Shamim A. Sheikh and Murat T. Toklucu[3] investigated the effects of different variables on confined concrete behavior. These effects include volumetric ratio of lateral reinforcement ρ_s, spiral spacing s and specimen size. Strength and ductility of confined concrete increased with an increase in the amount of lateral steel, the strength enhancement being much less sensitive than ductility. Specimens containing a code-required amount of spiral steel ($\rho_s \cong 1.1$ percent), and s/D_c ratios less than or equal to 0.24, behaved in a very ductile manner. In poorly confined

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[3] Shamin A. Sheikh and Murat T. Toklucu, "Reinforced Concrete Columns Confined by Circular Spirals and Hoops," ACI Structural Journal, Title no. 90-S56, Sep.-Oct. 1993.

columns, the spiral steel did not yield at maximum concrete stress. The ρ_s values in most of those columns were less than 1.0 percent or s/D_c ratios were large (≥ 0.36). This parameter was also considered in this research which used this information as a guideline.

From the test results and theoretical predictions of stress-strain curves of confined concrete, S. H. Ahmad and S. P. Shan[4] (1982) proposed that increasing yield strength of spirals should not influence the compressive strength of the confined concrete. However, as shown in Figure 1.3, increasing the yield strength does influence the slope of the descending section to maintain strength of concrete until failure.
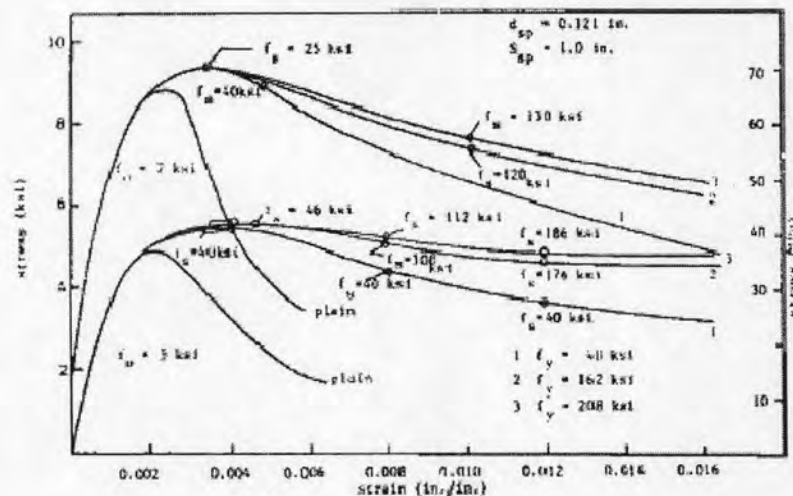

Figure 1.3 Stress-strain curves of confined concrete for various levels of confinement

This report showed that, although using a high percentage of confining reinforcing spiral steel, strength was not increased proportionally. Unlike a passive confining system, an active confining system similar to a spiral post-tensioning system can increase strength of concrete significantly.

Referring to Figure 1.4, for the same level of confining stress, $\sigma_{l,\text{active}}$, and $\sigma_{l,\text{passive}}$, axial strength of active confinement is greater than passive confinement

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[4] S. H. Ahmad and S. P. Shan, "Stress-Strain Curves of Concrete Confined by Spiral Reinforcement," ACI Structural Journal, Title no. 79-46, Nov.-Dec. 1982.

according to the lateral strain component. Pre-compressed lateral strain improves aggregate interlock action and can be determined by plastic theory via dilation behavior as represented in Figure 1.5. Sawtooth model represents mechanism of aggregate interlock action and ψ is the dilation angle that will be stated in theory of plasticity for confinement in chapter 2.

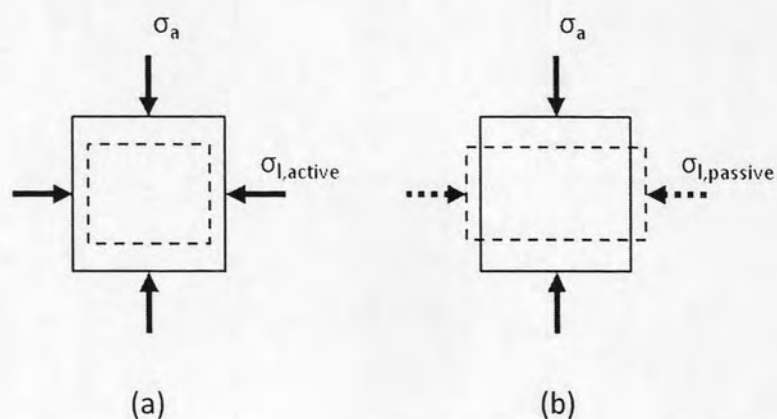(a)   (b)

Figure 1.4 deformed shape of concrete element subjected to (a) active confinement and (b) passive confinement
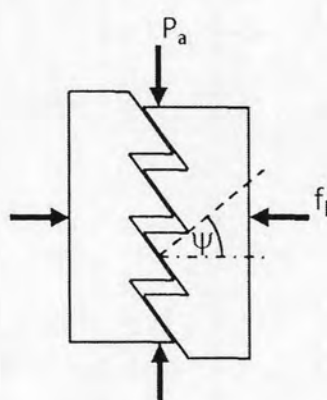

Figure 1.5 Sawtooth model

1.3 Research Objective

This research was performed to study the behavior of concrete under active confinement by using spiral prestressing system. Applying conventional material that widely used in realistic construction, prestress steel was used to develop laterally confined stress and also longitudinal compressive prestress. By the effects of active

confinement by using spiral prestressing system, this dissertation attempts to determine the mathematical stress-strain model for axially loaded concrete cylinders with spiral prestressing confinement considered as a structural model of spirally post-tensioning column. The improvement of peak strain, ultimate strength, ultimate strain, and safety margin (increasing of elastic range) was investigated according to the effect of active confinement by using spiral prestressing system.

1.4 Research Significance

The author believes that the work described herein is ground-breaking research. No other evidence of experimental or analytical work of this nature has been discovered in the literature or in discussions with various experts in the field. The method of spirally reinforcing concrete members has the potential for use in enhancing the overall strength and shear resistance of columns, piers, thick-walled pipes, and tunnels. It is hoped that this important piece of research will stimulate others to pursue this innovative avenue of study.

1.5 Research Program

This dissertation introduces an innovative method for providing active lateral confinement of circular concrete members while preserving axial integrity. Initially, all related issues were carefully reviewed up to and including the practicality of fabrication and testing of specimens. A preliminary numerical study using finite difference analysis was performed with a planned series of tests to verify the calculated results. A material model analysis was used to confirm a suitable material model for use in finite element analysis. Subsequently, verified analytical techniques were used to perform a parametric study using the structural model.

1.6 Thesis Overview

Following are brief summaries of the main chapters.

Chapter 2: Theoretical Approach – This chapter introduces all related issues including prestressing concepts and theory of plasticity of confinement. The

innovative idea of using spiral prestressed steel to provide the confining stresses is presented in light of these historical research efforts. Plastic theory is used to explain the active confinement phenomenon through schematics and associated rules of yielding and strain hardening.

Chapter 3: Experimental Approach – A test program using four specimens was designed and implemented to demonstrate the response of spiral post-tensioning systems applied to circular concrete thick-walled members. Three spirally prestressed simply supported specimens and one control specimen with straight prestressing were tested under single point loading at mid-span causing bending and shear with shear effects being dominant. Special consideration of the prestressing sequence was developed to avoid torsional-bending failure during prestressing.

Chapter 4: Analytical Approach – Finite difference and finite element analyses were performed to predict the behavior of concrete under spiral post-tensioning effects. A finite difference analysis was utilized for preliminary determination of the capacity of test specimens while a finite element technique was performed to model uniaxial compression behavior which was then applied to determine a structural model.

Chapter 5: Structural Model – The structural model was used to perform parametric studies to determine the general behavior of concrete under spiral post-tensioning systems and to enhance the model itself.

Chapter 6: Conclusions and Discussion – A summary of the written dissertation is presented and includes a final word on the analytical approach, experimental approach, and the proposed structural model. Based on the seminal work developed herein, proposals for future research directions in this area are presented.