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STRENGTH AND DUCTILITY OF CONCRETE COLUMNS REINFORCED WITH WELDED WIRE FABRIC AND/OR REBARS

By

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A thesis
Submitted Under Supervision of
Dr. M. Saatcioglu
In Partial Fulfillment
of the Requirement for the Degree of
Master of Applied Sciences

Department of Civil Engineering
Faculty of Engineering
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Abstract

Experimental and analytical research was carried out to investigate the characteristics of concrete confined by welded wire fabric. Seven column specimens were tested under monotonic concentric loading. Different arrangements of welded wire fabric were used in the columns. The column reinforcement consisted of only welded wire fabric, without the use of any reinforcing bars. Two companion columns without welded wire fabric were also tested to establish plain concrete strength from specimens of same size and shape. The test result showed that columns developed some increase in strength due to concrete confinement. The increase in confinement was relatively small because of the low reinforcement ratio associated with the welded wire fabric used. The ductility enhancement was also limited, and the welded wire fabric buckled shortly after the peak load. It was concluded that, unless special size welded wire fabric was used to have adequate percentage of steel, the standard size mesh was not suitable for use as column reinforcement.

The test results, as well as those obtained from previous research were compared against analytical predictions obtained from the use of Saatcioglu and Razvi model for confined concrete. The results showed good agreement between the test results and those obtained analytically. Having established the validity of the model, a parametric study was carried out as part of the analytical research. A total of 140 columns were considered in the parametric study. The objective of the parametric investigation was to establish the significance of confinement parameters for columns reinforced with welded wire fabric, reinforcing bars, and a combination of the two. It was found that, the mechanism of confinement was not any different in columns confined by welded wire fabric, as compared to those confined by reinforcing bars. The combined use of reinforcing bars and welded wire fabric offered the optimum solution, where the bars formed the main reinforcement, and the mesh provided superior concrete confinement.

Acknowledgements

I wish to express my sincere appreciation to Dr. M. Saatcioglu for his patience, guidance and advice throughout this research program.

I also wish to thank the technical staff of structural lab of Civil Engineering Department for their assistance.

I would also like to take this opportunity to convey my appreciation to my friends and colleagues, especially Ali E. Ghabrouni, J. Alsiwat, R. Razvi for their encouragement and generous help during this work.

Dedication

To my special brother, Abbas Ibrahim

I dedicate this thesis to my brother Abbas whose understanding, support and love has given me all the strength I needed.

Contents

2 Experimental Program 12

List of Figures

List of Tables

Notations

A_g = gross area of column cross section.
A_s = area of longitudinal steel.
E_c = modulus of elasticity of plain concrete.
f_c = concrete stress.
f'_{cc} = strength of confined concrete.
f'_c = ultimate strength of plain concrete obtained from standard cylinder test.
f'_{co} = strength of concrete in specimen of the same shape and size.
f_l = average pressure on core concrete.
f_{le} = effective pressure on core concrete.
f_y = yield strength of lateral tie.
K = ratio of additional strength due to confinement to the strength of plain concrete
k_1 = ratio that relates the average lateral pressure to confined concrete strength.
k_2 = reduction factor to change average pressure to effective pressure in concrete.

s = tie spacing.
s_l = centre to centre of longitudinal steel,supported with a tie corner.
ϵ_1 = strain corresponding to the maximum stress in concrete.
ϵ_{o1} = strain corresponding to maximum stress in plain concrete.
ϵ_{o85} = strain of plain concrete corresponding to 85% of peak stress on the falling branch of the curve.

ϵ_{85} = strain of confined concrete corresponding to 85% of peak stress on the falling branch of the curve.

ρ_{gross} = ratio of area of longitudinal steel to gross area of column.

ρ_v = ratio of volume of tie steel to volume of concrete core measured centre to centre of outer tie.

ρ_{core} = ratio of area of longitudinal dteel to volume of concrete core.

Chapter 1

Introduction

1.1 General

The unprecedented damages caused by earthquakes have called the attention of structural engineers for the last two decades. As a result, increasing research emphasis has been placed on seismic resitant design of structures.

Design of earthquake resistant structures to dissipate earthquake induced energy by post-elastic deformations of members forms the current design criteria for reinforced concrete structures. This requires the critical elements to be designed for ductility as well as strength. Columns in frame structures may become critical elements, especially at the first storey level. Observations during past earthquakes showed that failure of an entire structure was triggered by the failure of columns [31]. Inelasticity in columns does not necessarily lead to failure. Plastic hinging of columns at the base of a structure may even be relied upon for energy dissipation, if the columns are designed properly. Columns thus are required to behave in a ductile manner with stable plastic hinges. Ductility of concrete columns can be attained by careful detailing of the transverse reinforcement. The transverse steel, in the form of hoops or spirals, confine the concrete in plastic hinge regions and improve overall ductility of the member. Previous research has demonstrated that strength and ductility of concrete in axial compression improve very significantly when confined by reinforcement.

Lateral pressure exerted by the reinforcement cage on the core concrete limits internal cracking in concrete, and produces increase in strength and deformability of the member. Concrete confinement assumes an important role especially in seismic resistance of compression members where the increased ductility of member is required to maintain strength and stability of the structure during inelastic response.

Although a large volume of research data is available on confinement characteristics of spiral and tie reinforcement, no research data is available on the use of welded wire fabric as column reinforcement. On the other hand, it is reasonable to expect that welded wire fabric, with closely spaced vertical and horizontal reinforcements may potentially provide better confinement characteristics than that of ordinary reinforcing bars. Furthermore, it has the practical advantage of being available in a pre-assembled form, as horizontal and vertical reinforcements welded together.

In the earlier phase of this research program, Razvi and Saatcioglu [17] investigated, for the first time,the use of W.W.F. as confinement reinforcement. They tested 34 small scale columns to study the effect of W.W.F., while ordinary reinforcing bars were used as main longitudnal reinforcement. Their conclusion was that the presence of W.W.F. improved confinement of concrete. However, W.W.F. was not effective in controlling the buckling of main column bars, which led to the rupturing of W.W.F. Their research program was limited to the study of the combined use of W.W.F. with reinforcing bars. As a result, the investigation of the use of W.W.F., as the only column reinforcement is adopted as the main objective of the current study.

1.2 Objective

The overall objective of the research program is to evaluate the use of welded wire fabric (W.W.F.) as column reinforcement. The behavior of concrete columns, reinforced only with W.W.F. is investigated experimentally. The objective includes investigation of confinement charatristics of W.W.F. when used with and wihtout reinforcing bars. It also includes analytical investigation of the significance of column confinement parameters when the reinforcement used consists of only W.W.F., combination of W.W.F. and reinforcing bars, and only reinforcing bars.

1.3 Scope

The scope comprises of experimental and analytical research. Seven concrete columns, reinforced with welded wire fabric, were designed built and tested in the experimental program. The columns were tested under monotonically applied concentric compression. The test data was evaluated to extract stress-strain relationships of confined core concrete from the overall response. These relationships, as well as others obtained from previous investigations were reproduced analytically by using an analytical model for confined concrete. The same model was then used as part of the analytical research, to conduct a parametric study. A total of 140 columns were analyzed to establish the significance of W.W.F. as column reinforcement. The analytical study was extended to cover columns reinforced with W.W.F. combined with reinforcing bars as well as those reinforced with conventional reinforcing cages, consisting of ordinary deformed reinforcing bars.

1.4 Previous Research

The research on concrete confinement dates back to 1928, when Richart et al. [19] showed improvements in strength and ductility of concrete resulting from lateral hydrostatic pressure. The researchers tested concrete cylinders under different levels of hydrostatic pressure, and established an emprical relationship between the lateral pressure and increase in axial strength. This relationship formed the basis of the confinement steel requirements in building codes [1,4]. Richart et al. [20] later tested concrete cylinders reinforced with circular spirals, and concluded that the passive confinement pressure provided by the spiral reinforcement provided uniform lateral pressure which could be computed from the hoop tension.

Early reasearch conducted by Richart et al. provided the basic understanding of concrete confinement in circular columns, where the lateral confining pressure was uniform due to the geometry of the section. This was interprated as the confinement action being limited to circular columns for many years. In fact the building codes, to date, allow a lower safety factor (capacity reduction factor) for spirally reinforced circular columns, recognizing the additional strength and ductility in these columns. Very little recognition was given to the confining effect of rectilinear reinforcement.

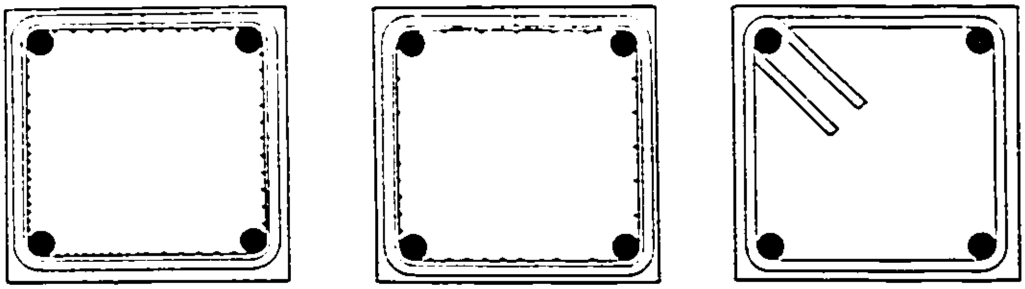
Confinement action provided by rectilinear reinforcement was studied by Chan [5], Roy and Sozen [21], Soliman and Yu [32], Sargin, Ghosh and Handa[24], and Kent and Park[10]. The emphasis in these research programs was placed on the volumetric ratio and spacing of transverse reinforcement. The results showed conflicting evidence of strength enhancement, although the ductility improvement was acknowledged by all researchers. These research programs resulted in analytical models for confined concrete, some of which did not reflect the strength improvement due to confinement.

Researchers prior to 1975 concentrated on spacing and volumetric ratio of transverse steel to improve the confinement action. Park and Paulay [14] for the first time discussed the effect of reinforcement arrangement on concrete confinement. They showed that the tie arrangement and resulting distribution of longitudinal reinforcement also played an important role on concrete confinement. In 1980, Sheikh and Uzumeri demonstrated the improvement in concrete confinement in square columns, resulting from favourable tie arrangements, even if the volumetric ratio and spacing of lateral reinforcement remained constant. They defined "effectively confined core area" as the area bound between the closely spaced longitudinal and tie reinforcement, and concluded that as this area increased due to the close spacing of reinforcement, so did the improvement in strength and ductility of confined concrete. Sheikh and Uzumeri [30] also proposed an analytical model for confined concrete, based on the effectively confined core area. Their model was the first one to consider both the distribution of longitudinal as well as lateral reinforcement in confining concrete. Sheikh [29] in 1982 conducted a comparative study of confinement models and provided a review of the previous analytical models.

Two recent research work on concrete confinement, one by Scott, Park and Priestley [25], and the other by Faftis and Shah [6] did not consider the distribution of longitudinal reinforcement as a parameter. However, the recent work by Mander, Park and Priestley [11], resulted in a theoretical model which incorporated the tie arrangement as well as the previously found confinement paremeters. Accordingly, the lateral pressure exerted by reinforcement is computed and reduced on the basis of the effectively confined core area presented by Sheikh and Uzumeri [30]. The model is applicable to circular. square, and rectangular sections subjected to slow and fast rates of loading.

Behavior of confined columns was also investigated under cyclic loading. Park, Priestley and Gill [15] in 1982, and Ozcebe and Saatcioglu [12] in 1987 demonstrated experimentally that proper detailing of both transverse and longitudinal reinforcement improved column strength and ductility.

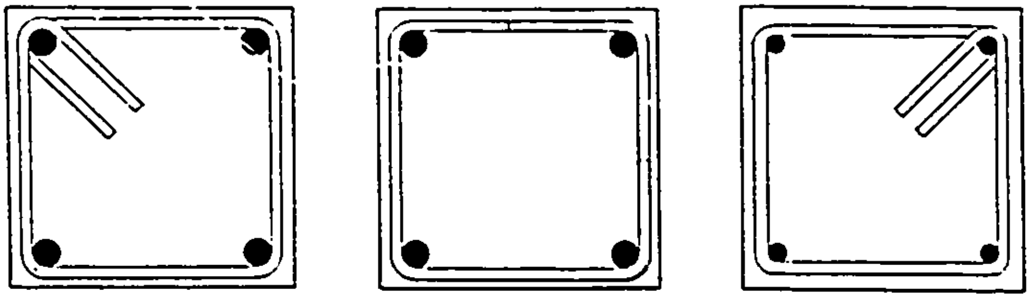
It was clear from the previous research that closely spaced lateral, as well as longitudinal reinforcement improved strength and ductility of confined concrete. This led to the study of welded wire fabric, which met the conditions favourable for confinement. Razvi and Saatcioglu [17] started an experimental research program which formed the first phase of the current research project at the University of Ottawa. They tested 34 small scale columns, with various arrangement of welded wire fabric and/or hoop reinforcement. This was the first test program on the use of W.W.F. as column reinforcement. Figures 1.1. and 1.2 illustrate the cross-sectional arrangements used in the experimental program. In all the specimens, deformed reinforcing bars were used as longitudinal column reinforcement. W.W.F. was used either as the only lateral reinforcement, or in combination with square perimeter hoops. When used with hoop steel W.W.F. was either placed between the hoop steel and the longitudinal reinforcement, or inside the reinforcement cage. The following conclusions were reported by the



COLUMN PAIR 1
4 No. 15
Ties 6.5 mm at 70 mm
WWF 12.7 x 12.7 x 1.45

COLUMN PAIR 2
4 N. 15
Ties 6.5 mm at 70 mm
WWF 25.4 x 25.4 x 1.89

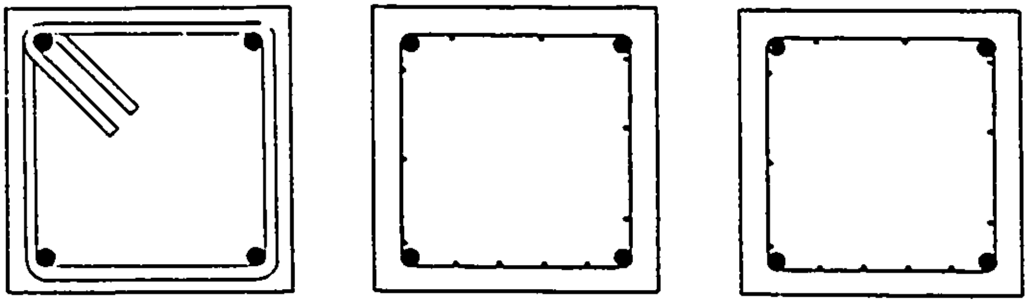
COLUMN PAIR 3
4 No. 15
Ties 6.5 mm at 35 mm



COLUMN PAIR 4
4 No. 15
Ties 6.5 mm at 70 mm

COLUMN PAIR 5
4 No. 15
Ties 6.5 mm at 70 mm

COLUMN PAIR 6
4 No. 10
Ties 6.5 mm at 35 mm



COLUMN PAIR 7
4 No. 10
Ties 6.5 mm at 70 mm

COLUMN PAIR 8
4 No. 10
WWF 25.4 x 50.8 x 3.42
(WELDED)

COLUMN PAIR 9
4 No. 10
WWF 25.4 x 50.8 x 3.42
(MECHANICALY CONNECTED)

Figure 1.1: Column Cross-Sections Tested by Razvi and Saatcioglu[17]
Column Pairs 1-9

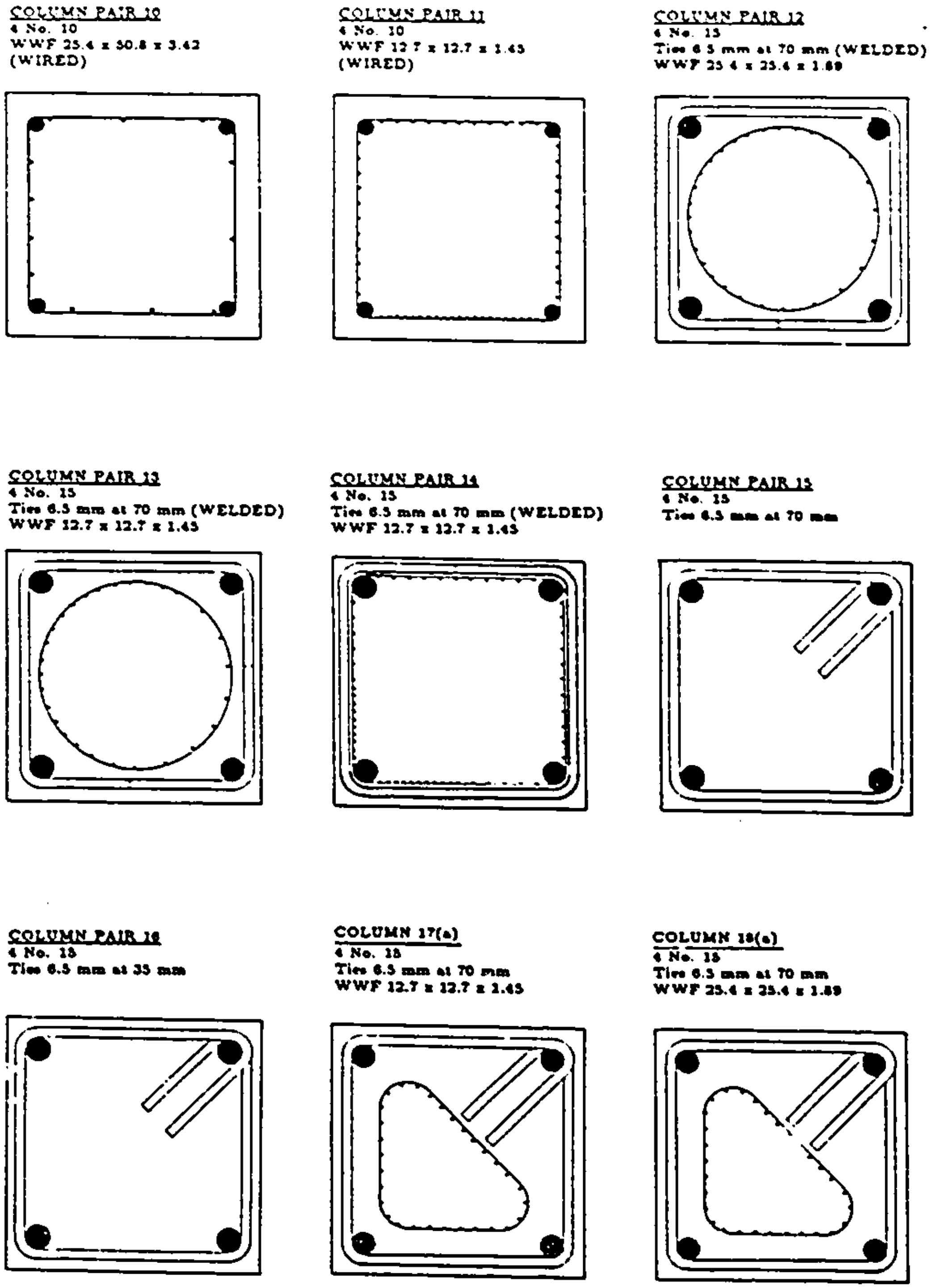


Figure 1.2: Column Cross-Sections Tested by Razvi and Saatcioglu[17]
Column Pairs 10-16 and Columns 17(a) and 18(a)

researchers:

- The use of W.W.F. resulted in as much as 40% increase in concrete strength. This increase was equivalent to that obtained by the use of closely spaced hoop steel with twice the steel area.

- W.W.F. placed inside the core, in a circular shape, was more effective than that used between the hoop and longitudinal reinforcement.

- W.W.F. was effective in preventing the longitudinal reinforcement from buckling. The combination of longitudinal reinforcing bars and W.W.F. resulted in a brittle failure. Bending and buckling longitudinal reinforcement under compression led to the fracture of W.W.F. Therefore, the use of hoops to support longitudinal reinforcement was recommended.

- For the same volumetric ratio of steel, W.W.F. with finer grid size produced better confinement.

Saatcioglu and Razvi [22] recently developed an analytical model for confined concrete. The model is based on the concept of equivalent lateral pressure, and can be used to predict stress-strain relationship of confined concrete under slow and fast rates of loading. It is general enough to treat different concrete sections with circular spirals, square and rectangular hoops with and without cross ties, welded wire fabric and any combination of these reinforcements. The model is adopted in this investigation, for the analytical parametric study. The details of the model are given in chapter 3. The authors compared the results of analytical predictions based on the proposed model with a large volume of test data, and showed that the model can be used for columns of different geometry and reinforcement arrangements. This model is the only analytical tool that can be applied to columns reinforced with W.W.F.

Chapter 2

Experimental Program

2.1 General

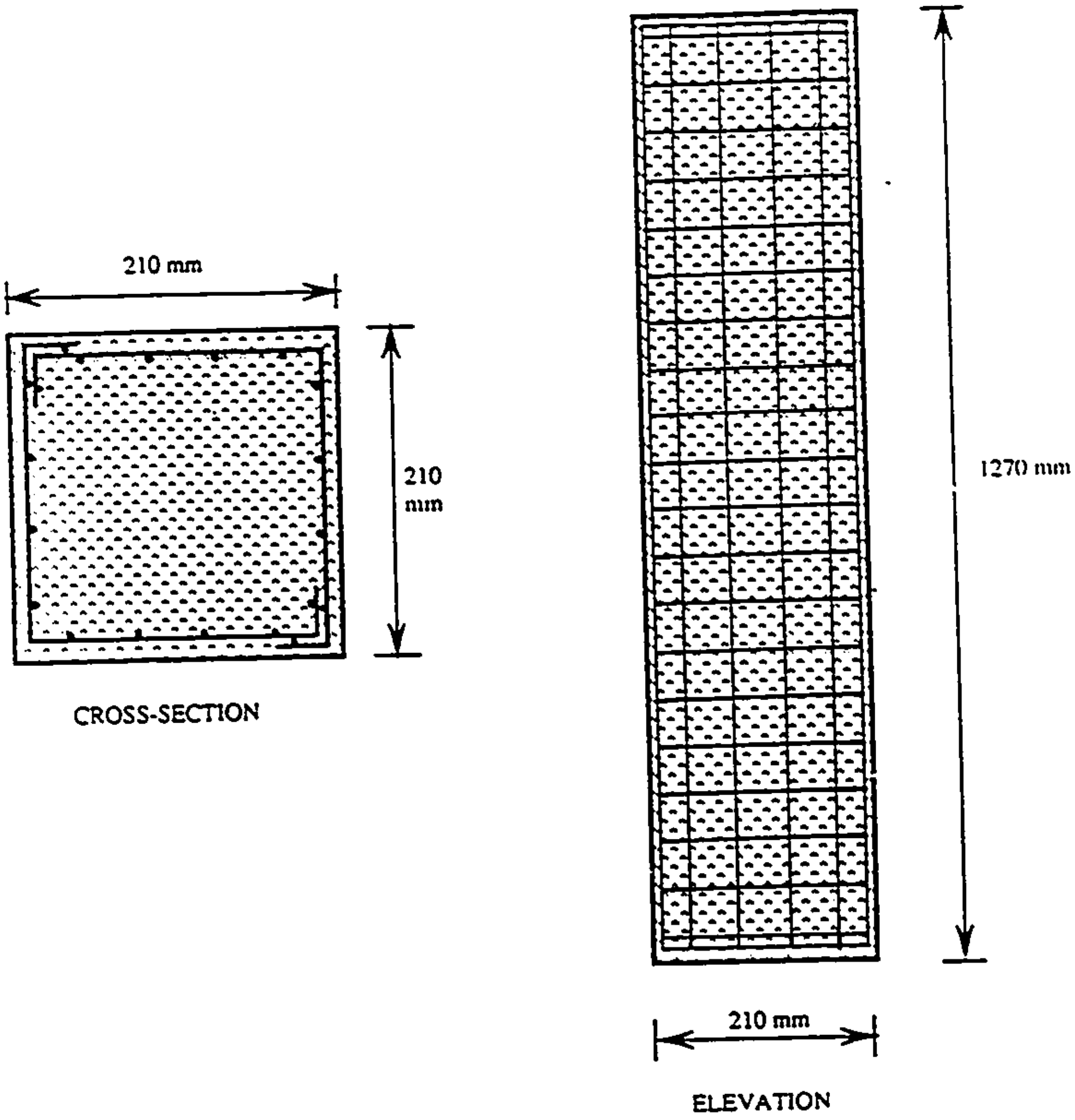
The experimental research involves tests of reinforced concrete columns. In addition, material testing is included to establish the stress-strain characteristics of concrete and W.W.F. used in the column specimens. Details of the experimental program, including material and geometric properties of column specimens, and the test procedure are discussed in this chapter.

2.2 Column Specimens

Seven square columns were designed and prepared for testing. Column dimensions were 210mm × 210mm × 1270 mm as illustrated in Fig. 2.1. Five of the columns were reinforced with W.W.F. The reinforcement used in all of the five specimens was 10-gage W.W.F. only. Column RC1 and RC2 were reinforced with perimeter W.W.F. without cross ties. The only difference between the two specimens was the way W.W.F. was tied at 90-degree overlaps. Column RC1 reinforcement was tied by means of tie wires, which was only intended to assemble the cage, and not to contribute towards keeping the W.W.F. together under lateral expansion of concrete. The companion column had W.W.F. tied together by means of mechanical connectors, which were stronger than W.W.F. itself, and intended to resist the opening action of W.W.F. under lateral expansion. Figure 2.2 shows the cross-sectional properties of Columns RC1 and RC2.

Column RC3 and RC4 were reinforced with perimeter W.W.F., connected by mechanical connectors and one or two cross ties as shown in Fig.2.2. The core size in the four specimen shown in Fig. 2.2, measured center to center of the perimeter wires, was 204 mm × 204 mm. This produced a core area to gross area ratio of 94.4%.

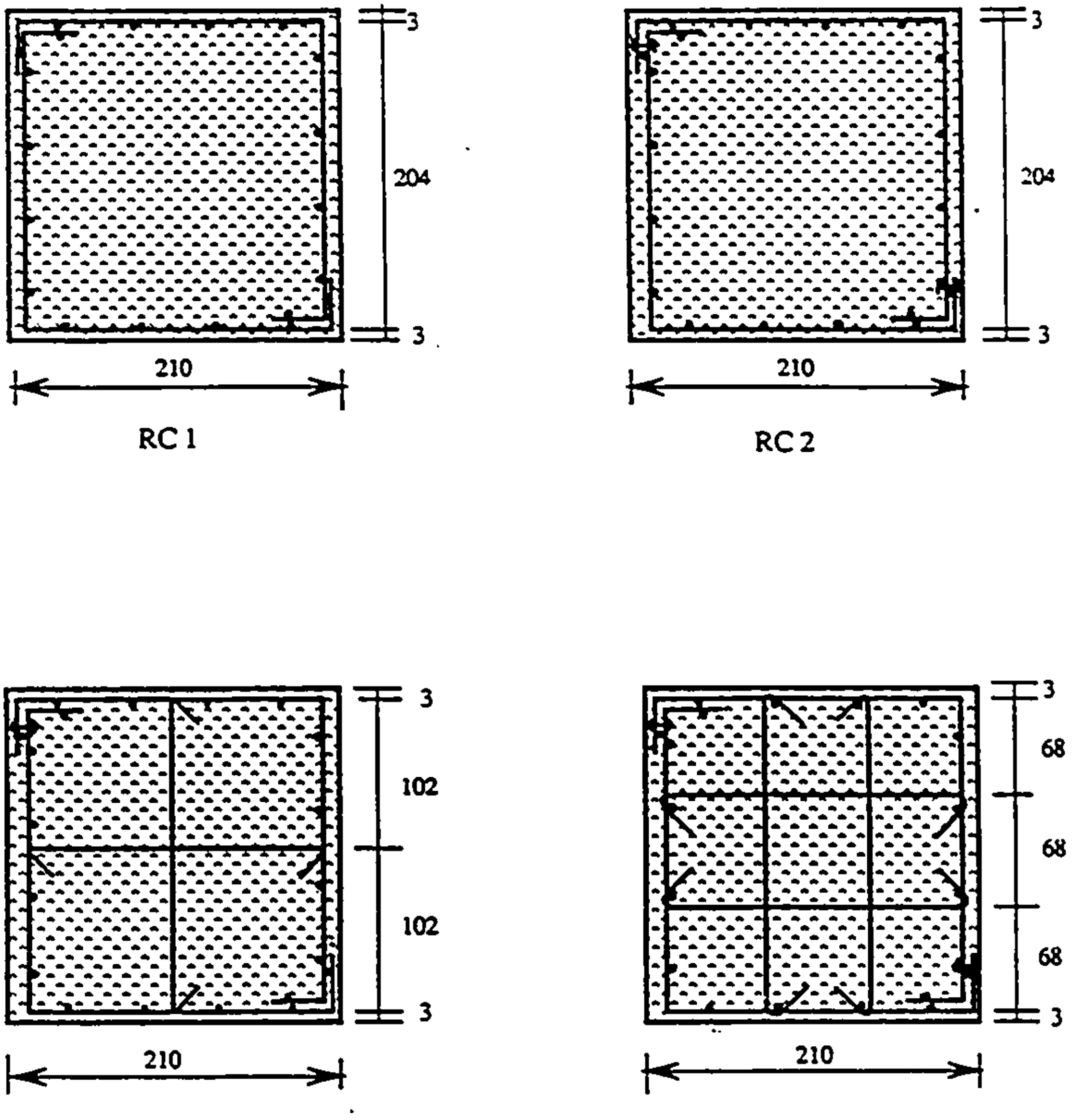
Column RC5 was reinforced with a double layer of W.W.F. connected by mechanical connectors. This led to an increase in percentage of steel in the section, and produced a slight reduction in the core area. The core dimen-



CROSS-SECTION

ELEVATION

Figure 2.1: Geometry of a Typical Test Specimen



RC 1

RC 2

RC 3

RC 4

Figure 2.2: Section Detail of Columns RC1-RC4

sion was measured to be 175 mm × 175 mm, resulting in a core to gross area ratio of 69.4%. Figure 2.3 illustrates the cross-sectional arrangement for column RC5.

Table 2.1 provides a summary of the test specimens and their properties. Aside from the specimens reinforced with W.W.F., two plain column specimens, with the same geometric properties as those of the reinforced columns, were tested under identical conditions. The purpose of these two tests was to determine the plain concrete strength, and establish the differences in plain concrete strength when obtained from a standard cylinder test and a test of specimen having the same size and geometry as the columns. The cross-sections for these specimens, labelled as PC1 and PC2 are shown in Fig. 2.3.

One of the factors that affect the concrete strength in a column member is the concrete pouring practice. Segregation of aggregates, and bleeding of concrete may result in nonuniform placement of concrete in the member. In this investigation all the specimens were cast horizontally because of the inherent simplicity associated with casting in this position.

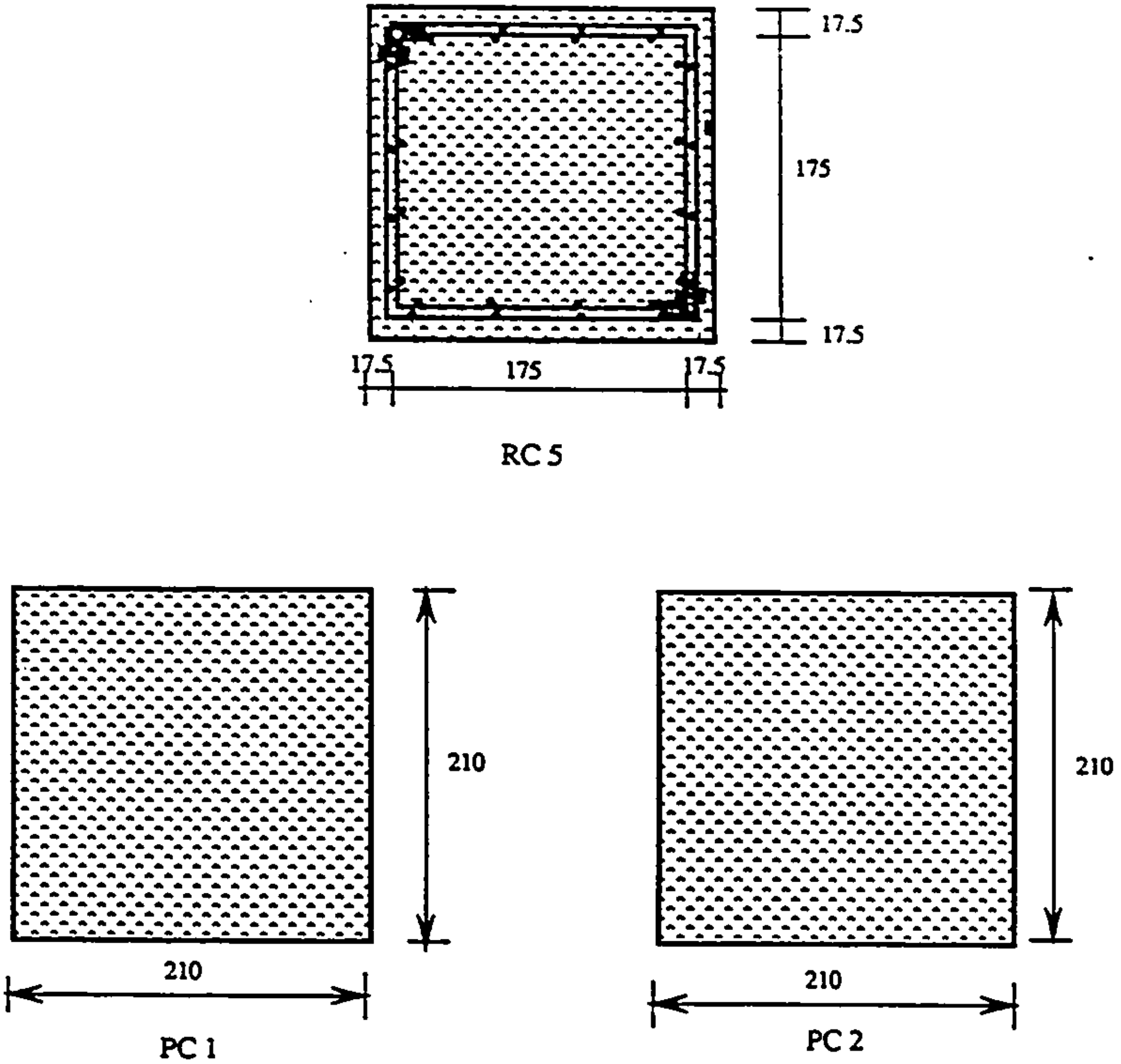


Figure 2.3: Section Detail of Columns RC5, PC1 and PC2

Table 2.1: Details of specimens

Column No.	*RC1*	*RC2*	*RC3*	*RC4*	*RC5*
Spacing(mm)	50.8×50.8	50.8×50.8	50.8×50.8	50.8×50.8	50.8×50.8
Gage	10	10	10	10	10
f'_c(MPa)	27.92	29.85	29.24	28.97	27.92
f_y(MPa)	530	530	530	530	530
ρ_v(%)	0.354	0.354	0.398	0.472	0.825
ρ_{gross}(%)	0.413	0.413	0.413	0.413	0.784
ρ_{core}(%)	0.437	0.437	0.437	0.437	1.129
Length(mm)	1270	1270	1270	1270	1270

2.3 Material Properties

2.3.1 Concrete

Ready mix concrete with a concrete slump of 89mm(3.5in) was used. The maximum size of coarse aggregate was 10mm($\frac{3}{8}in$). The average stress strain relationship of concrete at 60 days was obtained by testing 3 standard cylinders. The relationship is shown in Figure 2.4 and represents only the concrete properties at the age of 60 days.

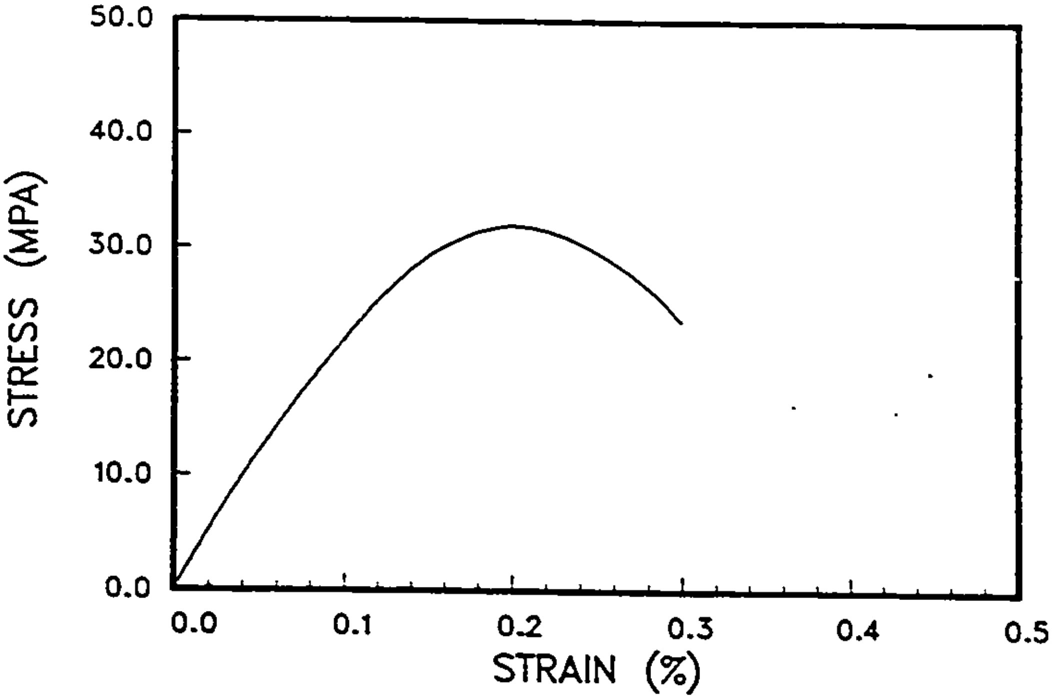


Figure 2.4: Stress-Strain Relationship of Plain Concrete

2.3.2 Welded Wire Fabric

One size of welded wire fabric was used throughout the experimental program. The wires were of gage 10, with a grid size of 50.8mm × 50.8mm. Coupon tests were performed to establish the stress-strain relationship of W.W.F. Figure 2.5 shows the stress strain relationship from tension coupon tests. Since a clear yield point could not be recorded during the test, the yield point was established by the 0.2% offset procedure. Table 2.2 contains details of W.W.F. properties.

Table 2.2: Details of W.W.F.

$Spacing(mm)$	$Gage$	$A_{gage}(mm^2)$	$f_y(MPa)$
50.8 × 50.8	10	9.10	530

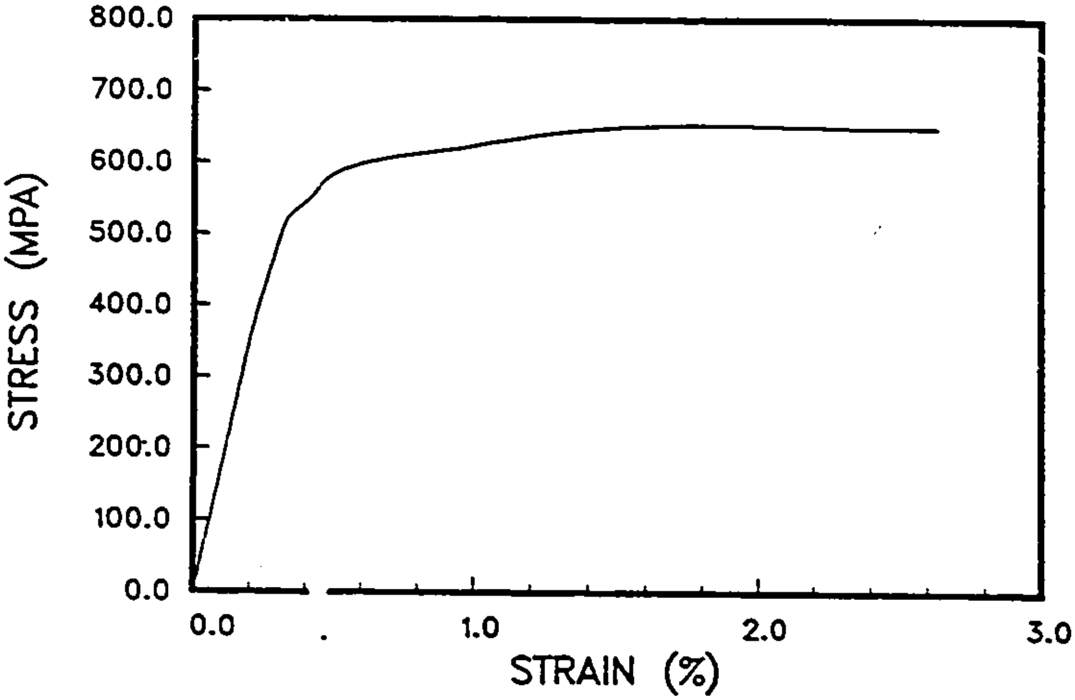


Figure 2.5: Stress-Strain Relationship of W.W.F.

2.4 Test Set-up and Procedure

The columns were tested under concentric loading, applied monotonically. A Tinius Olsen Testing Machine was used for testing, at the Structures Laboratory of the University of Ottawa. A special effort was made to minimize accidental eccentrities. Even though the specimens were carefully centered relative to machine head, some eccentricity was recorded. Therefore, trial loadings of small magnitude were initially applied, and the strains on all four faces were monitored until the eccentricity was minimized.

The load was applied slowly until failure has taken place, as indicated by a significant drop in load resistance. Each test lasted approximately 5 to 10 minutes. Figure 2.6 shows the test machine used in the experimental program.

The specimens had a constant cross-section, and hence constant capacity along the column height. To insure failure to take place in the instrumented test region, external confinement was provided at the ends. The external confinement consisted of steel brackets, covering all four column faces at the top and bottom ends.

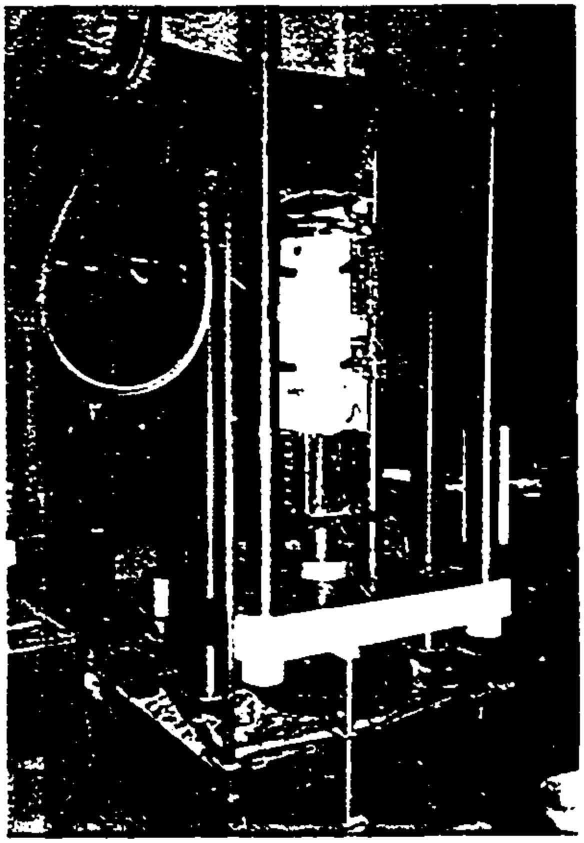


Figure 2.6: Test Set-up

2.5 Instrumentation

The columns were instrumented in the test region to measure axial strains. Linear variable differential transducers were placed on all four faces for strain measurements. The test region was the mid - height region of each column specimen. The gage length for each transducer was 300 mm. Three transducers with 150 mm stroke capacity were used for axial deformation measurements.

A load cell was placed between the bottom machine head and the column specimen to record the axial loading. This was done in addition to the machine indicator, which could not be connected to the data acquisition system. An HP 9845B Desk top Computer and an HP 3497A Data Acquisition Control Unit were used to record the data. Both the load and strain readings were recorded using the same data acquisition system. Figure 2.6 illustrates a typical instrumentation of the test region.

2.6 Test Results

The columns showed similar response under increasing concentric compression. Description of the behavior of each specimen is given in this section.

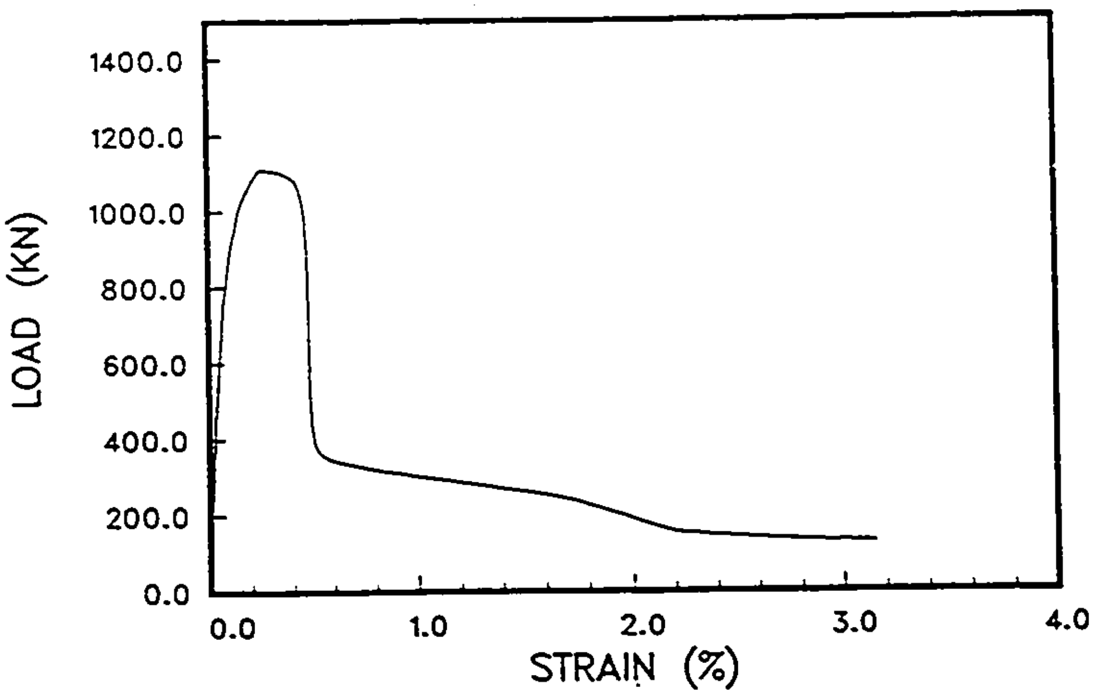


Figure 2.7: Load vs Average Strain for Column RC1

2.6.1 Column RC1

Column RC1 was designed with a single layer of W.W.F. which resulted in a longitudinal reinforcement ratio of 0.413% and volumetric reinforcement ratio of 0.354%. The cage was made of two pieces, and the pieces were tied with wire of 1.5mm diameter at the overlaps. No cross ties were provided. As the load reached its peak value the cover spalled, the wires opened, and the load became eccentric and dropped instantly. The failure was of the shear type. The amount of reinforcement provided was too small to prevent shearing of the column. Figure 2.7 illustrates the axial load versus axial strain relationship obtained during the test of column RC1.

2.6.2 Column RC2

Column RC2 was designed with a single layer of W.W.F. which resulted in a longitudinal reinforcement ratio of .413% and volumetric ratio of 0.354%. The cage was made of two pieces and tied with mechanical connectors. No cross ties were provided. This column showed a better behavior than RC1. As the load reached its peak value the cover spalled, the wires started to rupture under confining pressure and the load became eccentric. The drop in the load was more gradual than that for RC1. The failure plane was diagonal as one would expect from a column with low steel content. Figure 2.8 illustrates the axial load versus axial strain relationship obtained during the test.

2.6.3 Column RC3

Column RC3 was designed with a single layer of W.W.F. which resulted in a longitudinal reinforcement ratio of 0.413% and volumetric ratio of 0.398%. The arrangement of the cage was the same as in RC2 except for a cross tie provided in each direction. The cross ties had 135° bent at both ends and placed at every other wire level with a vertical spacing of 102mm. The effect of the cross ties was not observed and no strength enhancement over RC2 was recorded. However, this column exhibited a slightly more ductile behaviour than RC2. The nature of the column failure was the same as in the previous tests. Figure 2.9 illustrates the axial load versus axial strain

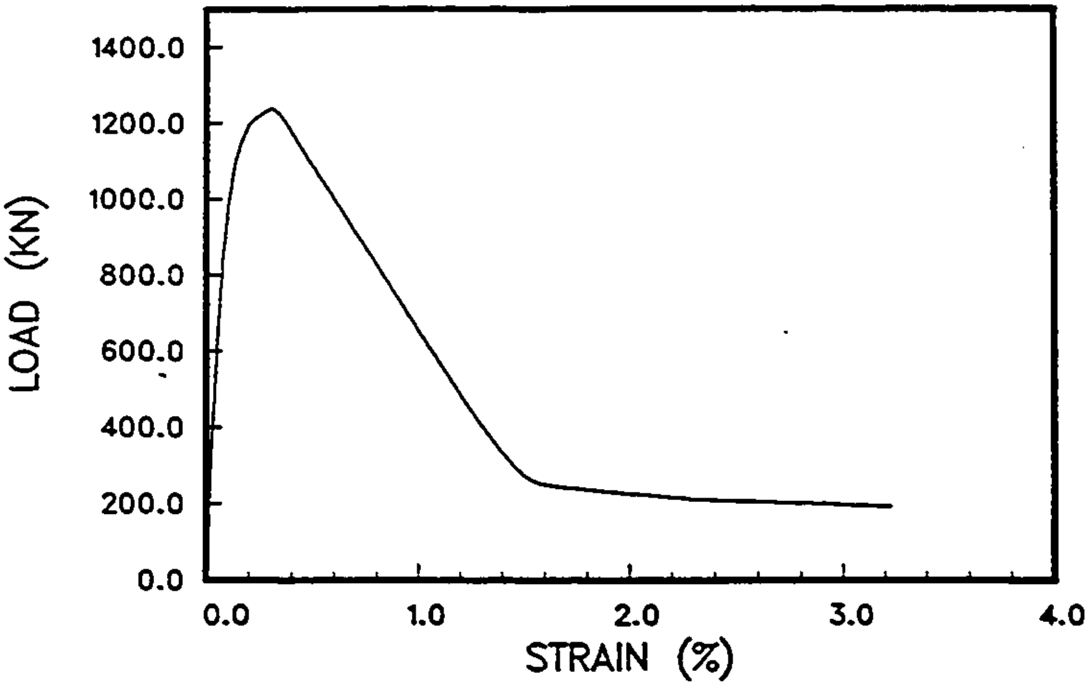


Figure 2.8: Load vs. Average Strain for Column RC2

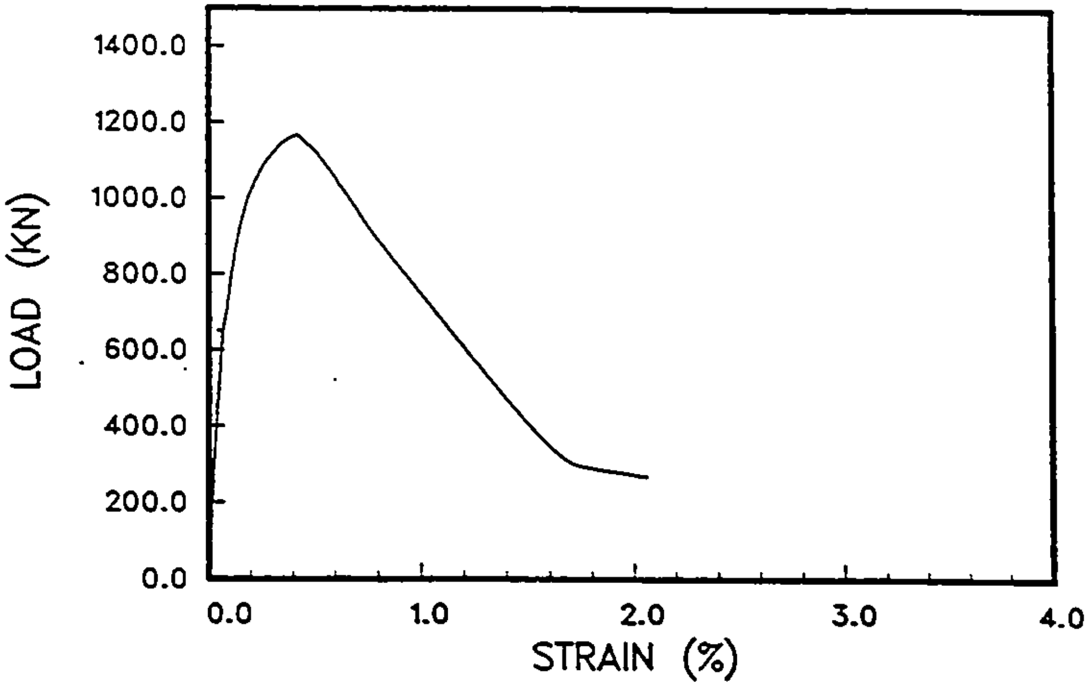


Figure 2.9: Load vs. Average Strain for Column RC3

relationship obtained during the test.

2.6.4 Column RC4

Column RC4 was designed with a single layer of W.W.F. which resulted in longitudinal and volumetric reinforcement ratio of 0.413% and 0.472%, respectively. The arrangement of the cage was the same as of RC2 except for the two cross ties provided in each direction. The cross ties had 135° hooks at both ends and placed at every other wire level resulting in a vertical spacing of 102mm. The presence of cross ties resulted in increased strength and ductility. Beyond an axial strain level of 1%, the confining

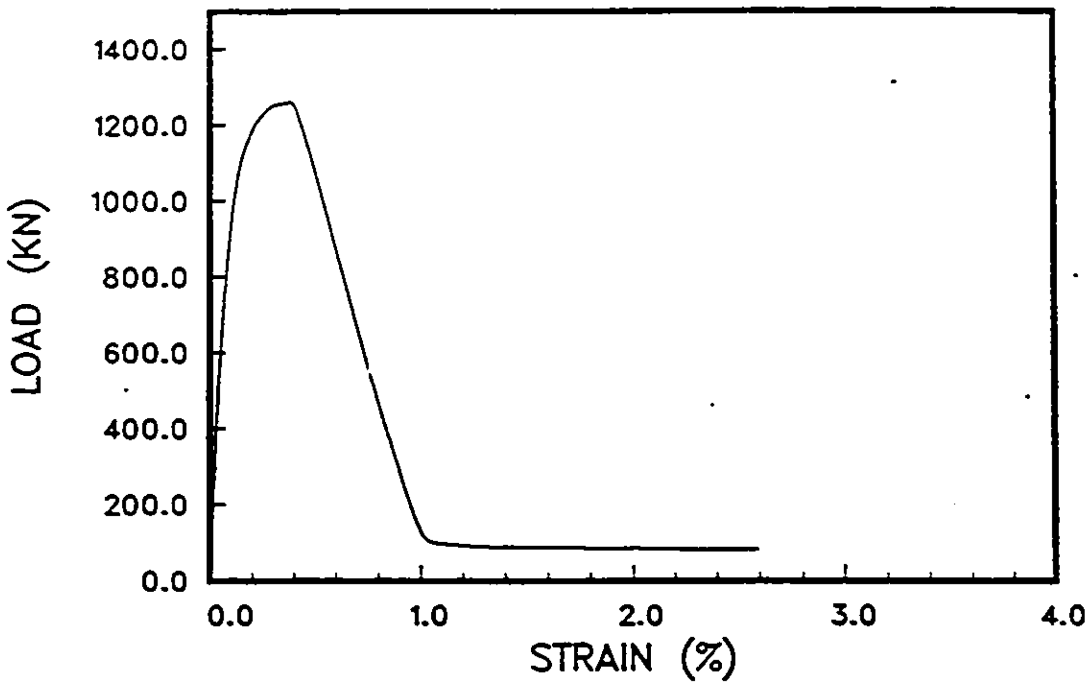


Figure 2.10: Load vs. Average Strain for Column RC4

pressure was so high that the wires ruptured and an instant drop in the load resistance was observed. Figure 2.10 illustrates the axial load versus axial strain relationship obtained during the test.

2.6.5 Column RC5

Unlike previous columns, specimen RC5 was designed to have a double layer which resulted in a longitudinal reinforcement ratio of 0.784% and a volumetric reinforcement ratio of 0.825%. The core area to gross area ratio was 69.4%. No cross ties were provided and the overlapping wires were connected with mechanical connectors. This specimen clearly demonstrated

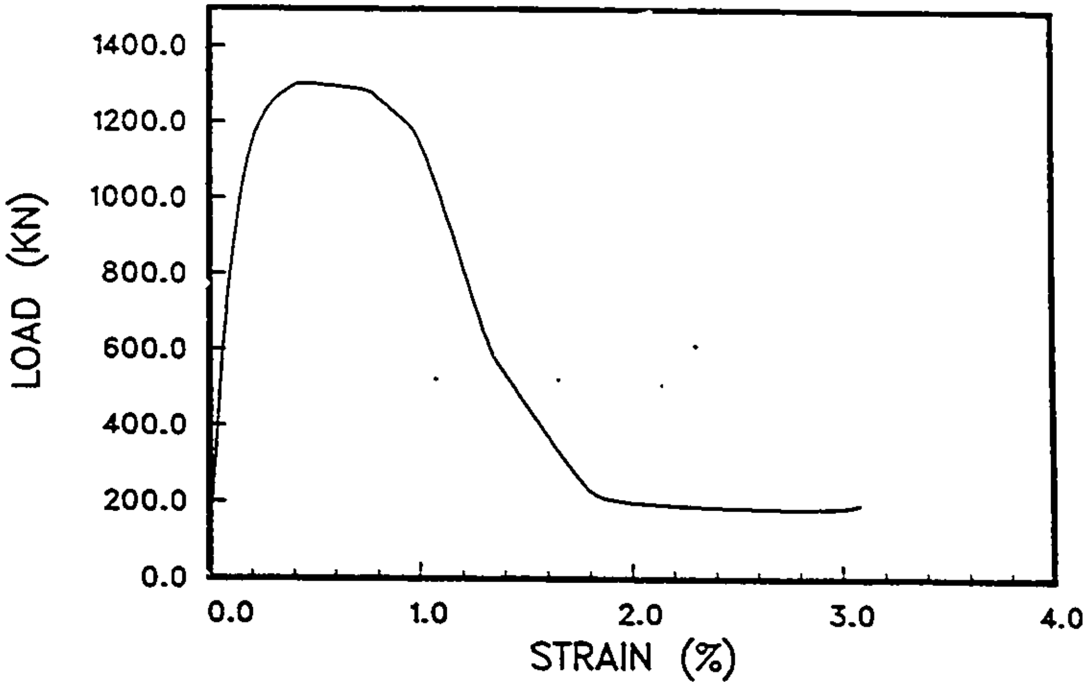


Figure 2.11: Load vs. Average Strain for Column RC5

the effectiveness of W.W.F. in confining the column. It showed an increase in strength of 17%, and improved ductility. However, as the peak load was being sustained, the wires buckled due to lack of stiffness. This led to a sudden drop in the load. Figure 2.11 illustrates the axial load versus axial strain relationship obtained during the test.

The test data for columns RC1 through RC5 were evaluated to obtain characteristics of the core concrete. This was done by subtracting the contribution of the reinforcing steel and the cover concrete to the overall load capacity of the columns. Core concrete stress-strain relationship, normalized with respect to the plain concrete strength, are then compared in Figure 2.12. This figure provides a summary of strength and ductility improve-

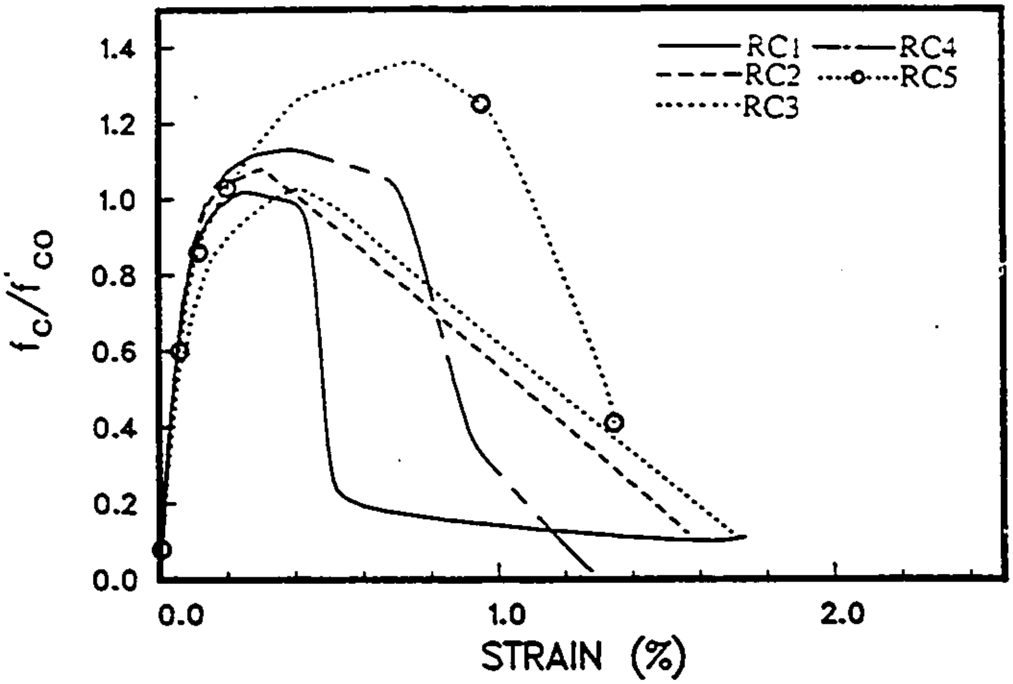


Figure 2.12: Comparison of Core Concrete Response for Columns RC1 through RC5

ments obtained in the core concrete by the use of different arrangements of W.W.F.

2.6.6 Column PC1 and PC2

These columns were plain concrete specimens with similar dimension as the others. The rationale behind testing these columns was to determine the value of α which relates the strength determined by a standard cylinder test to that of the in-place strength of concrete in the columns. The average

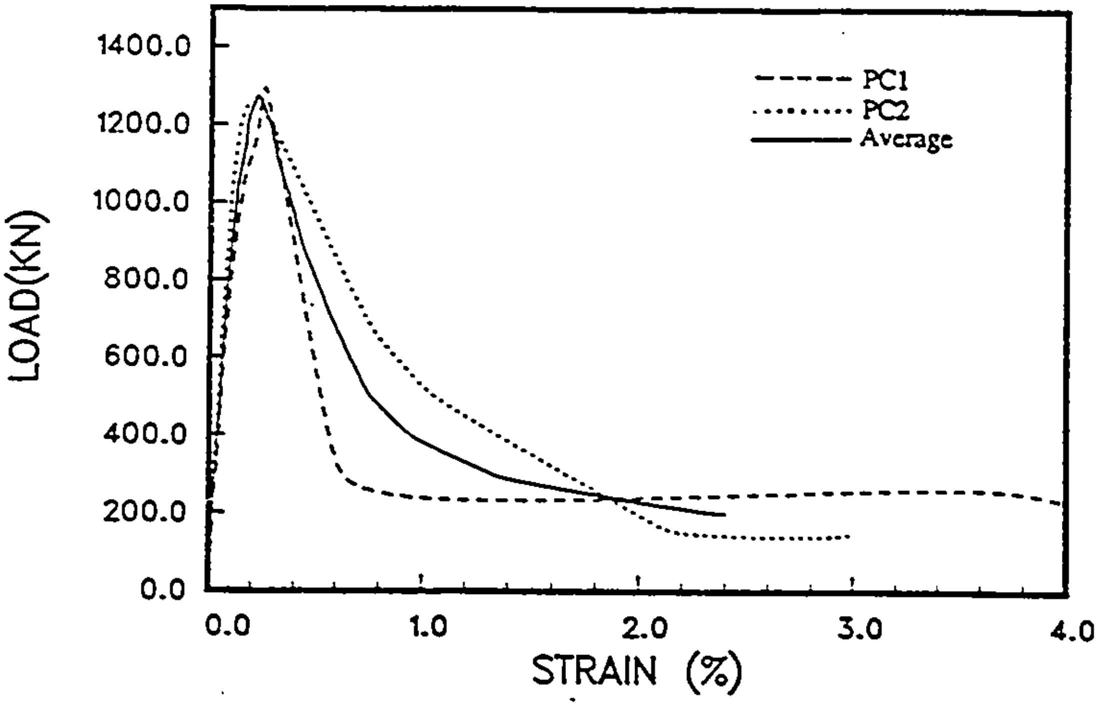


Figure 2.13: Load vs. Average Strain for Column PC1 and PC2

value of α, obtained from two tests was 0.82. This value was obtained by comparing the peak stress of the plain specimens with that of accompanying cylinder test results. Figure 2.13 illustrates the axial load versus axial strain relationship obtained during the tests.

Chapter 3

Analytical Prediction of Strength and Ductility

3.1 Description of Analytical Model

Saatcioglu and Razvi [22] at the University of Ottawa proposed an analytical model to predict stress-strain characteristics of confined concrete. This model was used in the current investigation to predict column response analytically. The proposed model is based on finding lateral confinement pressure and resulting improvement in strength and ductility. The procedure is simple and general in nature and is applicable to any square, circular, and rectangular cross-sections with tie, spiral, and/or welded wire fabric as confinement reinforcement. The lateral pressure is computed with due consideration to the amount of lateral reinforcement, spacing, and arrangement of both lateral and longitudinal reinforcement. Unlike the previous confinement models, the proposed procedure permits prediction of concrete confined by a combination of different types of reinforcement, making it possible to predict the behavior of columns reinforced with re-bars, re-bars and welded wire fabric, and welded wire fabric only.

The model was developed using the concept of lateral pressure induced by lateral ties on core concrete which was originally used by Richart et al. Accordingly, the confined concrete strength f'_{cc} is expressed as:

$$f'_{cc} = f'_{co} + k_1 f_l \qquad (3.1)$$

where f'_{co} is the unconfined concrete strength, f_l is the average lateral pressure. Unlike Richart's expression the value of k_1 is not constant. It is a function of lateral confining pressure, f_l. The following expression was suggested for k_1.

$$k_1 = 6.7 f_l^{-0.17} \qquad (3.2)$$

where f_l is in MPa. The variation of k_1 with lateral pressure f_l, is shown in Fig 3.1.

Concrete confined by closely spaced circular spirals is confined by passive pressure that can be considered to be uniform around the perimeter of the column. This lateral pressure can be computed from the hoop tension of steel. If this pressure is computed at the useful limit of the hoop steel, i.e., at yield, and taken equal to the active pressure f_l used in equation(3.1), the confined concrete strength can be determined from equation(3.1).

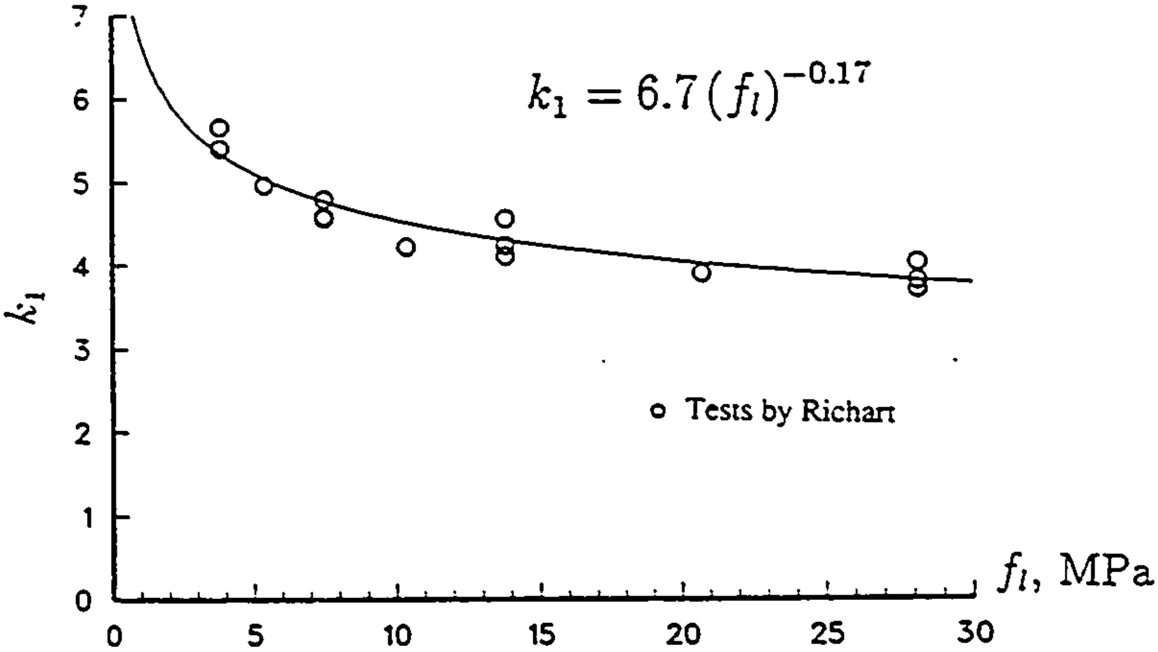


Figure 3.1: Variation of k_1 with Lateral Pressure[22]

While the uniform confining pressure can be determined for the spirally reinforced columns, it is difficult to establish the variation of stress in square columns. The variation of stress is shown qualitatively in Figure 3.2. For a given column section, as the number of cross-ties or inside hoops increase, the confinement pressure approaches to uniform pressure. The average confinement pressure is obtained by summing transverse forces, $A_s f_{yh}$ that develop at the location of each cross-tie, as well as at each leg of transverse hoop steel, and dividing by the area bound by the core dimension and tie spacing.

Utilizing the average confining pressure over estimates the actual effect of confinement in the critical region. Therefore, coefficient k_2 is introduced to find an equivalent uniform pressure which produces the same effect as that produced by a uniform fluid pressure. A large volume of experimental data was studied to establish the relationship for k_2. Based on regression analysis of experimental data, the following expression was suggested for k_2;

$$k_2 = 0.26\sqrt{(\frac{b_c}{s})(\frac{b_c}{s_l})(\frac{1}{f_l})} \tag{3.3}$$

where f_l is the average lateral pressure in MPa, b_c is the core dimension, s is the spacing of lateral ties in mm, and s_l is the spacing of laterally supported longitudinal bars in mm. Equation (3.1) in its general form becomes;

$$f'_{cc} = f'_{co} + k_1 k_2 f_l \tag{3.4}$$

where $k_2 = 1$ for spirally reinforced circular columns, and can be determined

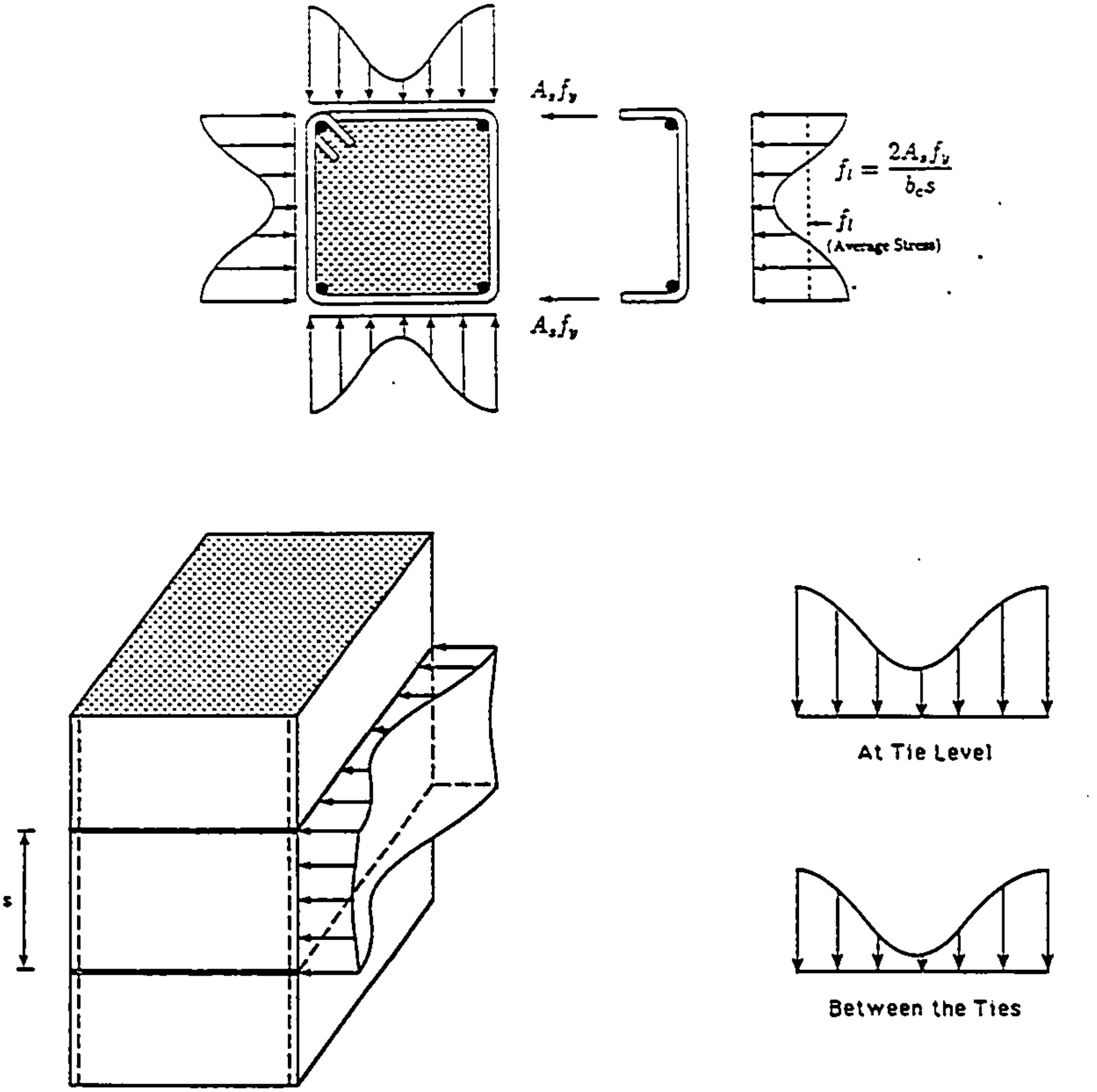


Figure 3.2: Variation of Lateral Pressure along the Perimeter and the Height of Rectangular Columns [22]

from equation(3.3) for square columns. Equation(3.4) can be rewritten in the following form:

$$f'_{cc} = (1 + K)f'_{co} \tag{3.5}$$

where

$$K = \frac{(k_1)(k_2)(f_l)}{f'_{co}} \tag{3.6}$$

Rectangular columns may be reinforced to develop different levels of confinement in two orthogonal directions. Furthermore, the effect of confining pressure along the long side of the section is more pronounced than that along the short side. However the procedure to find confinement pressure along each side remains the same as that of circular and square columns.

Figure 3.3 illustrates general features of the proposed stress-strain relationship. The ascending portion is characterized by a parabola, equation of which is given below.

$$f_c = f'_{cc}[2(\frac{\epsilon_c}{\epsilon_1}) - (\frac{\epsilon_c}{\epsilon_1})^2]^{\frac{1}{1+K}} \tag{3.7}$$

$$where \qquad \epsilon_1 = \epsilon_{o1}(1 + 5K) \tag{3.8}$$

where ϵ_{o1} is the strain corresponding to the peak stress of the plain concrete.

The strain corresponding to 85% of the peak stress on the descending portion can be obtained from the following expression;

$$\epsilon_{85} = 260\frac{f_l}{f_y}\epsilon_1 + \epsilon_{085} \tag{3.9}$$

where ϵ_{085} is the strain corresponding to 85% of the peak stress of plain concrete. If this data is not available, 0.0038 suggested by Hognestad can be used. Equation 3.9 is based on a regression analysis of test data.

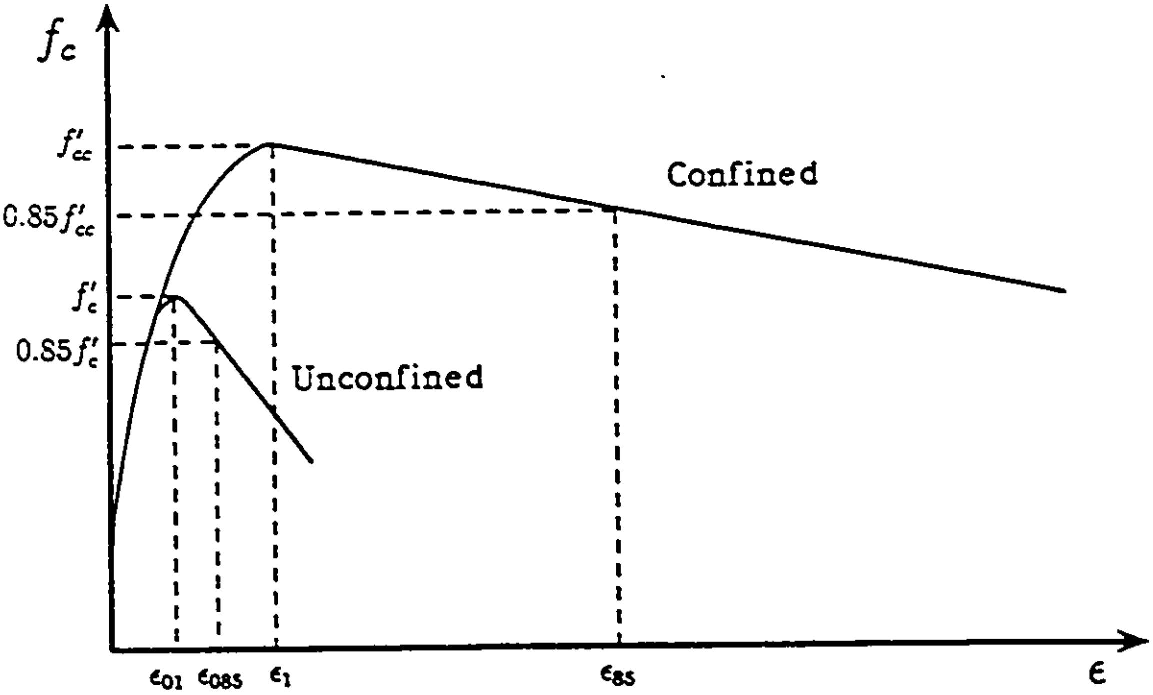


Figure 3.3: Stress-Strain Relationship of Confined Concrete proposed by Saatcioglu and Razvi[22]

3.2 Comparisons of Analytical and Experimental Results

Comparisons of test results with analytical prediction is made in this section to verify the analytical model. The comparisons include columns reinforced with welded wire fabric, re-bars and combinations of re-bars and welded wire fabric. The test results against which the model is compared are those obtained from the experiments conducted by the author, those conducted by Razvi[18] at the University of Ottawa, and a large volume of test results conducted by other researchers. The agreement between the model and the experimental results is excellent. Unlike the models proposed by previous researchers, the analytical model used in this investigation can predict the behaviour of confined concrete in a wide range of confinement parameters.

3.2.1 Columns Reinforced with Welded Wire Fabric only

In this section the results reported in Chapter 2 are compared with the analytical model. The comparisons are shown in Table 3.1 and Figures 3.4 through 3.8. The model predicts the strength of columns reasonably well in all cases.

The ductility prediction of RC1, is not good. This may be explained by the

Table 3.1: Comparison of Analytical vs. Experimental Results for Columns reinforced with W.W.F.

								f'_{cc}		
Col.	ρ_v (%)	d_b (*mm*)	s/b_c	s_l/b_c	k_1	k_2	f'_{co} (*MPa*)	*exp.* (*MPA*)	*anal.* (*MPa*)	*anal/exp*
RC1	0.354	3.40	0.247	0.967	7.51	0.55	22.89	23.45	26.74	1.14
RC2	0.354	3.40	0.247	0.967	7.51	0.55	24.48	26.36	28.30	1.07
RC3	0.398	3.40	0.247	0.483	7.18	0.42	23.98	24.66	27.74	1.13
RC4	0.472	3.40	0.247	0.322	6.91	0.43	23.75	26.90	28.45	1.06
RC5	0.825	3.40	0.288	0.288	7.07	0.33	22.89	28.62	28.06	0.98

difference in reinforcement arrangement for which the model was developed and that used in the column specimen. The analytical model is applicable to cases where the opening of the transverse reinforcement under lateral pressure is prevented either by a 135° hook or mechanical connectors at overlapping legs. Column RC1 had 90° overlapping wires tied only by 1.5 mm diameter wires. Opening and buckling of wires led to a sudden drop in strength as indicated by the response of RC1. All other comparisons show good to excellent agreement between the analytical and experimental results.

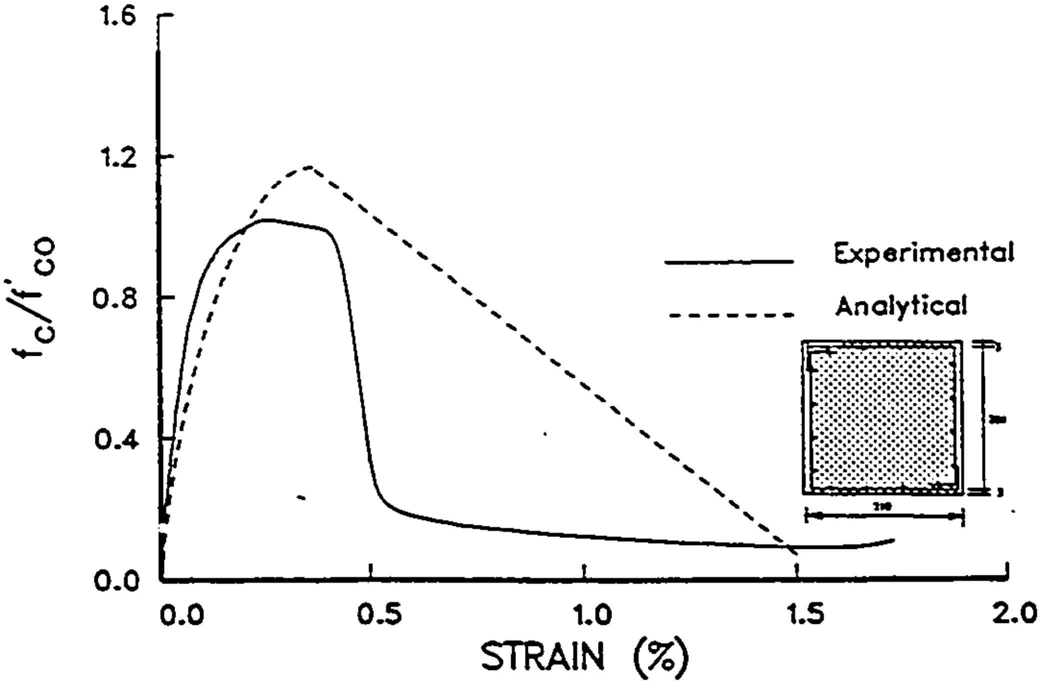


Figure 3.4: Comparison of Analytical and Experimental Results for Column RC1

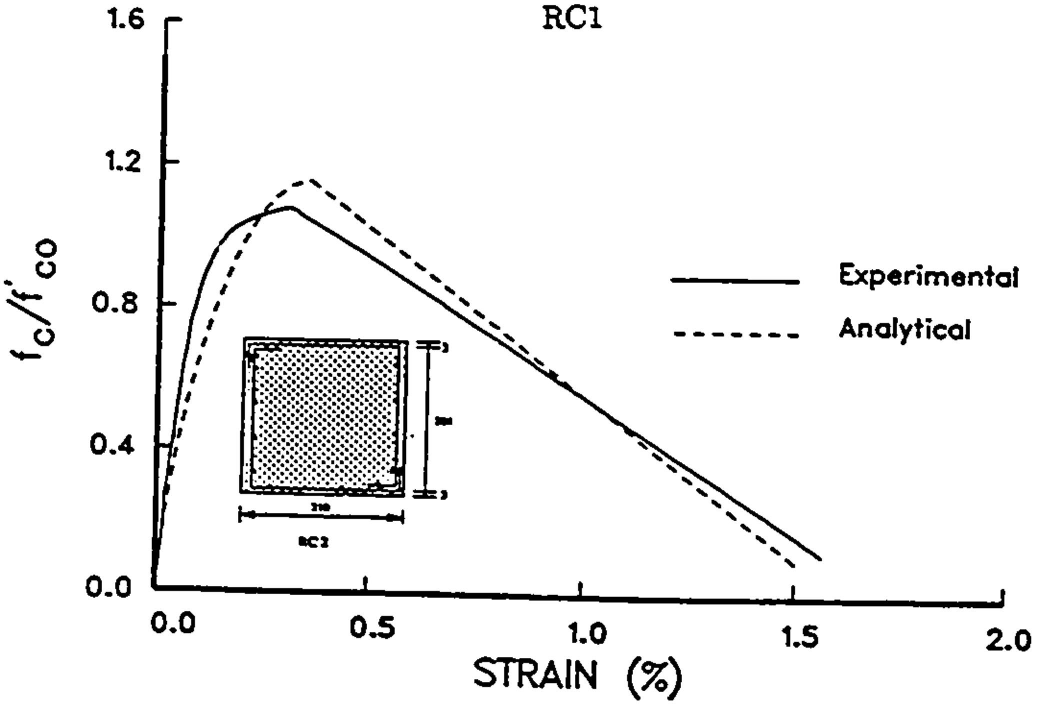


Figure 3.5: Comparison of Analytical and Experimental Results for Column RC2

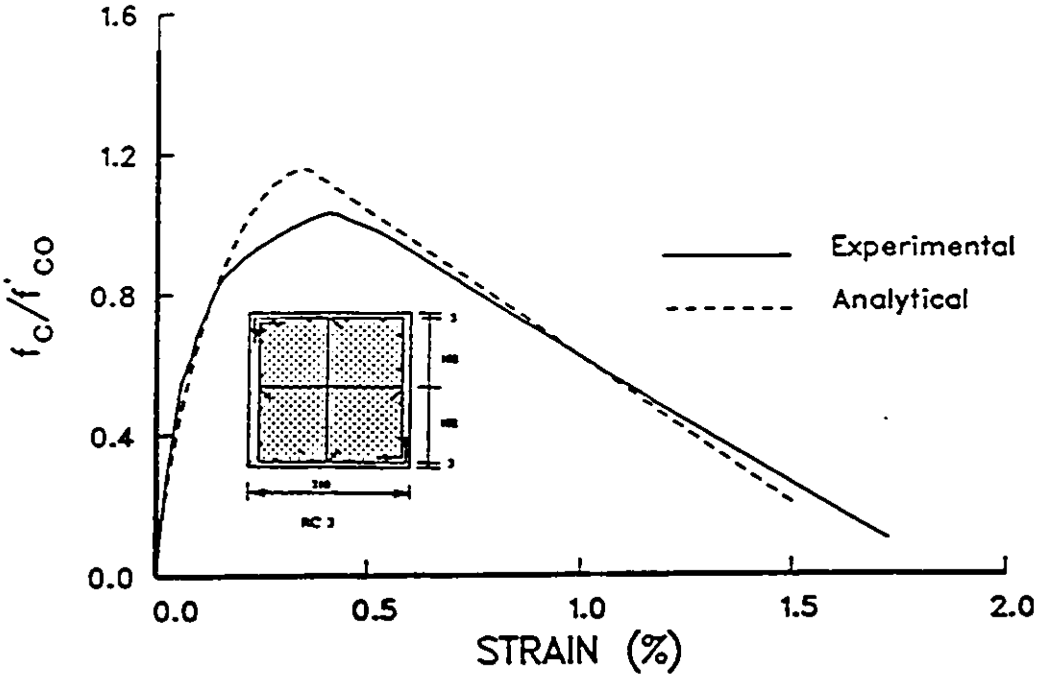


Figure 3.6: Comparison of Analytical and Experimental Results for Column RC3

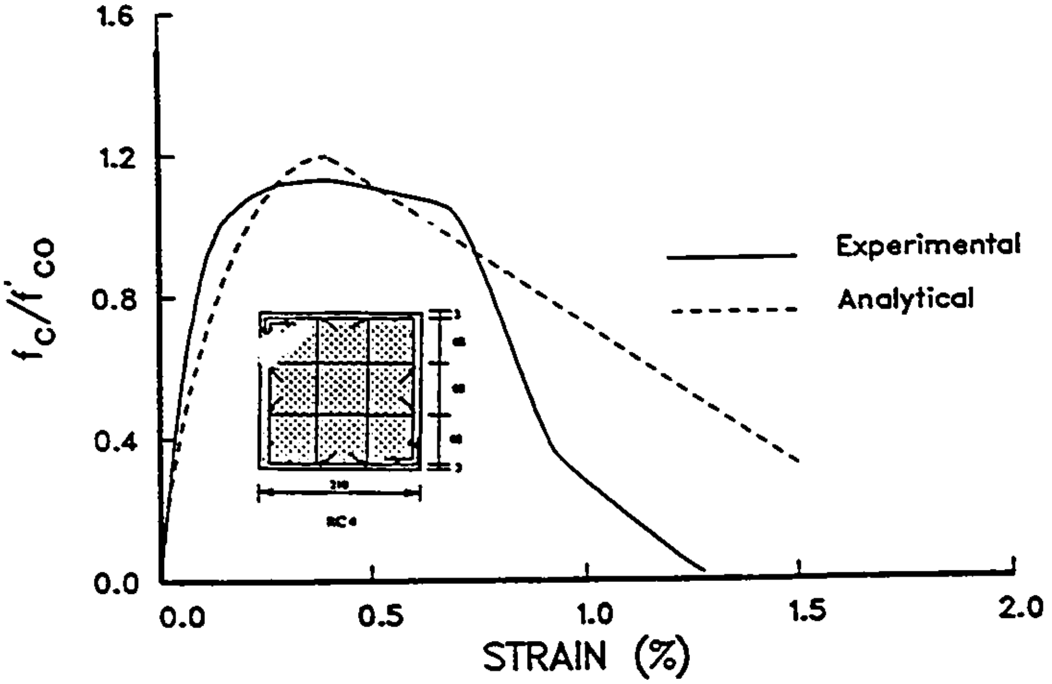


Figure 3.7: Comparison of Analytical and Experimental Results for Column RC4

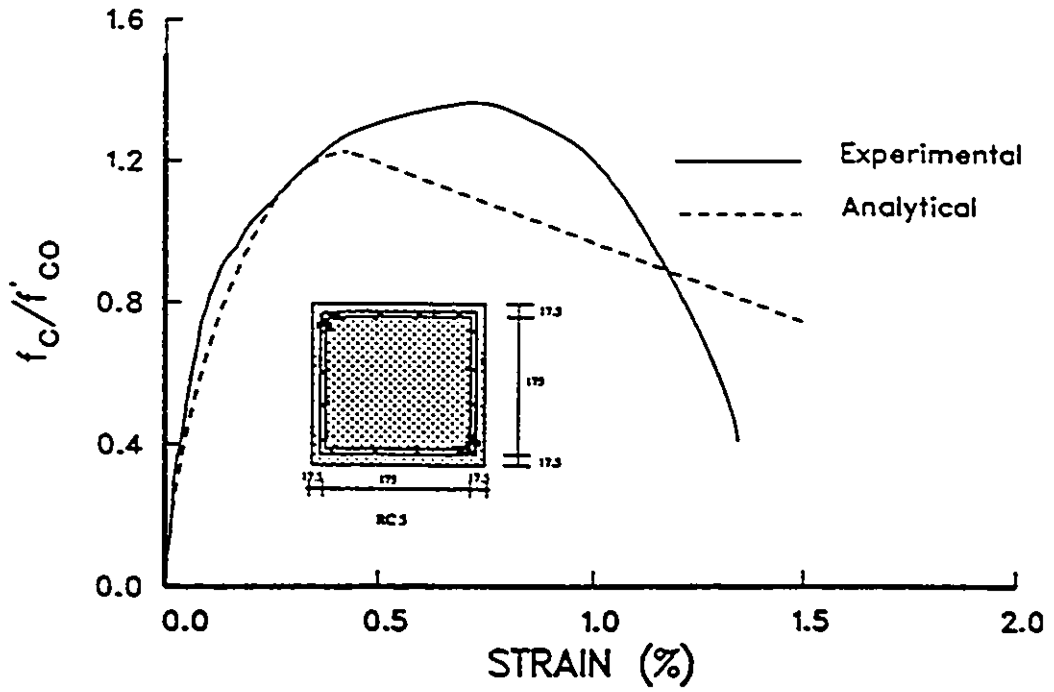


Figure 3.8: Comparison of Analytical and Experimental Results for Column RC5

3.2.2 Columns Reinforced with W.W.F. and Rebars

Three columns reinforced with W.W.F. and rebars, tested by Razvi[2] at the University of Ottawa, are compared with the analytical model. The comparison is tabulated in Table 3.2 and shown in Figures 3.9 through 3.11. The model predicts the strength and ductility of the columns very well. This shows the versatility of the model in predicting the behaviour of columns reinforced with a combination of different types of reinforcement.

Table 3.2: Comparison of Analytical and Experimental Results for Columns with W.W.F. & Hoops

								f'_{cc}		
Col.		d_b (mm)	s/b_c	s_l/b_c	k_2	k_1	f'_{co} (MPa)	exp (MPa)	$anal$ (MPa)	$anal/exp$
	Hoop	6.53	0.49	0.84	0.25					
12(a)						6.38	29	40.9	37.5	0.92
	WWF	1.90	0.21	1.0	1.0					
hline	Hoop	6.53	0.49	0.84	0.25					
13(a)						6.42	29	38.3	37.3	0.97
	WWF	1.45	0.11	1.0	1.0					
	Hoop	6.53	0.47	0.81	0.27					
14(b)						6.42	29	36.5	36.9	1.01
	WWF	1.45	0.11	1.0	1.0					

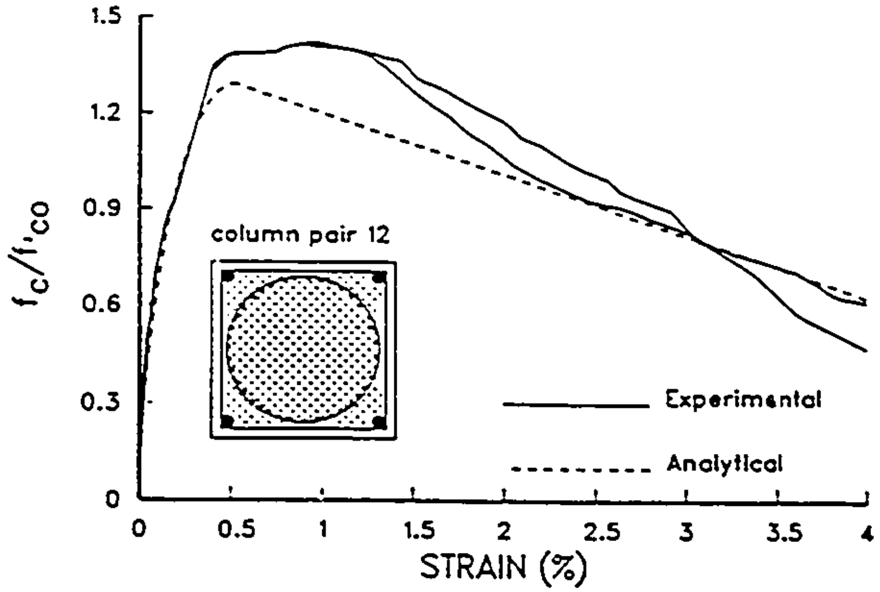


Figure 3.9: Comparison of Analytical and Experimental Results for Column 12 [22]

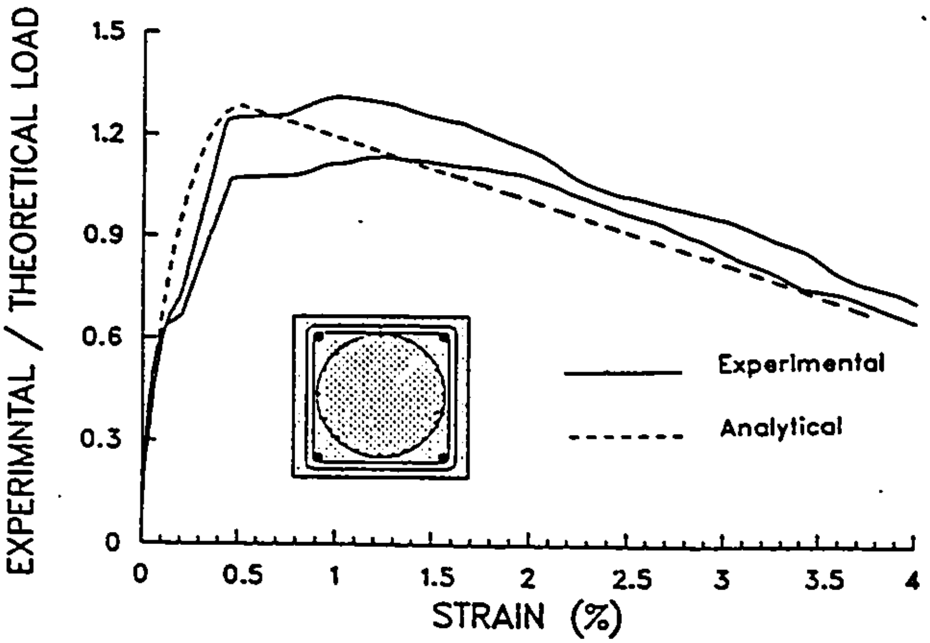


Figure 3.10: Comparison of Analytical and Experimental Results for Column 13 [22]

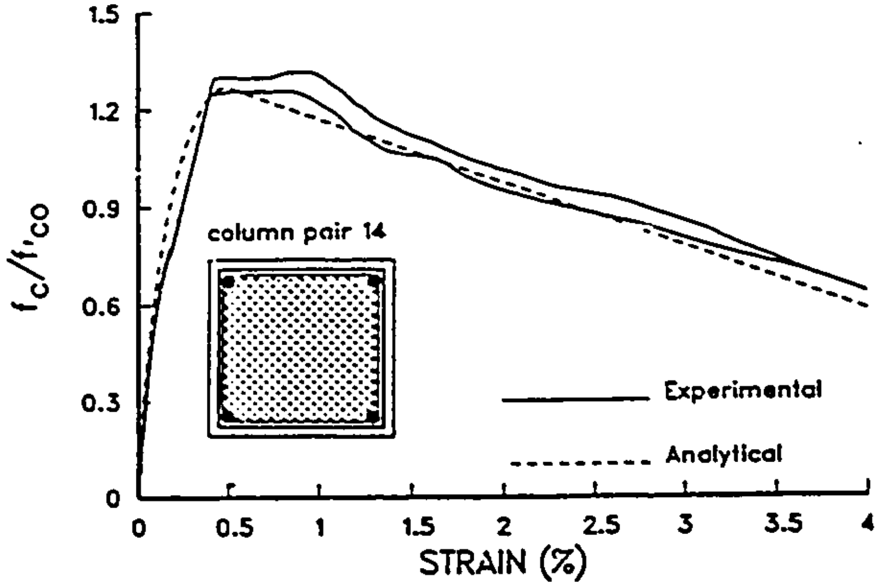


Figure 3.11: Comparison of Analytical and Experimental Results for Column 14 [22]

3.2.3 Columns Reinforced with Rebars

Six pairs of columns reinforced with rebars and lateral ties, tested by Razvi at the University of Ottawa are compared with the analytical model. The columns include well confined and poorly confined concrete. Comparisons show excellent agreement of the model with the test results. The comparisons are tabulated in Table 3.3 and are shown in Figures 3.12 to 3.17.

Table 3.3: Comparison of Analytical vs. Experimental Results for Columns Reinforced with Longitudinal Bars and Lateral Ties

							f'_{cc}		
Col.	d_b (mm)	s/b_c	s_l/b_c	k_1	k_2	f'_{co} (MPa)	exp (MPa)	$anal$ (MPa)	$anal/exp$
3(a)	6.53	0.24	0.84	6.42	0.26	32.0	40.0	40.2	1.01
4(a)	6.53	0.49	0.84	7.23	0.26	32.0	33.3	36.6	1.10
6(a)	6.53	0.25	0.87	6.44	0.24	39.0	51.9	47.1	0.91
7(a)	6.53	0.51	0.87	7.25	0.24	39.0	43.3	43.6	1.01
15(a)	6.53	0.49	0.84	7.23	0.26	29.0	35.1	33.6	0.96
16(a)	6.53	0.24	0.84	6.42	0.26	29.0	38.0	37.2	0.98

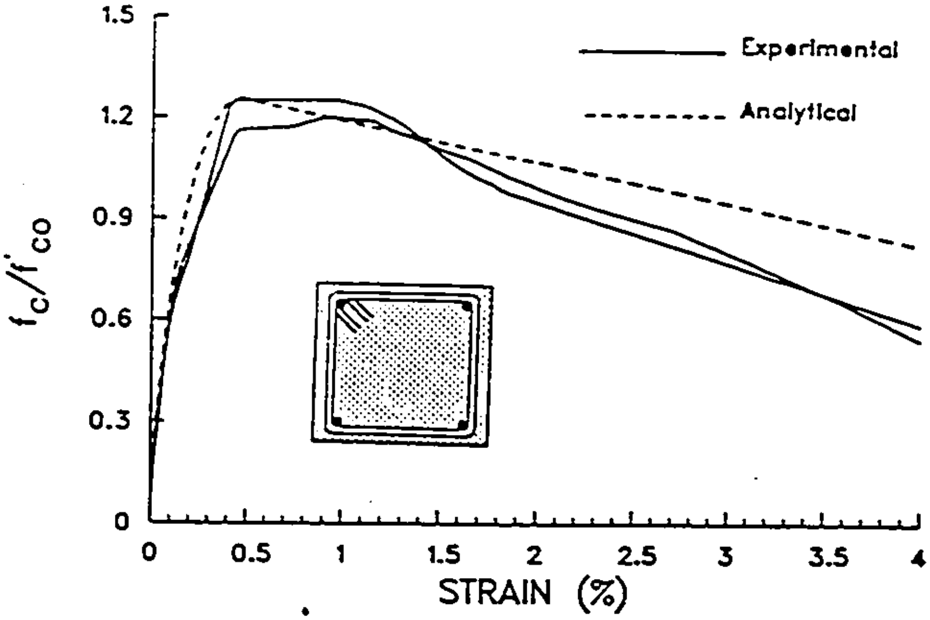


Figure 3.12: Comparison of Analytical and Experimental Results for Column 3 [22]

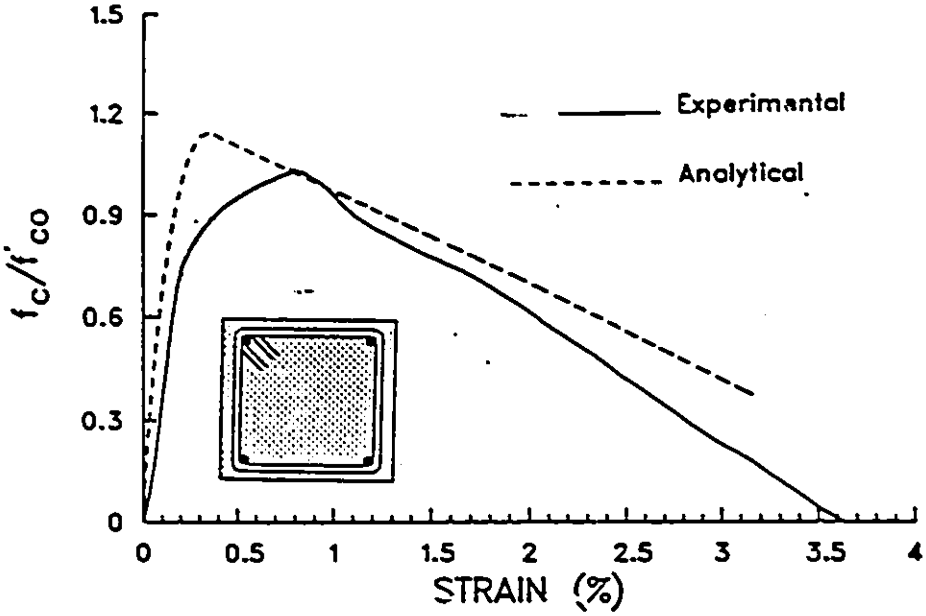


Figure 3.13: Comparison of Analytical and Experimental Results for Column 4(a) [22]

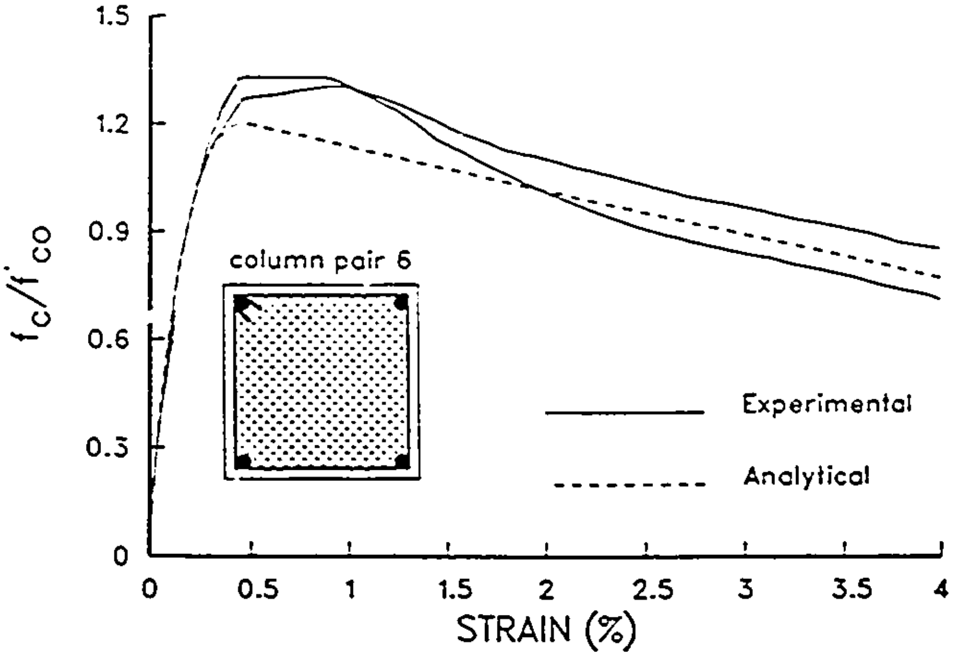


Figure 3.14: Comparison of Analytical and Experimental Results for Column 6 [22]

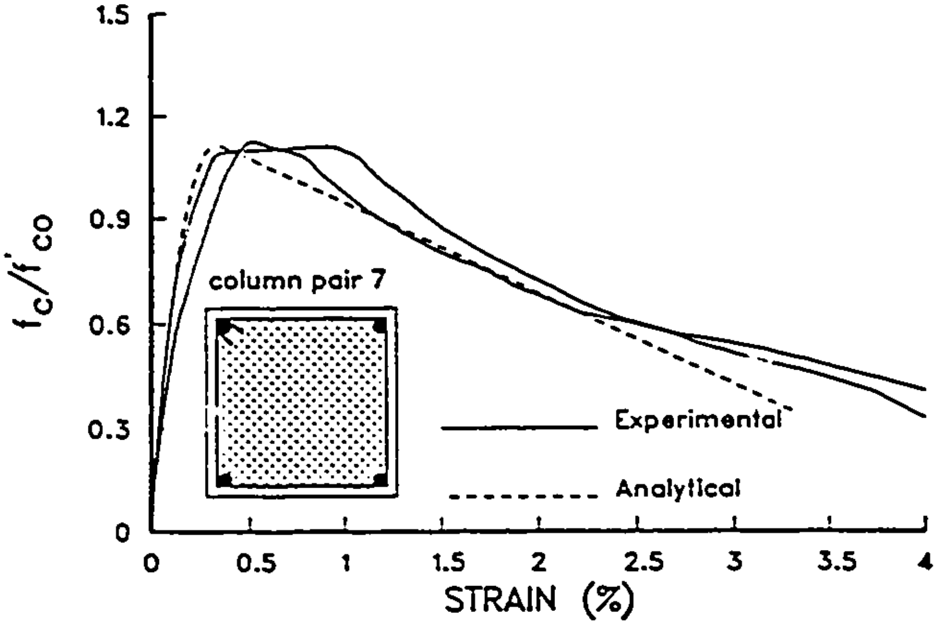


Figure 3.15: Comparison of Analytical and Experimental Results for Column 7 [22]

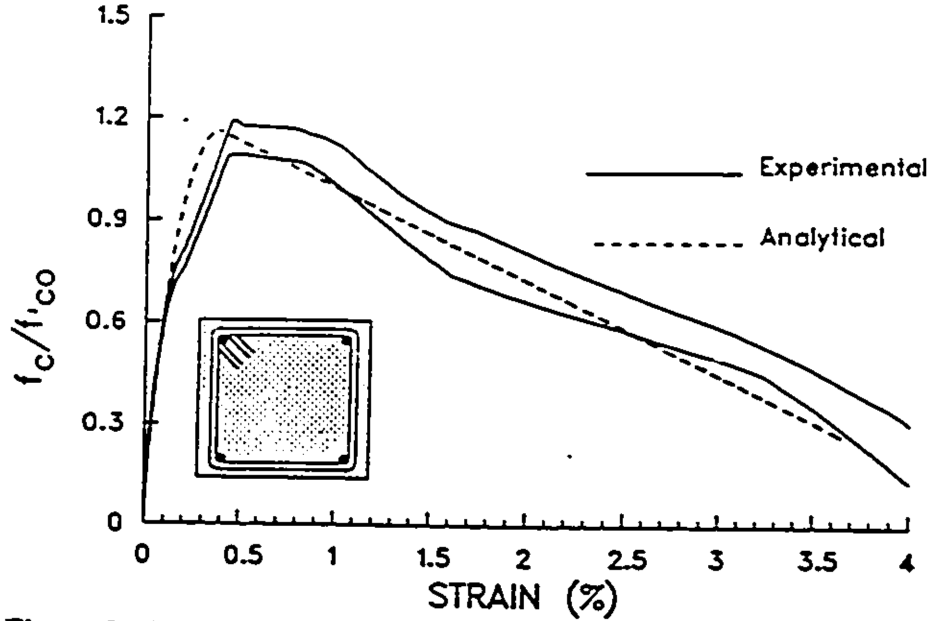


Figure 3.16: Comparison of Analytical and Experimental Results for Column 15 [22]

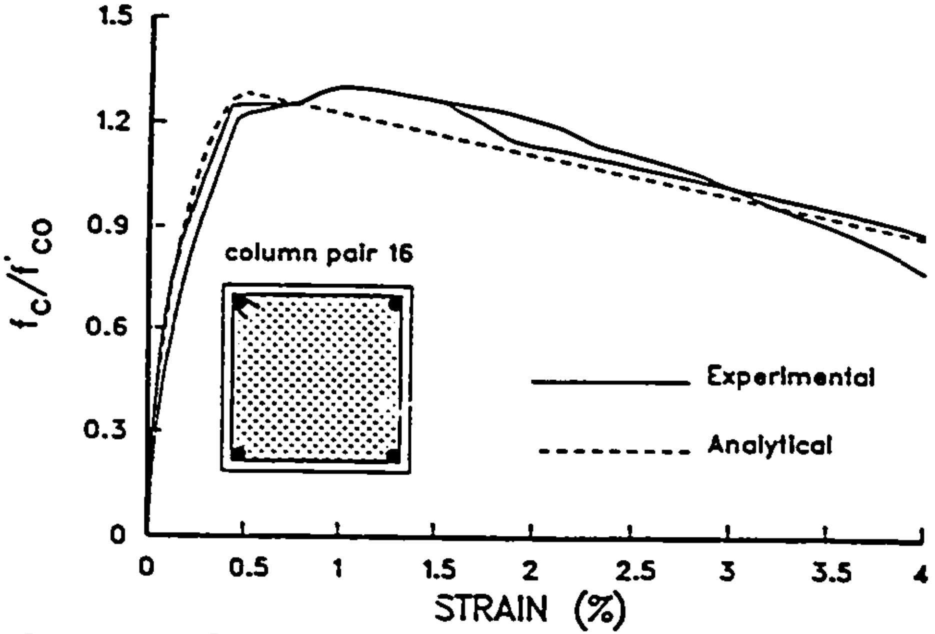


Figure 3.17: Comparison of Analytical and Experimental Results for Column 16 [22]

Chapter 4

Parametric Investigation

4.1 Introduction

The previous research discussed in Chapter 1 has identified important parameters of concrete confinement. It is clear that the volumetric ratio of confinement reinforcement, and spacing of lateral as well as laterally supported longitudinal reinforcement play important roles. The same parameters are also applicable to columns confined with W.W.F. While W.W.F. generally represents the low end of these parameters, reinforcement cage consisting of lateral and longitudinal reinforcing bars represents the high end of the same range of parameters. A parametric study was conducted in this part of the investigation to assess the relative significance of these parameters on column confinement. The results indicate the significance of each parameter and help determine if W.W.F. can be a reliable alternative to reinforcing bars either in the standard sizes used currently or in sizes permitting higher percentage of steel content.

More than 140 column sections with different reinforcement arrangements were investigated using the analytical model developed by Saatcioglu and Razvi[22]. Sectional properties of the columns considered, as well as the results are presented at the end of this chapter in Tables 4.1 to 4.17. The reinforcement arrangements considered are shown in Figs. 4.1 to 4.3. The arrangements include columns reinforced with W.W.F., re-bars, and combination of re-bars and W.W.F. The results are presented terms of strength enhancement coefficient K and ductility ratio $\frac{\epsilon_{85}}{.004}$.

4.2 Effect of Reinforcement Arrangement

Reinforcement arrangement of a column section reflects the distribution of longitudinal and transverse reinforcements and has a very significant effect on column ductility and strength. Longitudinal bars, if well spread around the perimeter of the core, and laterally supported by a corner of a hoop or a cross tie, produce uniform confinement pressure at the tie level. This results in improved confinement.

Three types of reinforcement arrangement were studied. They consisted of perimeter reinforcement with and without cross ties. The results are tabulated in Tables 4.9 and 4.10. Variations of strength enhancement and ductility ratio with reinforcement arrangement are shown in Figures 4.4 to 4.7. The results indicate that columns with well distributed longitudinal reinforcement where the longitudinal bars are laterally supported by ties and or cross-ties, show improved ductility and strength. The spacing of laterally supported longitudinal reinforcement is expressed in terms of s_l/d ratio. At a volumetric ratio of ρ_v=1.0%, the reduction of 33% in s_l/d ratio results in an increase of 12% and 6% in strength and ductility ratio, respectively. However, when the confinement pressure is not adequate due to lack of sufficient volumetric ratio, or tie spacing, reduction in s_l/d ratio alone does not result in significant improvements in ductility and strength. If the volumetric ratio is reduced by one half, the corresponding increases in strength and ductility associated with a 33% reduction in s_l/d are 2% and 0%.

4.3 Effect of Tie Spacing

The spacing of transverse steel is an important parameter of confinement. Theoretically, the clear distance between the ties should be zero for uniform confinement throughout the length of the member. Closer spacing of ties produces almost uniform lateral pressure along the member length and results in improved confinement. To investigate the effect of tie spacing on confinement, four tie spacings were considered for each group of volumetric ratio and configuration. This was done both for columns reinforced with

W.W.F. and those with re-bars. The results are shown in Table 4.11 and Table 4.12. Variation of strength enhancement and ductility ratio with tie spacing are shown in Figs. 4.8 to 4.11.

The results obtained show that reduction in the tie spacing improves confinement pressure. This results improved strength and ductility. The results indicate that a 33% reduction in s/d ratio result in an increase in strength and ductility ratio of 15% and 6%, respectively for ρ_v=1.0%. However, when the confinement pressure is not adequate due to lack of sufficient volumetric ratio and or well distributed laterally supported longitudinal reinforcement, some reduction in tie spacing does not result in significant improvement. The same reduction of 33% in s/d ratio show only 10% and 3% improvement in strength and ductility when the volumetric ratio is reduced by one half.

4.4 Effect of Volumetric Ratio of Lateral Ties

The ratio of the volume of lateral reinforcement to the volume of core concrete plays an important role on the magnitude of lateral confining pressure. High transverse steel content means high confining pressure and increased strength and ductility of confined concrete. The increase in confinement pressure associated with an increase in volumetric ratio is also closely related to the yield strength of steel, which marks the useful limit of confining pressure.

Volumetric ratios of 0.5 %, 1.0 %, 2.0 % and 3.0 % were considered to investigate the effect of volumetric ratio on concrete confinement. This was done for columns reinforced with re-bars only, and W.W.F. only. The results are tabulated in Tables 4.13 and 4.14. Variation of strength enhancement and ductility with volumetric ratio are shown in Figures 4.12 to 4.15. The results show a considerable increase in strength and ductility due to the increase in the volumetric ratio. An increase in volumetric ratio of 50% resulted in an increase of 17.4 % and 59 % in strength and ductility ratio, respectively. However, the improvement obtained is not proportional to the volumetric ratio, showing lower rate of improvement in the high volumetric ratio region. The volumetric ratio was found to play the major role on ductility of core concrete.

4.5 Effect of Combined Use of W.W.F. with Re-bars

The effect of using W.W.F. in combination with re-bars was investigated by analyzing twenty four column cross-sections. The volumetric ratio of lateral ties were maintained at 1.0%. Columns with and without cross-ties were considered. The volumetric ratio of W.W.F. was 1.0% and 0.5%. The arrangement of W.W.F. was of three types: without cross ties, with one cross tie in each direction, and with two cross ties in each direction. Total volumetric ratio of a column was either 1.5% or 2%. Two lateral tie spacings of 150mm and 100mm were considered. W.W.F. with four different grid sizes were used. The results are tabulated in Table 4.15 and plotted in Figures 4.16 to 4.17.

They indicate superior concrete behavior when W.W.F. is used in combination with re-bars. As a result of using W.W.F. with re-bars the increase in strength and ductility over those reinforced with re-bars alone was as high as 170% and 75%, respectively. Sections with d/2 tie spacing and no cross ties but combined with W.W.F. gave better results than those with d/6 tie spacing and 2 pairs of cross ties. The results were comparable to a column with ρ_v=3.0% and tie spacing of d/4 with two cross ties. The improvement over those reinforced with W.W.F. only results from the relatively high stiffness of longitudinal bars that do not permit early buckling. The buckling was observed while testing the column reported in chapter two. Hence, the use of W.W.F. with re-bars is recommended over the use of W.W.F. alone.

The relationship between lateral tie spacing and laterally supported longitudinal reinforcement spacing for various levels of strength enhancement and ductility ratio is given in Tables 4.16 and 4.17

Table 4.1: Properties of Columns with W.W.F.

Col. no.	h mm	d mm	d_b mm	f_{co} MPa	ρ %	f_y MPa	ρ_v %	Sect. type[1]	$\frac{s}{d}$	$\frac{s_1}{d}$	K	$\frac{\epsilon_{85}}{.004}$
1	350	318	6.91	25	0.37	400	0.5	1	0.31	0.92	.14	1.50
2	350	319	5.64	25	0.37	400	0.5	2	0.31	0.46	.19	1.58
3	350	320	4.89	25	0.37	400	0.5	3	0.31	0.31	.22	1.63
4	350	319	5.98	25	0.37	400	0.5	4	0.24	0.92	.16	1.53
5	350	320	4.89	25	0.37	400	0.5	5	0.23	0.46	.21	1.62
6	350	321	4.23	25	0.37	400	0.5	6	0.23	0.31	.25	1.68
7	350	320	4.89	25	0.37	400	0.5	7	0.16	0.92	.19	1.58
8	350	321	3.99	25	0.37	400	0.5	8	0.16	0.46	.25	1.68
9	350	322	3.45	25	0.37	400	0.5	9	0.16	0.31	.27	1.71
10	350	322	3.45	25	0.37	400	0.5	10	0.08	0.92	.25	1.68
11	350	322	2.82	25	0.37	400	0.5	11	0.08	0.46	.27	1.71
12	350	323	2.44	25	0.37	400	0.5	12	0.08	0.31	.27	1.71
13	350	315	9.77	25	0.74	400	1.0	1	0.32	0.89	.19	2.22
14	350	317	7.98	25	0.74	400	1.0	2	0.32	0.45	.27	2.47
15	350	318	6.91	25	0.74	400	1.0	3	0.31	0.30	.30	2.56
16	350	317	8.46	25	0.74	400	1.0	4	0.24	0.89	.21	2.29
17	350	318	6.91	25	0.74	400	1.0	5	0.24	0.45	.28	2.52
18	350	319	5.98	25	0.74	400	1.0	6	0.24	0.30	.33	2.68
19	350	318	6.91	25	0.74	400	1.0	7	0.16	0.90	.25	2.42
20	350	319	5.64	25	0.74	400	1.0	8	0.16	0.45	.33	2.68

[1] For section type refer to Figs 4.1 & 4.2

Table 4.2: Properties of Columns with W.W.F.(Cont'd)

Col. *no.*	h mm	d mm	d_b mm	f'_{co} MPa	ρ %	f_y MPa	ρ_v %	*Sect.* *type*	$\frac{S}{d}$	$\frac{S_l}{d}$	K	$\frac{\epsilon_{85}}{.004}$
21	350	320	4.89	25	0.74	400	1.0	9	0.16	0.30	.39	2.88
22	350	320	4.89	25	0.74	400	1.0	10	0.08	0.91	.33	2.68
23	350	321	3.99	25	0.74	400	1.0	11	0.08	0.45	.44	3.04
24	350	322	3.45	25	0.74	400	1.0	12	0.08	0.30	.48	3.15
25	350	311	13.82	25	1.47	400	2.0	1	0.32	0.88	.27	3.91
26	350	314	11.28	25	1.47	400	2.0	2	0.32	0.44	.34	4.45
27	350	315	9.77	25	1.47	400	2.0	3	0.32	0.30	.40	4.84
28	350	313	11.97	25	1.47	400	2.0	4	0.24	0.88	.29	4.11
29	350	315	9.77	25	1.47	400	2.0	5	0.24	0.44	.38	4.72
30	350	317	8.46	25	1.47	400	2.0	6	0.24	0.30	.45	5.16
31	350	315	9.77	25	1.47	400	2.0	7	0.16	0.89	.34	4.44
32	350	317	7.98	25	1.47	400	2.0	8	0.16	0.45	.45	5.56
33	350	318	6.91	25	1.47	400	2.0	9	0.16	0.30	.53	5.68
34	350	318	6.91	25	1.47	400	2.0	10	0.08	0.90	.45	5.15
35	350	319	5.64	25	1.47	400	2.0	11	0.08	0.45	.59	6.10
36	350	320	4.89	25	1.47	400	2.0	12	0.08	0.30	.70	6.79
37	350	308	16.93	25	2.20	400	3.0	1	0.33	0.86	.31	5.88
38	350	311	13.82	25	2.20	400	3.0	2	0.32	0.44	.40	6.84
39	350	313	11.97	25	2.20	400	3.0	3	0.32	0.29	.48	7.53
40	350	310	14.66	25	2.20	400	3.0	4	0.24	0.87	.34	6.23

Table 4.3: Properties of Columns with W.W.F.(Cont'd)

Col. no.	h mm	d mm	d_b mm	f_{co}' MPa	ρ %	f_y MPa	ρ_v %	Sect. type	$\frac{s}{d}$	$\frac{s_l}{d}$	K'	$\frac{\epsilon_{85}}{.004}$
41	350	313	11.97	25	2.20	400	3.0	5	0.24	0.44	.45	7.31
42	350	315	10.36	25	2.20	400	3.0	6	0.24	0.30	.53	8.09
43	350	313	11.97	25	2.20	400	3.0	7	0.16	0.88	.40	6.81
44	350	315	9.77	25	2.20	400	3.0	8	0.16	0.44	.53	8.08
45	350	317	8.46	25	2.20	400	3.0	9	0.16	0.30	.63	9.01
46	350	317	8.46	25	2.20	400	3.0	10	0.08	0.89	.53	8.06
47	350	318	6.91	25	2.20	400	3.0	11	0.08	0.45	.70	9.75
48	350	319	5.98	25	2.20	400	3.0	12	0.08	0.30	.83	10.99

Table 4.4: Properties of Columns with Re-bar

$Col.$ $no.$	h mm	d mm	d_b mm	f'_{co} MPa	ρ %	f_y MPa	ρ_v %	$Sect.$ $type$[2]	s/d	s_l/d	K	$\frac{\epsilon_{cc}}{.004}$
1	350	311	8.61	25	1.63	400	0.5	1	0.48	0.88	.13	1.43
2	350	317	7.03	25	1.96	400	0.5	2	0.47	0.45	.16	1.54
3	350	317	6.09	25	1.96	400	0.5	3	0.47	0.30	.19	1.58
4	350	312	7.03	25	1.63	400	0.5	1	0.32	0.88	.15	1.52
5	350	318	5.74	25	1.96	400	0.5	2	0.32	0.45	.19	1.59
6	350	319	4.97	25	1.96	400	0.5	3	0.31	0.30	.23	1.65
7	350	312	6.09	25	1.63	400	0.5	1	0.24	0.88	.17	1.55
8	350	318	5.74	25	1.96	400	0.5	2	0.24	0.45	.22	1.63
9	350	318	4.31	25	1.96	400	0.5	3	0.24	0.30	.26	1.70
10	350	313	4.97	25	1.63	400	0.5	1	0.16	0.88	.20	1.60
11	350	318	4.06	25	1.96	400	0.5	2	0.16	0.45	.26	1.70
12	350	319	3.52	25	1.96	400	0.5	3	0.16	0.30	.27	1.71
13	350	309	12.18	25	1.63	400	1.0	1	0.49	0.87	.17	2.15
14	350	315	9.95	25	1.96	400	1.0	2	0.48	0.45	.22	2.32
15	350	316	8.61	25	1.96	400	1.0	3	0.48	0.30	.26	2.44
16	350	310	9.95	25	1.63	400	1.0	1	0.32	0.87	.20	2.24
17	350	316	8.12	25	1.96	400	1.0	2	0.32	0.45	.26	2.44
18	350	317	7.03	25	1.96	400	1.0	3	0.32	0.31	.30	2.58
19	350	311	8.61	25	1.63	400	1.0	1	0.16	0.88	.22	2.32
20	350	317	7.03	25	1.96	400	1.0	2	0.16	0.45	.29	2.55

[2] For section type refer to Fig 4.3

Table 4.5: Properties of Columns with Re-bar (Cont'd)

Col. no.	h mm	d mm	d_b mm	f'_{co} MPa	ρ %	f_y MPa	ρ_v %	Sect. type	$\frac{s}{d}$	$\frac{s_1}{d}$	K	$\frac{epsilon_{s2}}{.004}$
21	350	317	6.09	25	1.96	400	1.0	3	0.16	0.31	.34	2.70
22	350	312	7.03	25	1.63	400	1.0	1	0.08	0.88	.26	2.46
23	350	318	5.74	25	1.96	400	1.0	2	0.08	0.45	.35	2.72
24	350	318	4.97	25	1.96	400	1.0	3	0.08	0.32	.40	2.90
25	350	307	17.23	25	1.63	400	2.0	1	0.49	0.86	.23	3.72
26	350	313	14.07	25	1.96	400	2.0	2	0.48	0.44	.30	4.17
27	350	314	12.18	25	1.96	400	2.0	3	0.48	0.30	.34	4.49
28	350	308	14.07	25	1.63	400	2.0	1	0.32	0.87	.27	3.98
29	350	315	11.49	25	1.96	400	2.0	2	0.32	0.44	.35	4.51
30	350	315	9.95	25	1.96	400	2.0	3	0.32	0.31	.41	4.88
31	350	309	12.18	25	1.63	400	2.0	1	0.24	0.87	.30	4.19
32	350	315	9.95	25	1.96	400	2.0	2	0.24	0.45	.39	4.79
33	350	316	8.61	25	1.96	400	2.0	3	0.24	0.31	.45	5.20
34	350	310	9.95	25	1.63	400	2.0	1	0.16	0.87	.35	4.54
35	350	316	8.12	25	1.96	400	2.0	2	0.16	0.45	.46	5.25
36	350	317	7.03	25	1.96	400	2.0	3	0.16	0.31	.54	5.73
37	350	305	21.10	25	1.63	400	3.0	1	0.49	0.85	.27	5.52
38	350	312	17.23	25	1.96	400	3.0	2	0.48	0.44	.35	6.32
39	350	313	14.92	25	1.96	400	3.0	3	0.48	0.29	.41	6.93
40	350	307	17.23	25	1.63	400	3.0	1	0.33	0.86	.32	5.98

Table 4.6: Properties of Columns with Re-bar (Cont'd)

$Col.$ no.	h mm	d mm	d_b mm	f'_{co} MPa	ρ %	f_y MPa	ρ_v %	$Sect.$ $type$	s/d	s_l/d	K	$\frac{\epsilon_{85}}{.004}$
41	350	314	14.07	25	1.96	400	3.0	2	0.32	0.44	.41	6.93
42	350	317	12.18	25	1.96	400	3.0	3	0.32	0.31	.47	7.53
43	350	308	14.92	25	1.63	400	3.0	1	0.24	0.86	.36	6.36
44	350	314	12.18	25	1.96	400	3.0	2	0.24	0.44	.46	7.42
45	350	317	10.55	25	1.96	400	3.0	3	0.24	0.31	.53	8.10
46	350	309	12.18	25	1.63	400	3.0	1	0.16	0.87	.42	6.98
47	350	315	9.95	25	1.96	400	3.0	2	0.16	0.45	.55	8.23
48	350	318	8.61	25	1.96	400	3.0	3	0.16	0.32	.63	9.03

Table 4.7: Section Properties of Columns Reinforced with Rebars and W.W.F.

#	h	d_b		f'_{co}	f_y	ρ_v		s/d		s_l/d		K	$\frac{\varepsilon_{cc}}{.004}$
		tie	*wwf*			*tie*	*wwf*	*tie*	*wwf*	*tie*	*wwf*		
	mm	*mm*	*mm*	*MPc*	*MPa*	(%)	(%)						
1	350	12.21	3.4	25	400	1.0	0.5	.48	.08	.92	.94	.41	4.05
2	350	12.21	2.8	25	400	1.0	0.5	.48	.08	.92	.47	.43	4.16
3	350	12.21	2.4	25	400	1.0	0.5	.48	.08	.92	.31	.43	4.16
4	350	12.21	4.8	25	400	1.0	1.0	.48	.08	.92	.93	.49	5.54
5	350	12.21	4.0	25	400	1.0	1.0	.48	.08	.92	.47	.59	6.22
6	350	12.21	3.4	25	400	1.0	1.0	.48	.08	.92	.31	.62	6.46
7	350	9.97	3.4	25	400	1.0	0.5	.47	.08	.46	.92	.41	4.05
8	350	9.97	2.8	25	400	1.0	0.5	.47	.08	.46	.46	.43	4.13
9	350	9.97	2.4	25	400	1.0	0.5	.47	.08	.46	.31	.43	4.13
10	350	9.97	4.9	25	400	1.0	1.0	.47	.08	.46	.91	.49	5.58
11	350	9.97	4.0	25	400	1.0	1.0	.47	.08	.48	.46	.59	6.27
12	350	9.97	3.5	25	400	1.0	1.0	.47	.08	.46	.31	.62	6.52
13	350	9.97	3.4	25	400	1.0	0.5	.32	.08	.90	.93	.46	4.28
14	350	9.97	2.8	25	400	1.0	0.5	.32	.08	.90	.47	.48	4.38
15	350	9.97	2.4	25	400	1.0	0.5	.32	.08	.90	.31	.48	4.38
16	350	9.97	4.9	25	400	1.0	1.0	.32	.08	.90	.92	.53	5.83
17	350	9.97	4.0	25	400	1.0	1.0	.32	.08	.90	.46	.63	6.50
18	350	9.97	3.5	25	400	1.0	1.0	.32	.08	.90	.31	.66	6.74

Table 4.8: Section Properties of Columns Reinforced with Rebars & W.W.F. (Cont'd)

#	h	d_b		f'_{co}	f_y	$\rho_v(\%)$		s/d		s_l/d		K	$\frac{\varepsilon_{85}}{.004}$
		tie	wwf			tie	wwf	tie	wwf	tie	wwf		
	mm	mm	mm	MPa	MPa								
19	350	8.14	3.4	25	400	1.0	0.5	.32	.08	.45	.92	.46	4.27
20	350	8.14	2.8	25	400	1.0	0.5	.32	.08	.45	.46	.47	4.35
21	350	8.14	2.4	25	400	1.0	0.5	.32	.08	.45	.31	.47	4.35
22	350	8.14	4.9	25	400	1.0	1.0	.32	.08	.45	.90	.53	5.87
23	350	8.14	4.0	25	400	1.0	1.0	.32	.08	.45	.46	.64	6.55
24	350	8.14	3.5	25	400	1.0	1.0	.32	.08	.45	.31	.67	6.79

Table 4.9: Effect of Reinforcement Arrangement (W.W.F.)

Column *no.*	ρ_v (%)	f_{co}' *(MPa)*	f_y *(MPa)*	$\frac{s}{d}$	$\frac{s_l}{d}$	K	$\frac{\varepsilon_{85}}{.004}$
10	0.5	25	400	0.08	0.92	0.25	1.68
11	0.5	25	400	0.08	0.46	0.27	1.71
12	0.5	25	400	0.08	0.31	0.27	1.71
22	1.0	25	400	0.08	0.91	0.33	2.68
23	1.0	25	400	0.08	0.45	0.44	3.04
24	1.0	25	400	0.08	0.30	0.48	3.15
34	2.0	25	400	0.08	0.90	0.45	5.15
35	2.0	25	400	0.08	0.45	0.59	6.10
36	2.0	25	400	0.08	0.30	0.70	6.79
46	3.0	25	400	0.08	0.89	0.53	8.06
47	3.0	25	400	0.08	0.45	0.70	9.75
48	3.0	25	400	0.08	0.30	0.83	10.99

Table 4.10: Effect of Reinforcement Arrangement (Re-bars)

Column *no.*	ρ_v (%)	f_{co}' *(MPa)*	f_y *(MPa)*	$\frac{s}{d}$	$\frac{s_l}{d}$	K	$\frac{\varepsilon_{85}}{.004}$
10	0.5	25	400	0.16	0.88	0.20	1.60
11	0.5	25	400	0.16	0.45	0.26	1.70
12	0.5	25	400	0.16	0.30	0.27	1.71
22	1.0	25	400	0.16	0.88	0.26	2.46
23	1.0	25	400	0.16	0.45	0.35	2.72
24	1.0	25	400	0.16	0.32	0.40	2.90
34	2.0	25	400	0.16	0.87	0.35	4.54
35	2.0	25	400	0.16	0.45	0.46	5.25
36	2.0	25	.400	0.16	0.31	0.54	5.73
46	3.0	25	400	0.16	0.87	0.42	6.98
47	3.0	25	400	0.16	0.45	0.55	8.23
48	3.0	25	400	0.16	0.32	0.63	9.03

Table 4.11: Effect of Tie Spacing (W.W.F.)

Column *no.*	ρ_v (%)	f_{co}' *(MPa)*	f_y *(MPa)*	$\frac{s}{d}$	$\frac{s_l}{d}$	K	$\frac{\epsilon_{85}}{.004}$
1	0.5	25	400	0.31	0.92	0.14	1.50
4	0.5	25	400	0.24	0.92	0.16	1.53
7	0.5	25	400	0.16	0.92	0.19	1.58
10	0.5	25	400	0.08	0.92	0.25	1.68
13	1.0	25	400	0.32	0.89	0.19	2.22
16	1.0	25	400	0.24	0.89	0.21	2.29
19	1.0	25	400	0.16	0.90	0.25	2.42
22	1.0	25	400	0.08	0.91	0.33	2.68
25	2.0	25	400	0.32	0.88	0.27	3.91
28	2.0	25	400	0.24	0.88	0.29	4.11
31	2.0	25	400	0.16	0.89	0.34	4.44
34	2.0	25	400	0.08	0.90	0.45	5.15
37	3.0	25	400	0.32	0.86	0.31	5.88
40	3.0	25	400	0.24	0.87	0.34	6.23
43	3.0	25	400	0.16	0.88	0.40	6.81
46	3.0	25	400	0.08	0.89	0.53	8.06

Table 4.12: Effect of Tie Spacing (Re-bars)

Column no.	ρ_v (%)	f_{co}' (MPa)	f_y (MPa)	$\frac{s}{d}$	$\frac{s_l}{d}$	K	$\frac{\varepsilon_{85}}{.004}$
1	0.5	25	400	0.48	0.88	0.13	1.48
4	0.5	25	400	0.32	0.88	0.15	1.52
7	0.5	25	400	0.24	0.88	0.17	1.55
10	0.5	25	400	0.16	0.88	0.20	1.60
13	1.0	25	400	0.48	0.87	0.17	2.15
16	1.0	25	400	0.32	0.87	0.20	2.24
19	1.0	25	400	0.24	0.88	0.22	2.32
22	1.0	25	400	0.16	0.88	0.26	2.46
25	2.0	25	400	0.48	0.86	0.23	3.72
28	2.0	25	400	0.32	0.87	0.27	3.98
31	2.0	25	400	0.24	0.87	0.30	4.19
34	2.0	25	400	0.16	0.87	0.35	4.54
37	3.0	25	400	0.48	0.85	0.27	5.52
40	3.0	25	400	0.32	0.86	0.32	5.98
43	3.0	25	400	0.24	0.86	0.36	6.36
46	3.0	25	400	0.16	0.87	0.42	6.98

Table 4.13: Effect of Volumetric Ratio (W.W.F.)

Column *no.*	ρ_v (%)	f_{co}' *(MPa)*	f_y *(MPa)*	$\frac{s}{d}$	$\frac{s_1}{d}$	K	$\frac{\varepsilon_{85}}{.004}$
1	0.5	25	400	0.31	0.92	0.14	1.54
13	1.0	25	400	0.32	0.89	0.19	2.20
25	2.0	25	400	0.32	0.88	0.27	3.91
37	3.0	25	400	0.33	0.86	0.31	5.88
4	0.5	25	400	0.24	0.92	0.16	1.53
16	1.0	25	400	0.24	0.89	0.21	2.29
28	2.0	25	400	0.24	0.88	0.29	4.11
40	3.0	25	400	0.24	0.87	0.34	6.23
7	0.5	25	400	0.16	0.92	0.19	1.58
19	1.0	25	400	0.16	0.90	0.25	2.42
31	2.0	25	400	0.16	0.89	0.34	4.44
43	3.0	25	400	0.16	0.88	0.40	6.81
10	0.5	25	400	0.08	0.92	0.25	1.68
22	1.0	25	400	0.08	0.91	0.33	2.68
34	2.0	25	400	0.08	0.90	0.45	5.15
46	3.0	25	400	0.08	0.89	0.53	8.06

Table 4.14: Effect of Volumetric Ratio (Re-bars)

Column *no.*	ρ_v (%)	f_{co}' *(MPa)*	f_y *(MPa)*	$\frac{s}{d}$	$\frac{s_l}{d}$	K	$\frac{\epsilon_{85}}{.004}$
1	0.5	25	400	0.48	0.88	0.13	1.48
13	1.0	25	400	0.49	0.87	0.17	2.15
25	2.0	25	400	0.49	0.86	0.23	3.72
37	3.0	25	400	0.49	0.85	0.27	5.52
4	0.5	25	400	0.32	0.88	0.15	1.52
16	1.0	25	400	0.32	0.87	0.20	2.24
28	2.0	25	400	0.32	0.87	0.27	3.98
40	3.0	25	400	0.32	0.86	0.32	5.98
7	0.5	25	400	0.24	0.88	0.17	1.55
19	1.0	25	400	0.24	0.88	0.22	2.32
31	2.0	25	400	0.24	0.87	0.30	4.19
43	3.0	25	400	0.24	0.86	0.36	6.36
10	0.5	25	400	0.16	0.88	0.20	1.60
22	1.0	25	400	0.16	0.88	0.26	2.46
34	2.0	25	400	0.16	0.87	0.35	4.54
46	3.0	25	400	0.16	0.87	0.42	6.98

Table 4.15: Comparison of Columns Reinforced with Re-bars and Rebar-W.W.F. Combination

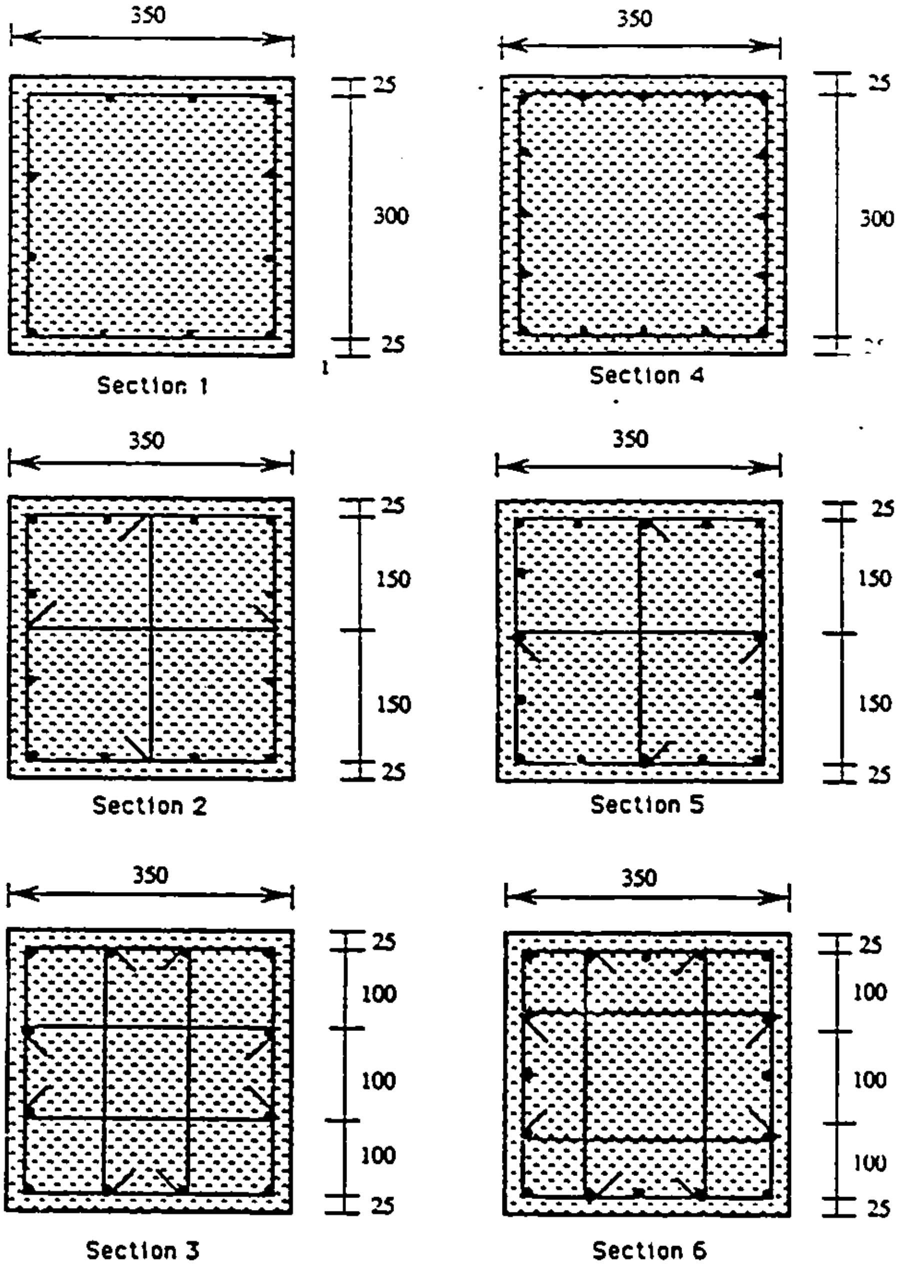
					Rebar		*Rebar&W.W.F.*	
ρ_v (%)	f'_{co} (MPa)	f_y (MPa)	$\frac{s}{d}$	$\frac{s_l}{d}$	K	$\frac{\varepsilon_{85}}{.004}$	K	$\frac{\varepsilon_{85}}{.004}$
2	25	400	0.49	0.88	0.23	3.72	0.62	6.46
2	25	400	0.48	0.45	0.30	4.17	0.63	6.52
2	25	400	0.32	0.88	0.27	3.98	0.66	6.74
2	25	400	0.32	0.44	0.35	4.51	0.67	6.79

Table 4.16: s/d & sl/d ratio for different levels of cofinement

Strength enhancement (K)	ρ_v =0.5%			ρ_v =1.0%			ρ_v =2.0%			ρ_v =3.0%		
	s/d	sl/d	$\frac{\varepsilon_{cu}}{.004}$	s/d	sl/d	$\frac{\varepsilon_{cu}}{.004}$	s/d	sl/d	$\frac{\varepsilon_{cu}}{.004}$	s/d	sl/d	$\frac{\varepsilon_{cu}}{.004}$
15%	0.62	0.25	1.50									
	0.43	0.50	1.50									
	0.34	0.75	1.50									
	0.31	0.83	1.51									
	0.24	1.01	1.51									
25%	0.31	0.16	1.68	0.32	0.56	2.41	0.50	0.72	3.70	0.75	0.49	4.80
	0.23	0.31	1.68	0.24	0.64	2.42	0.40	0.88	3.71	0.51	0.86	5.09
	0.16	0.46	1.68	0.16	0.90	2.42	0.32	1.01	3.76	0.33	1.14	5.24
	0.08	0.92	1.68	0.08	1.24	2.42						
50%				0.31	-0.70		0.32	0.07	5.48	0.32	0.25	7.71
				0.24	-0.21		0.24	0.20	5.35	0.24	0.35	7.81
				0.16	0.03	3.24	0.16	0.36	5.33	0.16	0.54	7.79
				0.08	0.23	3.20	0.08	0.74	5.49	0.08	0.97	7.83
75%							0.24	-0.40		0.32	-0.22	
							0.16	-0.11		0.24	-0.09	
							0.08	0.23	7.1	0.16	0.13	10.14
										0.08	0.39	10.25

Table 4.17: s/d & sl/d ratio for a given ductility ratio

Ductility Ratio	ρ_v =0.5%			ρ_v =1.0%			ρ_v =2.0%			ρ_v =3.0%		
	s/d	sl/d	K	s/d	sl/d	K	s/d	sl/d	K	s/d	sl/d	K
2				0.57	0.89	0.13						
				0.32	1.28	0.12						
4							0.50	-0.54				
							0.32	0.51	0.27			
							0.24	0.96	0.33			
6							0.32	-0.12		0.50	0.47	0.31
							0.24	0.03	0.59	0.32	0.81	0.32
							0.16	0.15	0.61	0.24	0.96	0.32
							0.08	0.50	0.57			
8							0.16	-0.80		0.32	0.19	0.53
							0.08	0.04	0.89	0.24	0.32	0.52
										0.16	0.47	0.52
										0.08	0.90	0.53

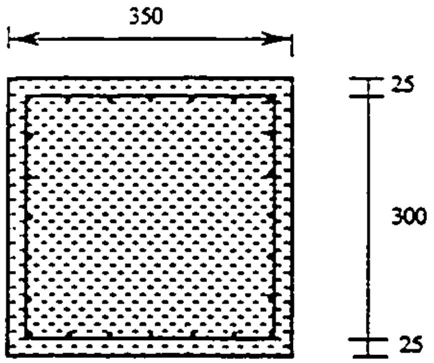


Section 1 Section 4

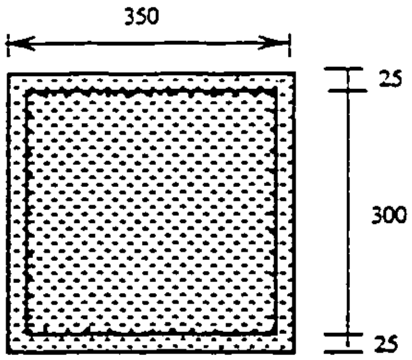
Section 2 Section 5

Section 3 Section 6

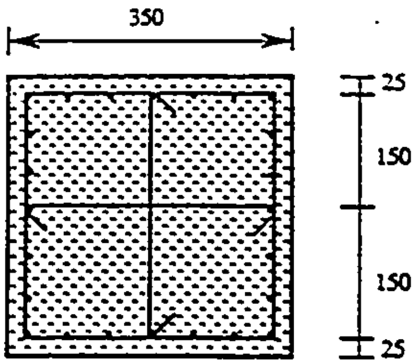
Figure 4.1: Details of Sections reinforced with W.W.F.



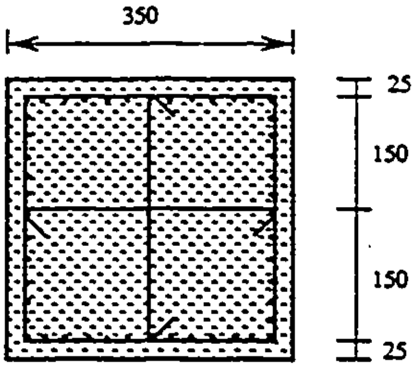
Section 7



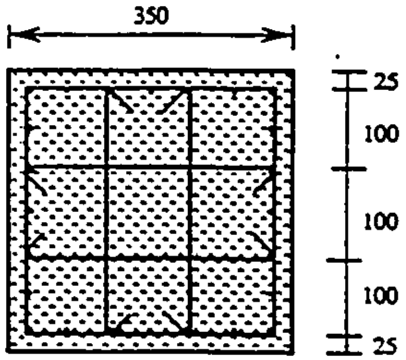
Section 10



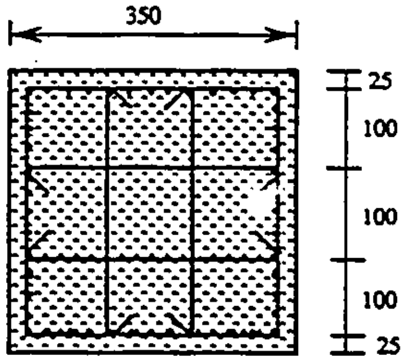
Section 8



Section 11

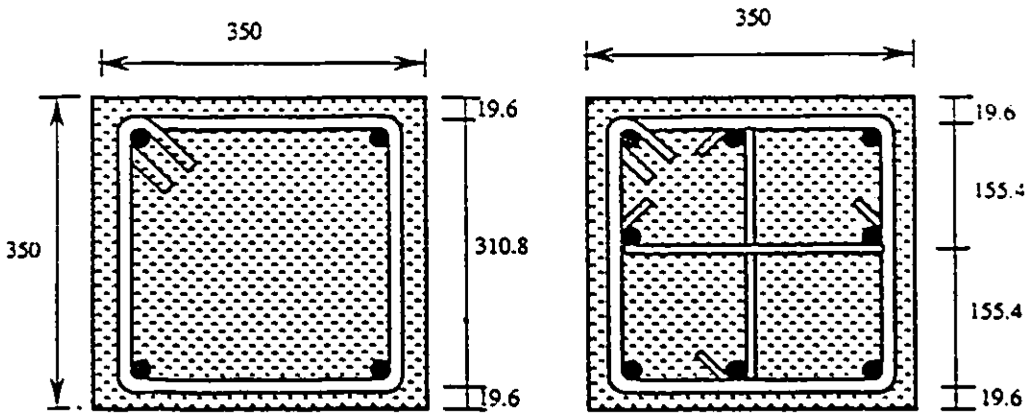


Section 9



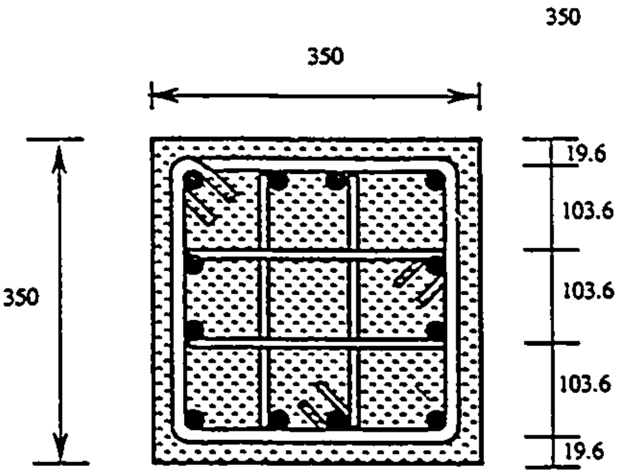
Section 12

Figure 4.2: Details of Sections Reinforced with W.W.F. (Cont'd)



Cross Section 1

Cross Section 2



Cross Section 3

Figure 4.3: Details of Sections Reinforced with Re-bars

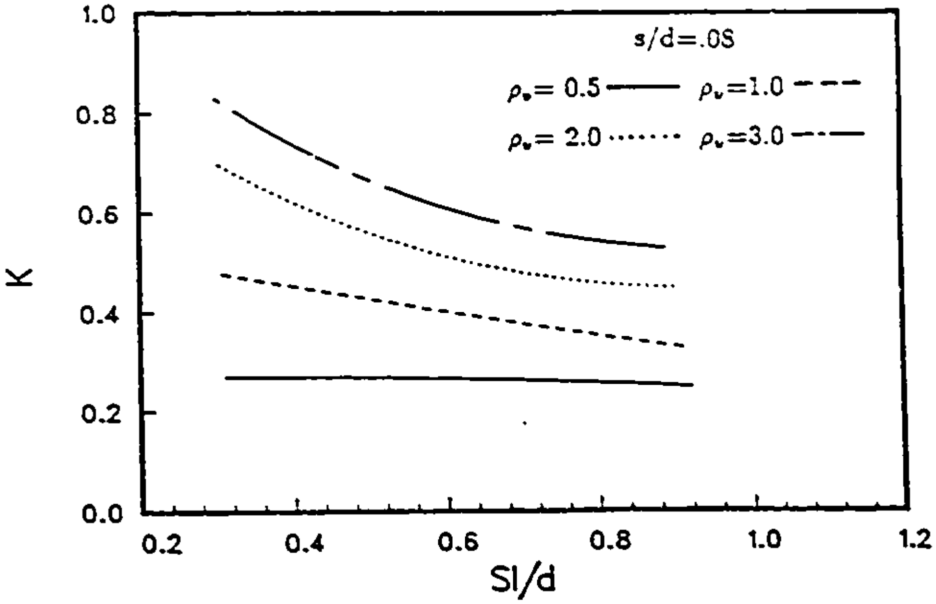


Figure4.4: Effect of Reinforcement Arrangement on Strength Enhancement (W.W.F.)

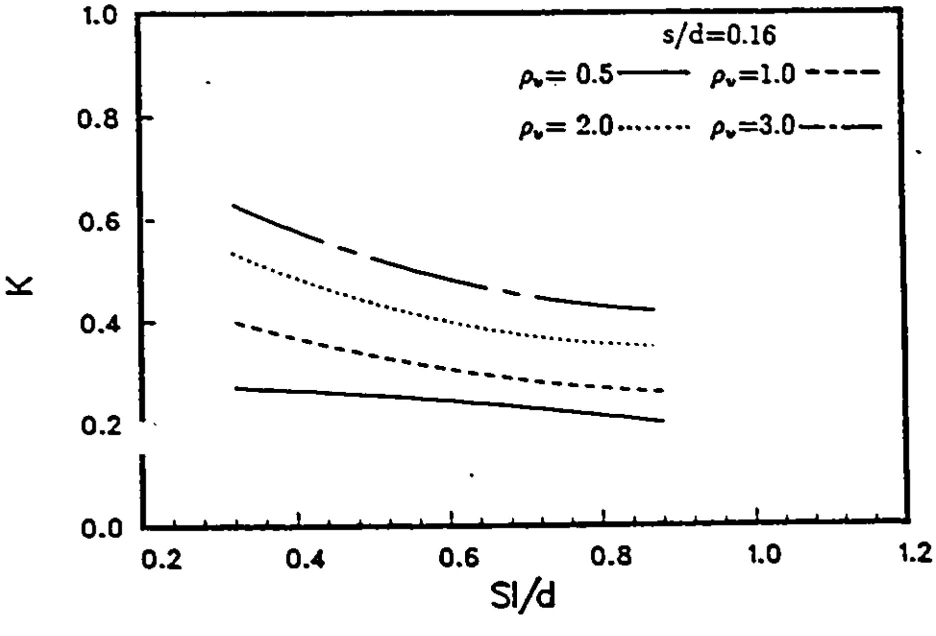


Figure4.5: Effect of Reinforcement Arrangement on Strength Enhancement (Re-bars)

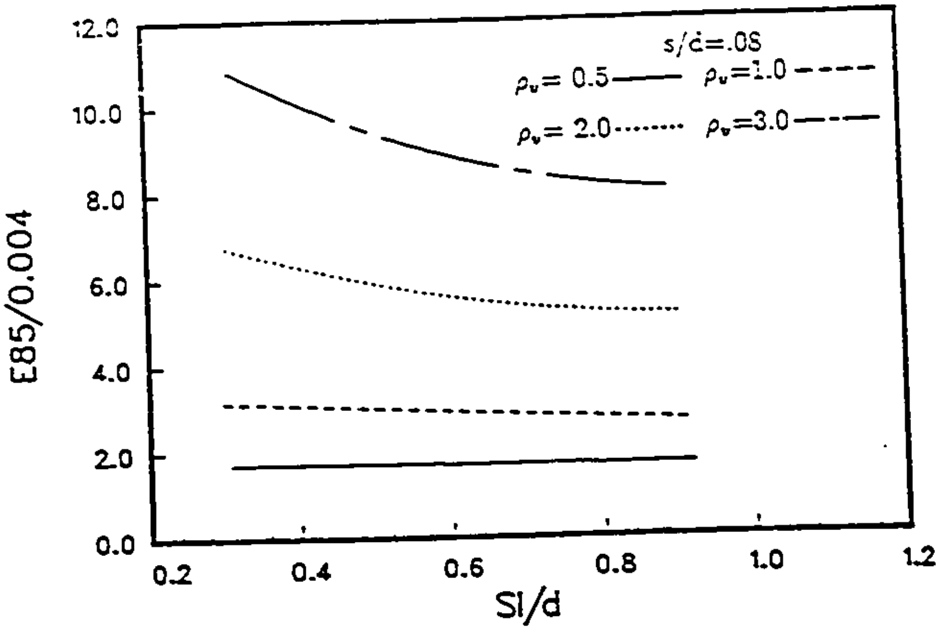


Figure4.6: Effect of Reinforcement Arrangement on Ductility (W.W.F.)

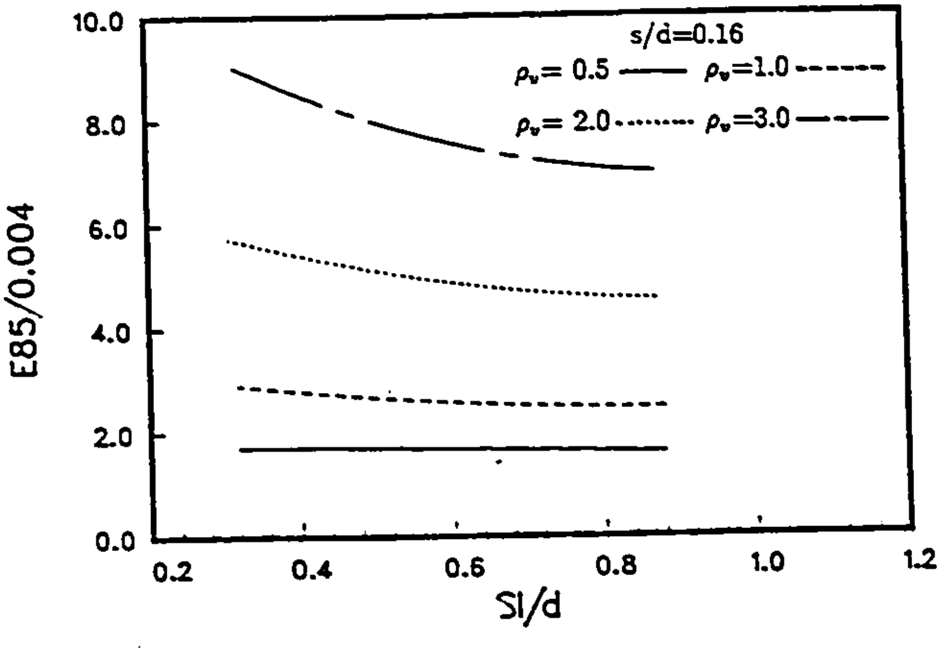


Figure4.7: Effect of Reinforcement Arrangement on Ductility (Re-bars)

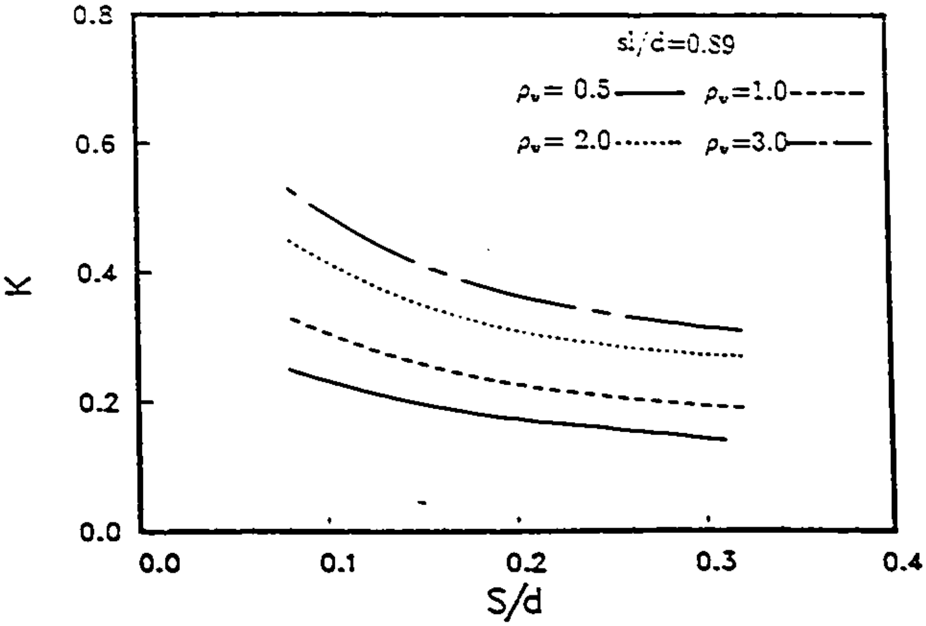


Figure4.8: Effect of Tie Spacing on Strength Enhancement (W.W.F)

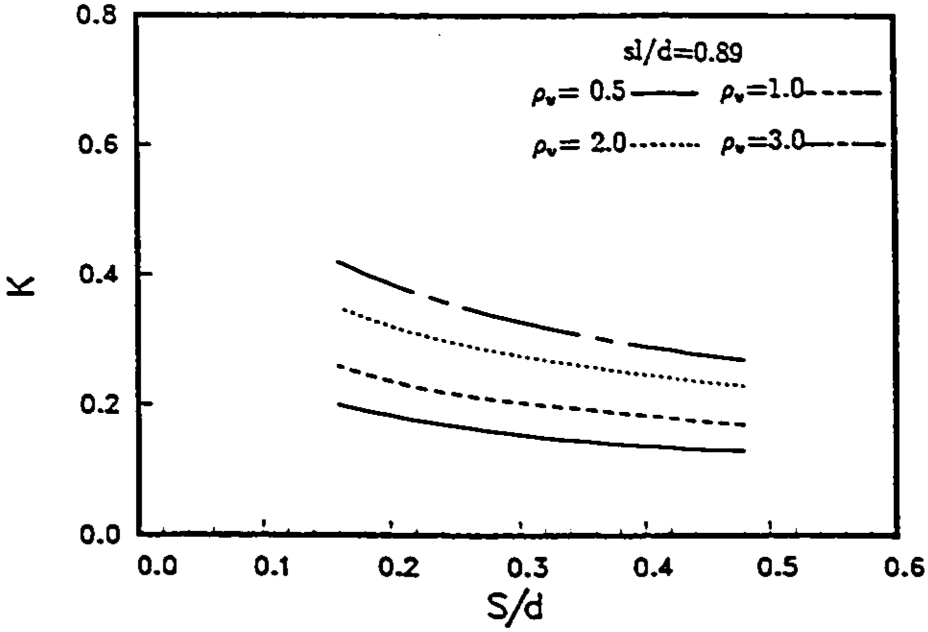


Figure4.9: Effect of Tie Spacing on Strength Enhancement (Re-bars)

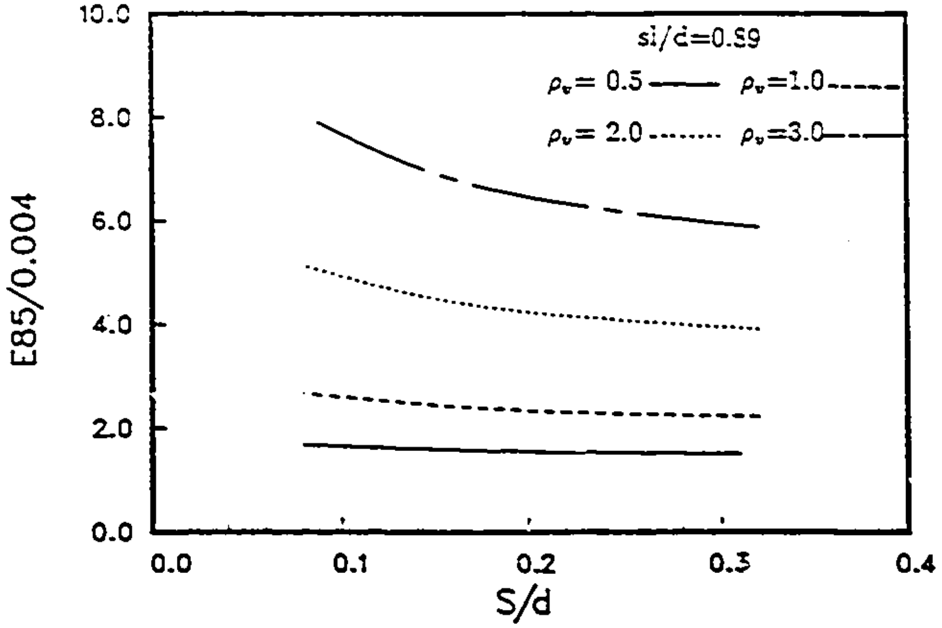


Figure 4.10: Effect of Tie Spacing on Ductility (W.W.F.)

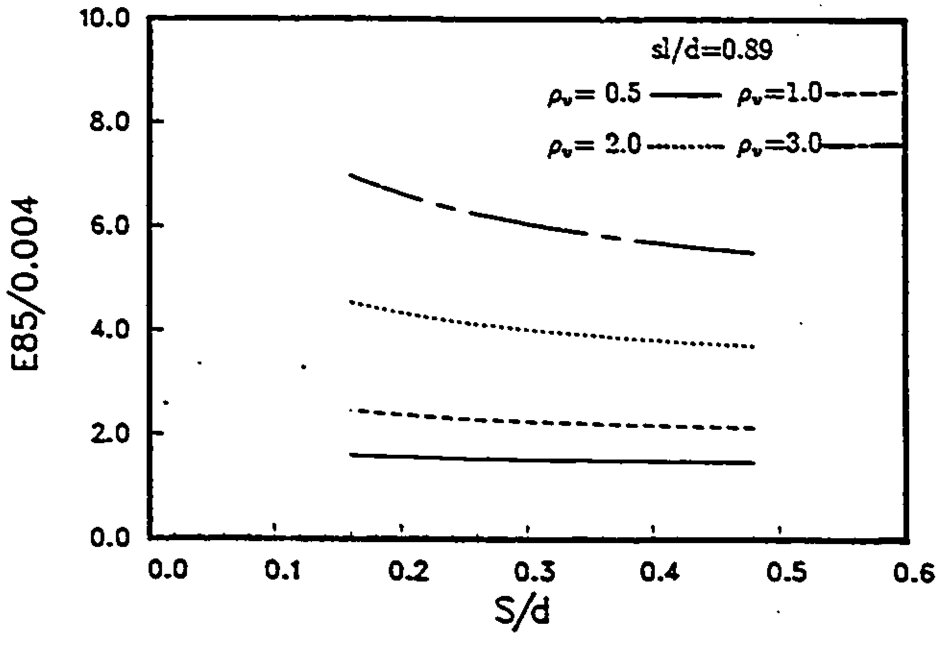


Figure 4.11: Effect of Tie Spacing on Ductility (Re-bar)

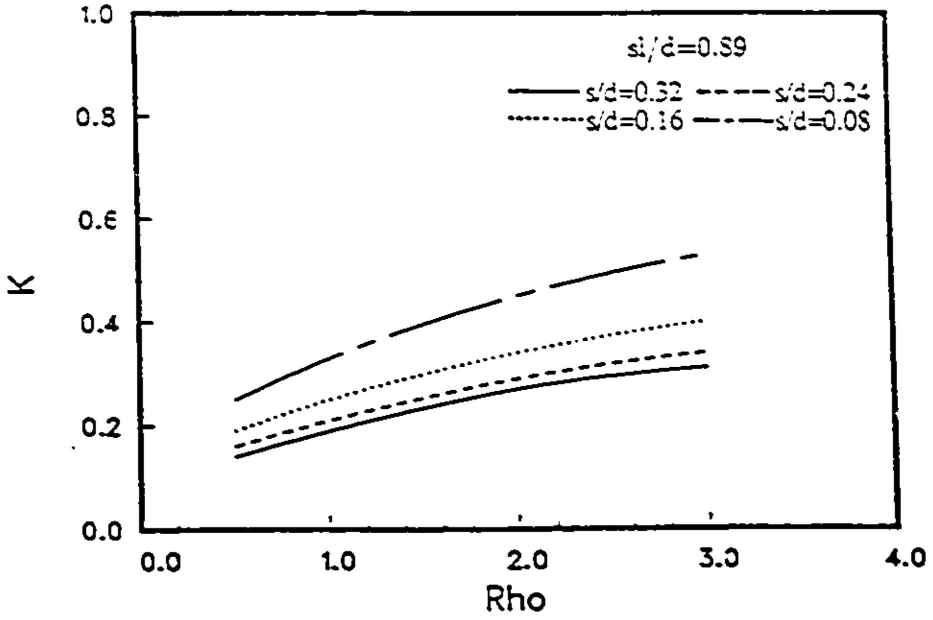


Figure4.12: Effect of Volumetric Ratio on Strength Enhancement (W.W.F.)

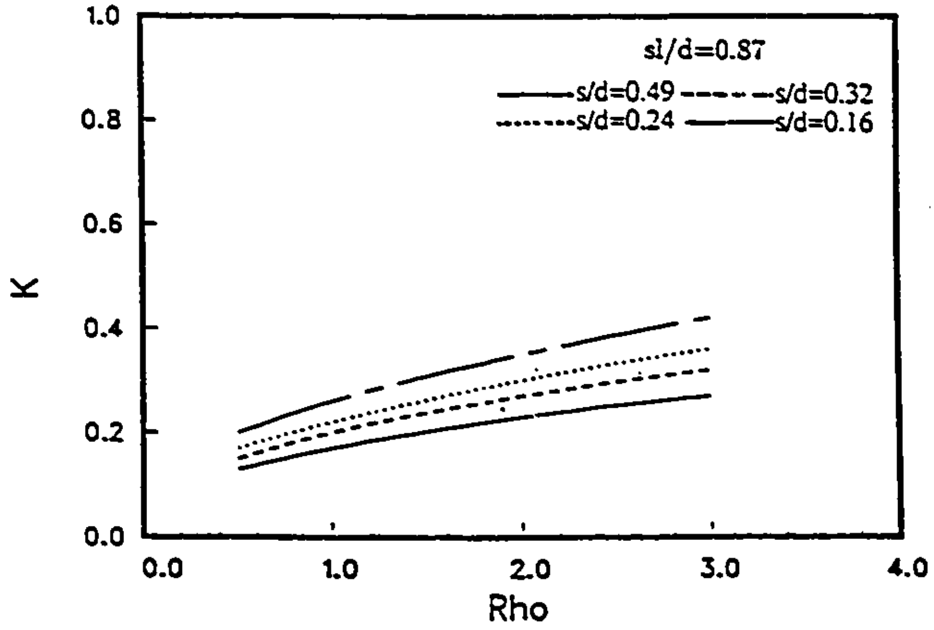


Figure 4.13: Effect of Volumetric Ratio on Strength Enhancement (Re-bar)

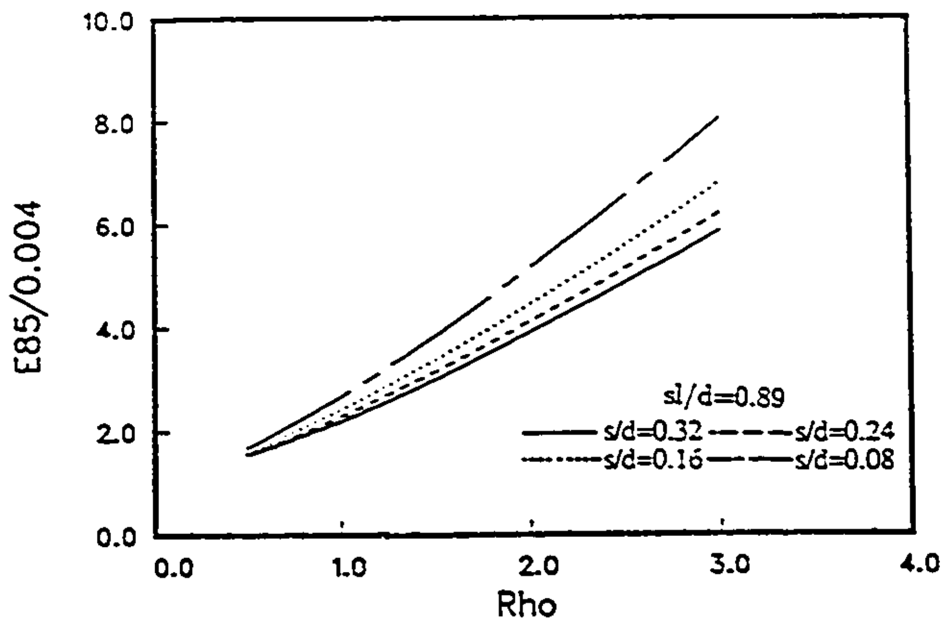


Figure 4.14: Effect of Volumetric Ratio on Ductility (W.W.F.)

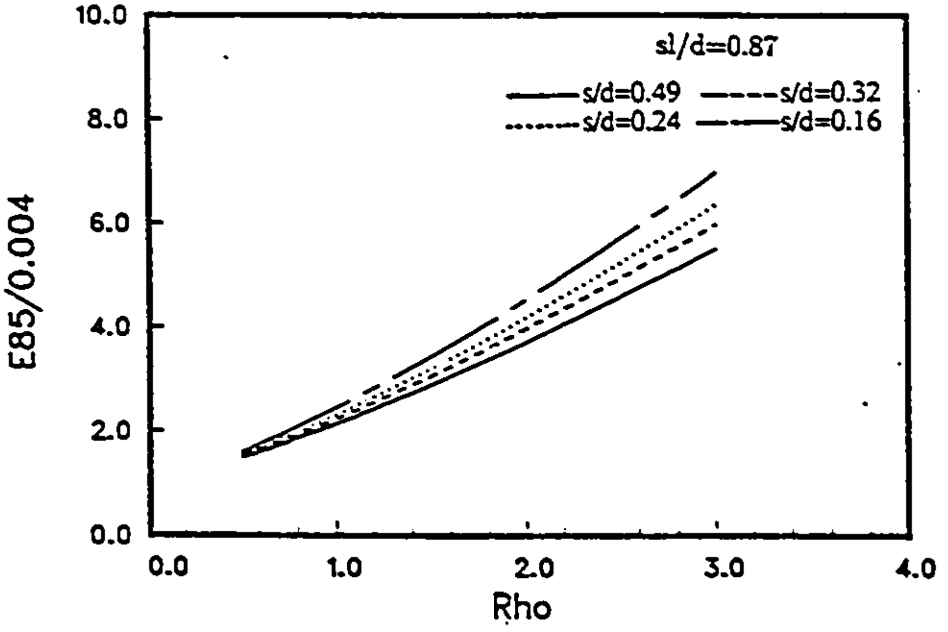


Figure 4.15: Effect of Volumetric Ratio on Ductility (Re-bar)

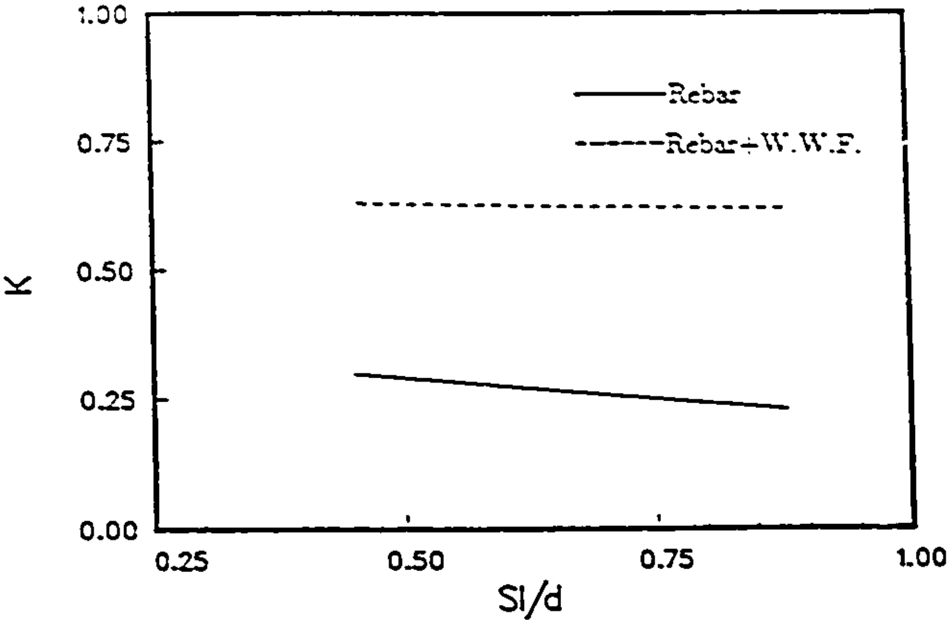


Figure 4.16: Effect of Use of W.W.F. combined with Rebars on Strength Enhancement

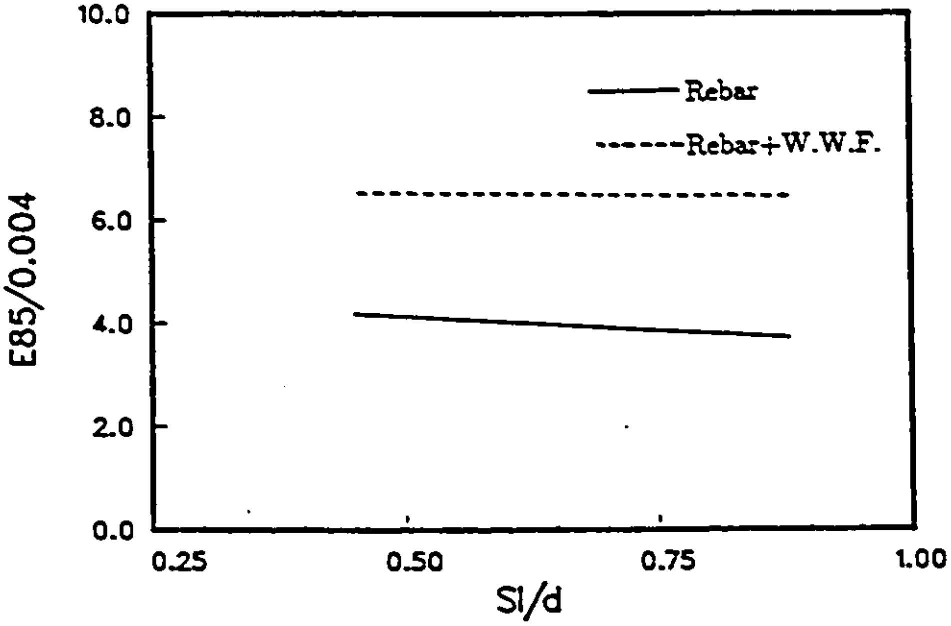


Figure 4.17: Effect of Use of W.W.F. combined with Rebars on Ductility

Chapter 5

Conclusion

Based on the results of the experimental and parametric investigations carried out, the following conclusions can be made:

1. The use of W.W.F. for concrete confinement in reinforced concrete columns improves strength and ductility. However, W.W.F. lacks the required stiffness to sustain axial compression and can not provide the required ductility without a reinforcement cage. Once the peak load is reached the wires buckle and the shear failure may follow. Therefore, further research is required to verify the use of W.W.F. with larger size wires, if W.W.F. is to be the only reinforcement in the column.

2. Columns with a volumetric reinforcement ratio of less than 0.5% behave similar to plain concrete columns.

3. The analytical model proposed by Saatcioglu and Razvi[3] to predict stress-strain relationship of confined concrete is found to be excellent in predicting test results. The advantage of the model over previously proposed models lies in its simplicity, ability to predict the behavior of poorly as well as well confined columns, and versatility in predicting behavior of columns reinforced with different types of reinforcement.

4. Strength and ductility of columns improve with reduction in tie spacing. The effect of tie spacing is directly related to the level of confinement pressure that can be developed. If the volumetric ratio of steel is too low, or the distribution of laterally supported longitudinal reinforcement is not good, reduction in tie spacing alone is not sufficient to develop the necessary confinement pressure. For ρ_s=1.0% it was shown that a 33% reduction in s/d ratio results in an increase in strength and ductility ratio of 15% and 6%, respectively. The same reduction in spacing show only 10% and 3% improvement in strength and ductility when the volumetric ratio is reduced by one half. Tie spacing becomes more pronounced when the other confinement parameters are favorable.

5. Reinforcement arrangement of a column section, which reflects the distribution of longitudinal reinforcement as well as tie arrangement, has a significant effect on strength and ductility of columns. Columns with well distributed longitudinal reinforcement, where each rein-

forcement is laterally supported by a corner of a hoop or a cross tie, show improved strength and ductility even if the tie spacing is not small. It was shown that at a volumetric ratio, ρ_v=1.0% the reduction of 33% in s_l/d ratio resulted in an increase of strength and ductility ratio of 12% and 6%, respectively. However, when the volumetric ratio was reduced by one half, the corresponding increases in strength and ductility were 2% and 0% for the same reduction in s_l/d ratio

6. Increase in volumetric ratio of transverse reinforcement improves strength and ductility of columns. However, if the spacing of lateral and longitudinal reinforcements are too large, the increase in volumetric ratio alone does not improve strength and ductility appreciably. An increase in volumetric ratio of 50% results in an increase in strength and ductility ratio of 17.4% and 59%, respectively. The volumetric ratio was found to play the major role on ductility of core concrete.

7. Use of W.W.F. as confinement reinforcement in columns with longitudinal reinforcement tied by lateral ties results in a significant improvement in strength and ductility of columns. Combined use of W.W.F. with re-bars may produce strength and ductility increases of up to 170% and 75%, respectively, over those reinforced with re-bars alone. Therefore, combined use of W.W.F. with ordinary reinforcement cage is found to be an ideal substitution for confining reinforcement consisting of closely spaced re-bars.

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