CHAPTER I

INTRODUCTION

1.1 General

The behavior of confined concrete has been investigated extensively during the last two decades. However, due to the complexity of the problem, earlier studies did not consider the behavior of reinforced concrete columns with the consideration of the interaction between core concrete and the reinforcement cage. Most of these studies have been based on experiments conducted to obtain the behavior of the materials of interest separately, i.e. confined concrete and longitudinal reinforcement. Many mathematical models for predicting behavior of confined concrete and buckling of longitudinal reinforcement have been proposed.

Under severe loading conditions, such as strong ground motions, the post-peak information of reinforced concrete structures is necessary for the assessment of the structural performance. Furthermore, reinforced concrete frames subjected to cyclic loading or ground motions often experience large lateral deformation and the load-displacement relationships frequently reach the post-peak range. Therefore, a reliable analytical prediction of post-peak behavior of the reinforced concrete structure is essential in assessing the behavior of the overall structure.

As a reinforced concrete column is subjected to external loads, it is well known that the core concrete expands. The expansion of the core concrete will be resisted by the transverse steel as a passive confinement mechanism. The progressive deformation of the transverse steel as loading increases leads to decreasing in the restraining capability of the longitudinal reinforcement from buckling.

Although it was well known that the transverse steels had profound influence on both confinement of core concrete and buckling of longitudinal reinforcement, very few of the earlier studies considered completely the interaction between the core concrete and reinforcement cage. Neglecting this interaction results in unrealistic prediction of the onset of buckling of longitudinal reinforcement. From this point of view, it is necessary to conduct a simple but reliable procedure to predict the behavior of reinforced concrete columns with consideration of core concrete and reinforcement interaction.

1.2 Literature Review

1.2.1 Confinement Model for normal- and high-strength concrete

Earlier studies date back to the 1920s. Richart et al. (1928) were among the first to study the confinement of normal-strength concrete provided by uniform hydrostatic pressure. Researchers prior to 1980 did not consider the distribution of longitudinal reinforcement and the resulting transverse steel arrangement as a confinement parameter (Razvi and Saatcioglu, 1999).

Sheikh and Uzumeri (1982) and later Mander et al. (1988) made use of the concept of an effectively confined concrete area to determine the confinement effectiveness coefficient, K_e, defined as the ratio of the effective confinement pressure to the nominal value obtained from equilibrium consideration. Saatcioglu and Razvi (1992) have proposed an empirical formula, based on regression analyses of test results, to determine K_e. In both of these approaches, it is either explicitly or implicitly assumed that the perimeter ties and crossties reach the yield strength at the peak response. However, Ahmad and Shah (1982) and Madas and Elnashai (1992) showed that this assumption is not always valid.

A rational method was introduced by Cusson and Paultre (1995) based on strain compatibility and transverse force equilibrium to obtain stress-strain relationship for high-strength square RC columns. The actual column is replaced by an equivalent circular column. Thus, only extension in the hoops is considered. An iterative procedure is needed for determining the steel stress at the peak confined strength. Modification of the Cusson and Paultre model has been made to extend its applicability to square and circular columns made of normal or high-strength materials [Paultre and Légeron (1999), Légeron and Paultre (2003)]. A simpler approach based on regression analysis of test results was proposed by Razvi and Saaticioglu (1999) to determine the stress in transverse steel at peak confined strength. An empirical formula was given for this purpose, avoiding the need to perform lengthy iterations.

Although the influence of flexural stiffness of perimeter ties on the confining pressure has been investigated by experiments [Sun et al. (1996) and Sato and Yamaguchi (2000)], very few researchers studied this problem analytically. Assa et al. (2001a and 2001b) proposed analytical models based the expansion of concrete core and the transverse deformation of perimeter ties for determining the confining pressure at peak strength for circular RC columns. Furthermore, for RC tied columns, the nonuniform confinement pressure along the height of the column is transformed to an equivalent uniform confining stress provided by an equivalent circular envelope, using the strain energy concept.

1.2.2 Buckling of Longitudinal Reinforcement

Extensive studies have been conducted on bare reinforcing bars. Mau and El-Mabsout (1989) formulated a beam-column finite element model to study the average stress-strain behavior of reinforcing bars in compression. They reported that the effect of buckling diminished if the slenderness ratio was less than 5. Monti and Nuti (1992) conducted a series of monotonic and cyclic tests on reinforcing bars with nominal yield strength of 440 MPa and different slenderness ratios. Experimental results indicated that the average stress-strain curve was almost the same as local behavior in case of slenderness ratio equal to 5. Based on four hardening rules (kinematic, isotropic, memory, and saturation), analytical equations representing the average stress-strain relationship were formulated and verified with cyclic test results. A series of cyclic loading tests of reinforcing bars with different slenderness ratio was also conducted by Rodriguez et al. (1999). In this study, the stress and strain at the onset of buckling were experimentally investigated. It was concluded that the point of the onset buckling depended on the maximum tensile strain attained in the cyclic history.

The behavior of longitudinal bars inside reinforced concrete columns has been known to be different from that of bare bars. Papia, Russo and Zingone (1988) considered the influences of arrangement, spacing and stiffness of transverse steels in the determination of critical buckling length of longitudinal bars in RC columns. The approximation of compressive concrete strain at buckling of longitudinal reinforcement was later proposed by Papia and Russo (1989).

Suda et al. (1996) carried out experiments on the post buckling behavior of reinforcing bars. A special device called stress sensor was developed to measure the post-yielding stress of longitudinal bars inside the columns. Based on the experimental data, empirical equations were proposed for the average stress-strain relationship of longitudinal bars including post-buckling behavior. Gomes and Appleton (1997) proposed a simple model based on the equilibrium of plastic mechanism of buckled reinforcing bar to obtain the initiation of the buckling point and the softening stress-strain curve. This simplified formulation taking into account the geometrical and material nonlinearity of the reinforcing bars was used to obtain the softening behavior of the reinforcement after buckling.

Suda and Masukawa (2000) proposed a new analytical model for longitudinal reinforcement inside reinforced concrete members. This model included the consideration of tensile characteristic of concrete cover, flexural stiffness and initial curvature of longitudinal reinforcement and the influence of transverse steel stiffness on buckling length. Unlike other researchers, Dhakal (2000) proposed an analytical model, based on results from finite element analyses, to estimate the post-buckling behavior of reinforcing bars. The critical buckling length and the compressive strain at spalling of concrete cover were also given with the consideration of the stiffness of transverse steels and the tensile characteristic of concrete cover, respectively.

Bayrak and Sheikh (2001) proposed an analytical procedure to predict the formation of the plastic hinges in reinforced concrete columns. This procedure considered the interaction between the confined core concrete and the longitudinal bars under compression. However, the stress-strain relationship of longitudinal bar was not given explicitly. Recently, Moyer and Kowalsky (2003) found that the amount of tensile strain that the reinforcing bars within a concrete column had been subjected to directly affected the buckling behavior upon reversal of loadings.

1.3 Objectives and Scope of Study

It is evident that there is paucity of research work which takes into account the interaction between core concrete and reinforcement cage in predicting the nonlinear behavior of reinforced concrete structures. This study presents an analytical procedure that can be used to predict the behavior of square RC columns with consideration of the interaction between core concrete, longitudinal reinforcements, and transverse steel. The results from 3-D finite element elastic analyses are used to obtain simple relations for the variation of confining stress over the vertical hoop spacing and the confining force transferred by the perimeter ties. The strength enhancement in core concrete confined by rectilinear ties with various tie configurations can be determined from the proposed procedure with direct consideration of the influence of flexural flexibility of the ties and the variation of confining stress along the vertical direction. The reinforcing bar buckling model proposed Dhakal (2000) is incorporated for determining the envelope moment-curvature relationship of reinforced concrete columns.

The results are verified against the experimental results from various researchers. Finally, the proposed confinement model, without consideration of buckling of rebars, is incorporated in the nonlinear finite element analysis program FINITE to obtain the cyclic behavior of reinforced concrete columns and plane frames.

1.4 Assumptions

The investigation of cyclic behavior of reinforced concrete columns and plane frames in this study is based on the following assumptions:

1. The transverse reinforcing bars are assumed to behave as an elasto-plastic material.
2. Bond between the perimeter ties and concrete core is neglected.
3. The perimeter tie is modeled as beam elements with the ends fixed. In case the hoop is restrained internally by a crosstie, the intermediate crosstie

support is also assumed to be restrained against rotation. Crossties (if provided) are modeled as axial bar elements.

4. Simple relations for the variation of confining stress over the vertical hoop spacing and the confining force transferred by the perimeter ties are determined from results of 3-D finite element analyses of concrete core-hoop system assuming elastic properties..
5. In the reinforcement buckling model based on the research work of Dhakal (2000), the transverse reinforcing bars in the central half of the buckling length are assumed to have no contribution in restraining the buckled longitudinal bars. Also bending of the hoops are ignored.
6. The moment-curvature relationship of reinforced concrete columns subjected to axial and lateral loadings is determined based on the classical Euler-Bernoulli's assumption, i.e. plane sections of the members are assumed to remain plane, throughout the deformation.