CHAPTER VI

DISCUSSION AND CONCLUSION

Since the 1900s, many engineers have dedicated their efforts to developing and understanding the effects of confinement in concrete structures. Considere (1899) opened up the history of confinement theory in terms of triaxial tests being reconsidered as active confinement. Subsequently, engineers such as Richart (1928) developed the model for tri-axially stressed concrete which was mainly applied for a passive confinement using lateral steel reinforcement. Many proposed models of passive confinement were exhibited with many types of confining materials and many methods of confinement. These included hoop stirrup steel reinforcement, spiral stirrup steel reinforcement, steel tube casing, and fiber reinforced polymer (FRP) wrapped columns. Those passively confined implementations are mainly utilized to maintain strength after concrete has yielded and referred to as passive confinement being used to enhance ductility. Recently, passive confinement has been widely developed in many fields of study and is a well recognized procedure in current codes of practice.

There are various researchers who have endeavored to establish a thorough understanding of actively confined structures. Unlike passive confinement, active confinement can improve the strength of concrete from the initial stage of loading. The increasing strength relates to the magnitude of confined stress. Saatcioglu and Murat (1999) invented hardware devices to grip the prestressed wire on the outside perimeter of concrete columns to create a laterally confined hoop stress. The objective of their work was to retrofit existing concrete columns constructed before 1970. At that time, ACI 318-71 code did not provide for adequate ductility of concrete columns in seismic zones. Therefore, the existing structures at that time needed to be upgraded or strengthened and active confinement was considered to be a viable option.

This dissertation attempts to develop an active confinement by utilizing spiral post-tensioning systems to generate both laterally confined stress and also longitudinal compressive prestress to offset any unintentional longitudinal cracking tension such as might result in the case of horizontal, individual hoop prestressing. According to the theory of plasticity for confinement as indicated in Figure 2.5, longitudinal prestress can stabilize the stage of stresses within the yield criterion and the axial strength of a concrete structure can be increased theoretically to infinite value. There are other factors involved in the strength of concrete such as buckling due to the structural geometry and creep due to large magnitudes of confining stresses. However, this dissertation limits the margin of study to focusing on the stage of stresses relating to the theory of plasticity.

To verify an innovative idea of applying spiral post-tensioning systems to concrete structures, four tests were performed. An analytical approach was exploited to determine the structural model of spiral post-tensioning system and the proposed model was evaluated in comparison with test results. This section is presented in three categories, namely, conclusions, proposed structural model, and research direction.

6.1 Conclusions

This dissertation has focused on active confinement provided by spiral post-tensioning systems applied to structural concrete materials. This study was simplified to reduce any unexpected complexity and to emphasize behavior of confined and loaded concrete regions. The interaction between prestressing tendons and concrete was interpreted as loading on the exterior surface of the concrete along the lines of prestressing tendons. It was indicated that prestress losses due to friction and anchorage take-up compensated each other and were assumed to be uniform throughout the prestressed strand as illustrated in Figure 2.2. Other losses such as creep loss and steel relaxation that gradually became distributed all along the length of prestress strands were considered and additional prestress force was applied from the jacking stage to offset those losses.

Length-to-diameter ratio, L/D was set to $L/D = 2$ corresponding to the standard cylinder for compressive strength test to check the conformity of the stress distribution from the finite element analysis with the standard test.

Stress changes in strands due to load application were neglected according to small deformation assumptions and levels of initial prestress in the strands. Higher initial prestress forces caused lower percentages of differences to the stress in the strands due to load.

Direct axial compressive strength tests to evaluate confinement effects could not be performed due to unavailability of high capacity loading equipment required and the limitation of specimen size. Test specimens were mounted as simply support beams and point-loaded at mid-span. Furthermore, specimens were designed as thick-walled pipes to reduce shear capacity. Although this experimental study did not directly indicate the effects of active confinement provided by spiral post-tensioning systems for axially loaded specimens, the results do show how specimen strength and ductility under shear and moment are improved significantly. The results have demonstrated the beneficial aspects of spiral post-tensioning of circular members subjected to shear and bending. This is a more rigorous test of the system than would be the case if such members were simply loaded under axial compression. Due to the complexity of combined stresses due to prestress forces and short-span loading test specimens were setup to evaluate these effects.

Losses due to prestress were taken into account by increasing jacking forces accordingly to offset loss effects. During post-tensioning a sequential prestressing procedure was strictly followed to avoid accidental failure caused by imbalances of torsional-bending stresses between tendons. Applying prestress simultaneously to counterbalancing pairs of clockwise versus counter-clockwise strands is, in general, suggested for the construction sequence.

According to the experimental results, all specimens failed in a brittle mode because of the high contact stresses between the unbonded prestress tendons and the concrete. Spacing of prestress tendons indicated by the ratio s/D, which was 0.56 for the specimens tested, was determined to be too high for developing full ductile behavior. Referring to the study of Shamim A. Sheikh and Murat T. Toklucu (1993), for ductile behavior, s/D ratios should be no greater than 0.24. Principal stress directions at the middle of specimen depths varied between 25° and 35° to the longitudinal axis as the result of combined shear stress from loading and pre-compression stress from prestressing. Stiffness of the specimens increased proportionally to the levels of prestress. First cracking occurred near mid-span at the bottom of all specimens. Cracking strength and ultimate strength increased proportionally with the levels of prestress. Comparing specimen H2 to the control specimen (HC1) with straight tendons having the same level of prestress, cracking strength and ultimate strength of specimen H2 were dramatically higher than those of the control specimen HC1, being about 41% and 45% higher, respectively.

While finite element analysis was useful for determining the overall behavior of test specimens, predicted results for ultimate strength of test specimens were highly overestimated. The method, however, was capable of representing the effects of active confinement, deep beam action, and combined stresses due to prestressing and loading. A comparison of finite element results to the finite difference results that base on bending theory with assumed confined concrete model showed that both methods made similar predictions as shown in Table 4.2 except specimen HC1 that FEM result is different to FDM result according to shear effect and arch action. Furthermore, by the effect of shear and arch action, FEM result of specimen HC1 is also close to the experimental result. The main reason for the discrepancy between the predicted ultimate strengths of specimens using finite elements is related to the localized failure of the concrete before the strength reach overall failure. As a result the concrete failed along the tendons due to a complex localized stress field in the contact zone.

Triaxial model tests were performed to verify the active confinement effect of the concrete plastic model. The results agreed with the previously proposed models as indicated in Figure 4.12.

Parametric studies of uniaxial compression models were achieved by finite element analysis with a concrete plastic model to determine the structural model of spirally post-tensioning system.

6.2 Proposed Structural model

From parametric studies of uniaxial compression models for concrete structures with spirally post-tensioned systems, a proposed structural model was established and is presented in this section.

Stresses from prestressed strands can be calculated as shown below:

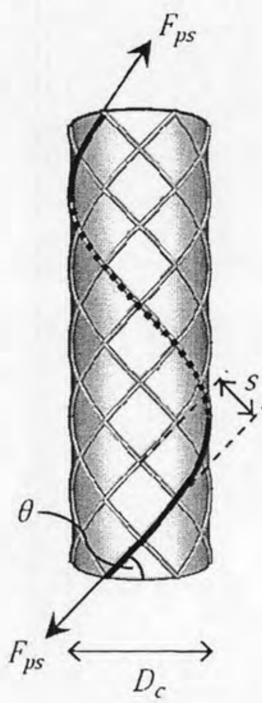

Figure 6.1 Strands Alignment

$$f_l = \begin{cases} \dfrac{4A_{ps}f_{ps}\cos^2\theta}{D_c s} & \text{for cylinder section} \quad (6.1) \\ \dfrac{2A_{ps}f_{ps}\cos^2\theta}{ts} & \text{for pipe section} \quad (6.2) \end{cases}$$

$$s = \frac{2\pi D_c}{n}\sin\theta \qquad (6.3)$$

$$F_a = nA_{ps}f_{ps}\sin\theta \qquad (6.4)$$

$$f_a = \frac{F_a}{A_g} \qquad (6.5)$$

$$\frac{f_a}{f_l} = 2\tan^2\theta \qquad (6.6)$$

The proposed structural model can be represented as illustrated in Figure 6.2 which shows an ascending portion, a horizontal portion at the ultimate strength, and a portion descending at slope, Z.

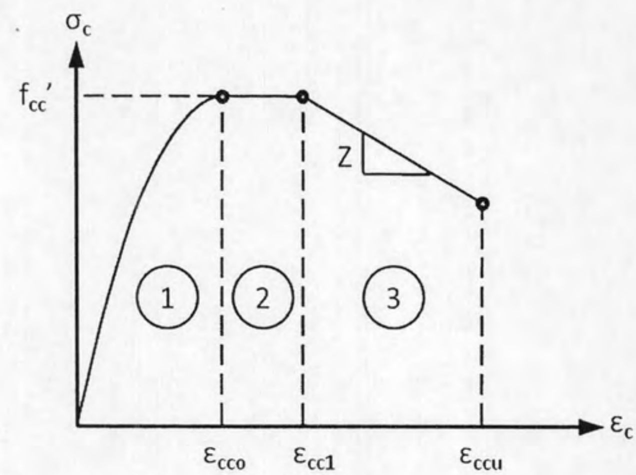

Figure 6.2 Proposed structural model for an axially loaded model of a cylindrical concrete member under spiral prestressed confinement

The proposed structural model was presented in terms of the five parameters, k_c, ε_{cco}, ε_{cc1}, ε_{ccu} and Z, as expressed below:

$$f'_{cc} = f'_c + k_c f_l \tag{6.7}$$

$$k_c = \begin{cases} 3.9 & \text{for } \sqrt{f'_c}^{\,-1} f_l^{\,-0.107} \leq 0.04 \\ 271\sqrt{f'_c}^{\,-1} f_l^{\,-0.107} - 7.1 & \text{for } \sqrt{f'_c}^{\,-1} f_l^{\,-0.107} > 0.04 \end{cases} \tag{6.8}$$

$$\varepsilon_{cco} = 0.0009\, f'_{cc}/f'_c + 0.0016 \tag{6.9}$$

$$\varepsilon_{cc1} = 0.0013\, f'_{cc}/f'_c + 0.0014 \quad (6.10)$$

$$\varepsilon_{ccu} = -3 \times 10^{-6} f'_c + 0.0056 \quad (6.11)$$

$$Z = 122.45 f'_c + 4036 \quad (6.12)$$

This dissertation has focused on concrete material under actively confining spiral post-tensioning systems. The effects of dilation and direct interaction of prestress tendons with contact concrete regions were not directly considered. It is suggested that these matters provide interesting research for future projects.

6.3 Future Research Direction

This dissertation is a preliminary study of actively confined concrete using spiral prestressed steel. The seminal work concerning this idea as developed herein should be encouraged and developed for future consideration. The future research direction can be divided into three major areas: 1) the development of a more refined finite element analysis model; 2) the extended application of spiral prestressing systems, and; 3) large scale testing of axially loaded members

Because of the truly innovative nature of this research it was not possible to address all concerns at this time. The purpose of the research here was to determine if in fact spiral post-tensioning systems are viable both from a structural point of view as well as from a construction point of view. In fact the results presented herein have demonstrated that both of these ideas are indeed realistic. The finite element analysis in this research considered only active confinement behavior of concrete under spiral post-tensioning systems. In subsequent research, the model should be developed to include load-transfer interaction between tendon and concrete regions and possible localized failure related thereto and interaction of stresses from the prestressed steel and member loading. The complex action of local failure should be further investigated by this interaction modeling.

As pointed out, the experimental part of this research was directed towards evaluation of continuous spiral prestressing effects on the strength, behavior, and ductility of short circular thick-walled cylinders subjected to single point load bending and shear. The test results showed a favorable and desirable response for concrete members with spiral post-tensioning in resisting bending and shear combined. It is also expected that the spiral configuration of strands will substantially benefit columns that may also be subjected to torsional stresses that may result from lateral loads caused by winds and earthquakes.

Full-scale testing of uniaxial compression specimens should also be performed to verify the analytical approach for uni-compressive model of spiral prestressing system. A system of bonded post-tensioning tendons would most certainly increase ductility and reduce local failure effects as experienced in this research. In a practical sense, bonding of tendons can be achieved by casting an outer shell on the member after post-tensioning is complete. In this case dry steel tendons should be used with no vinyl pre-ducting wrap such as that used in the DSI Monostrand® system.