



**ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES**

**EXPERIMENTAL AND ANALYTICAL INVESTIGATION ON
CONFINED REINFORCED CONCRETE COLUMN**

BY MELAT AYELE

October 2010

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**A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF
ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CIVIL
ENGINEERING.**

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Notation

A_c – Concrete core area;

A_{ce} – Effectively confined concrete core area;

A_g – Gross area of column;

A_s – Cross sectional area of transverse reinforcement steel;

A_{sx} – Total area of transverse steel in the x – direction;

A_{sy} – Total area of transverse steel in the y – direction;

A_{sl} – Cross sectional area of longitudinal reinforcement bar;

B – Width of confined core measured to outside of hoops;

bc – Cross-sectional dimension of column core measured centre-to-centre of confining reinforcement;

d_c = the diameter of confined core to centerline of hoops or spirals

E_s – Young's modulus of elasticity of reinforcing steel;

E_{sec} – Secant modulus of confined concrete at peak stress;

f_c – Concrete stress at any strain level;

f_{cc} – Compressive strength of confined concrete;

f_{co} – Compressive strength of unconfined concrete;

$f_{c,cube}$ – Cube strength of concrete obtained from standard cubes;

$f_{c'}$ – Cylinder strength of concrete obtained from standard cylinder;

f_{le} – Effective confining lateral pressure due to transverse bar;

f_{lex} – Effective lateral pressure from transverse bar in the x direction;

f_{ley} – Effective lateral pressure from transverse bar in the y – direction;

f_y – Yield strength of transverse reinforcement;

f'_c – Specified concrete strength of concrete;

f_{yt} – Specified yield strength of transverse reinforcement;

K_s – Strength enhancement ratio due to lateral ties;

K_e – Confinement effectiveness coefficient due to lateral ties;

n – Number of laterally supported longitudinal reinforcement;

n_i = the number of laterally supported longitudinal bars

P – Axial compressive force on column;

P_0 – Nominal axial load strength at zero eccentricity;

s – Spacing of transverse reinforcement measured along the longitudinal axis of the member;

s_l – Centre-to-centre spacing of longitudinal reinforcement, laterally supported by corner of hoop or hook of cross tie;

$w_{c,i}$ = the i^{th} clear distance between laterally supported adjacent longitudinal bars

ϵ_{c1} – Strain corresponding to the cylindrical strength of concrete;

f_c – cylindrical strength of concrete;

ϵ_{co50} – Unconfined strain when the concrete stress has fallen to 50% of maximum stress;

ϵ_{c50h} – additional confined strain at 50% of the maximum stress on the falling branch;

ϵ_{cc85} – Strain at 85% strength level beyond the peak stress of confined concrete;

f_{cc85} – stress at 85% the peak stress of confined concrete;

ϵ_{cc1} , ϵ_{cc2} – the minimum and maximum strain value corresponding to the maximum stress, respectively

ϵ_s – Longitudinal strain in reinforcing steel;

ρ_h – ratio of the volume of transverse reinforcement to the volume of confined concrete core;

ρ_l – ratio of area of longitudinal reinforcement to the area of core section;

ρ_{cc} = the ratio of area of longitudinal reinforcement to the area of core section

SL3= square column confined by three layer wire mesh

SL2=square column confined by two layer wire mesh

SL1= square column confined by one layer wire mesh

CL3=circular column confined by three layer wire mesh

CL2=circular column confined by two layer wire mesh

CL1=circular column confined by one layer wire mesh

CT=column confined by cross tie arrangement

OV=Column confined by overlapping configuration

NH= column confined by normal hoop arrangement

US=unconfined square column

UC=unconfined circular column

A_{sh} =cross sectional area of transverse reinforcement bar

d_c = the diameter of confined core to centerline of hoops or spirals

s_h = center to centre vertical spacing between transverse reinforcement

s_{hc} = clear vertical spacing between transverse reinforcement and

ρ_{cc} = the ratio of area of longitudinal reinforcement to the area of core section

α =the angle between the transverse reinforcement and core length b_c

S_l =the spacing between laterally longitudinal reinforcement

n_i = the number of laterally supported longitudinal bars

$w_{c,i}$ = the i^{th} clear distance between laterally supported adjacent longitudinal bars

b_{cx} and b_{cy} = core dimensions to the center line of the perimeter hoop in the x and y direction respectively

ρ_s = ratio of the volume of transverse reinforcing steel to the volume of confined concrete

f_{co} and ϵ_{co} = the unconfined concrete strength and corresponding strain respectively

$\mu \phi$ is the required value of the curvature ductility factor;

v_d is the normalised design axial force

$\epsilon_{sy,d}$ is the design value of tension steel strain at yield;

h_c is the gross cross-sectional depth

h_o is the depth of confined core (to the centre line of the hoops);

b_c is the gross cross-sectional width

b_o is the width of confined core (to the centre line of the hoops);

α is the confinement effectiveness factor, equal to $\alpha = \alpha_n \times \alpha_s$, with:

d = the diameter of confined concrete section

t_j and f_{yj} = thickness and tensile yield strength of the jacket, respectively

n_{fl} = number of layers of the fiber mesh

A_{sf} and f_{yf} = area and yield strength of individual fibers respectively

h_i and t_i height and thickness of the jacket respectively

b_x and b_y = dimensions of the confined concrete section in the x and y directions respectively to the center line of the perimeter hoop in the x and y direction respectively

ρ_{sx} and ρ_{sy} = the ratio of area of Fiber reinforcement to the area of core section

Abstract

The intensity and frequency of earthquake are getting higher and higher during these few years. After different failure observed the importance of enhancing the ductility capacity became essential. The enhancement of strength and ductility in column requires confinement of concrete by transverse reinforcement or other mechanism. In this study, an experimental investigation was conducted to examine the effect of confinement in concrete columns subjected to axial loading. The experimental program include 33 small scale concrete column with 3 type of different geometric arrangement of transverse tie (cross tie, normal and overlapping) of square column and three different number of layer of square and circular column. For each experiment, stress–strain relationship was obtained and compared with models proposed earlier.

The test result indicate that the strength of column confined by cross tie, over lapping three layers square and circular specimens confined by wire mesh shows enhancement in strength very significantly. Significant enhancement in peak strain and ductility was observed in specimens confined by wire mesh and cross tie configuration especially specimen having circular cross section confined by three layer wire mesh. Circular and cross tie type of confinement preserve the strength in the descending region of the stress-strain curve and prevent the column from sudden failure after peak load. From all specimens the test result indicates that the cross ties configuration give higher strength and ductility.

From this research due to their higher strength and ductility, in seismic region it is recommended to use that the cross tie configuration and wire mesh with number of layer is more than two. However, due to size and capacity limitation of the machine stress-strain characteristics of experiment results in comparison with of the existing confinement model show considerable deviation in the post strength zones. A better achievement can be obtained by considering actual size of specimens.

1. INTRODUCTION

1.1 General

Concrete is an artificial stone like material obtained by mixing cement, sand, aggregate and water with predetermined proportions. Its compressive strength is higher to that of the natural stones, this makes it suitable for members subjected to compression. It is a brittle material and its tensile strength is small compared to its compressive strength. To offset this limitation, steel with its high tensile strength is used to reinforce concrete.

When unconfined, concrete is subject to compression stress levels approaching the crushing strength, high lateral tensile strains develop as a result of the formation and propagation of longitudinal micro cracks, these results in instability of compression zone and failure. Confining reinforced concrete column by transverse reinforcement in conjunction with longitudinal reinforcement acts to restrain the lateral expansion of the concrete, enabling higher compression stresses and more important, much higher compression strains to be sustained by the compression zone before failure occurs. [17]

The term confinement refers to the influence that lateral reinforcement exercises on concrete, which leads to a modification of the compression stress state from uni-axial to multi-axial state of stress. In practice a loading condition equivalent to hydrostatic compression results when transverse reinforcement in the form of closely spaced ties or spirals prevent lateral swelling of an element subjected to axial compression.[17]

It is well known that confining the core of a reinforced concrete column with lateral reinforcement will significantly increase the strength and ductility of the column. Confinement reduces the loss of strength due to spalling of the concrete cover and increases the ability of the concrete core to sustain large deformations without a dramatic loss in strength. The increase in strength, especially in ductile behavior, due to confinement is extremely important for reinforced concrete building columns. The degree of confinement is directly related to the configuration, size, longitudinal reinforcement spacing of the lateral reinforcement and the confining techniques.

1.2 Background of the problem

The intensity and frequency of earthquake are getting higher and higher during the past few years. This raises the concern of structural engineers to study whether the structures survive or not during earthquake. Traditionally, most engineers design the structures to have sufficient strength to resist the earthquake loads. However, it has been found that the structures designed with sufficient strength collapsed. After the observation of different failure due to lack of confinement (as shown in fig. 1.1 during San Fernando and other earthquake) the importance of enhancing the ductility capacity became apparent. The enhancement of strength and ductility in column requires confinement of concrete by transverse reinforcement and other mechanism.



Figure 1.1 Failures due to Lack of Confinement [8]

Extensive researches have been done on concrete confinement in the past few years. However, the results of this research could not effectively be reflected in codes. Even if the information obtained from the research is fundamental, it is fragmented, as a result it didn't significantly influence the established provisions of codes.

In Ethiopia researches were undertaken on this specific subject. The researches consider the effect of longitudinal steel, spacing of ties, and effect of yield strength and tie diameter. To gather preliminary data which helps the establishment of confinement model or to use the model established before, it needs further studies which include other parameters such as the effect of tie configuration, effect of shape, effect of other type of confinement mechanism and other parameters which are not included in the previous study.

1.3 Objective

The objective of this study is to determine experimental investigation on:

- Degrees of confinement of the circular and square reinforced concrete column using wire mesh.
- Effect of geometrical configuration of transversal ties on confinement of reinforced columns.
- Perform analytical and experimental study to describe the force displacement behavior of the confined concrete column.

1.4 Methodology

- Literature review on different confinement model.
- Experimental investigation which considers the geometric configuration of transverse tie and wire mesh on circular and square reinforced columns.
- Perform analytical study on confinement models.
- Conduct discussion with professionals

1.5 Thesis Overview

This thesis consists of seven chapters. The first chapter is an introduction part states the objectives, back ground, methodology and limitation employed during the research.

The second chapter discusses the literature survey carried on the confinement mechanism, confining technique, parameter affecting confinement, and the code provision. The third chapter deals on the experimental program which covers the specimen designation, component materials used in the study, description of test specimens, specimen construction and test procedures.

Chapter four contains the presentation of important test results and discussion. Chapter five focuses on literature review on different confinement model

Chapter six is comparison and discussion of the analytical results with the experiment.

Chapter seven is the conclusion part of the research and it contains recommendation based on the findings of the research. Finally a complete list of all test data is presented in appendix.

1.6 Limitations

This research is limited to examine the effect of confinement on reinforced concrete columns of square cross section with different configuration of transverse ties and different number of layer of wire mesh and for circular cross section the study examine specimen confined by wire mesh. The effect of spiral ties is not treated in this research.

2. LITRATURE REVIEW

2.1 General

For most framed structures to survive a major earthquake, they must undergo large inelastic deformation and thus dissipate energy by ductile behavior of structural members. Much of this energy is dissipated in plastic hinges to be formed at predetermined locations. To prevent plastic hinge formation in column it is important to insure columns ductility by using transverse steel in the form of hoops or spiral in the plastic hinge region. [8]

It is well known that the lateral steel in reinforced concrete columns serves three primary functions, first it provides shear reinforcement. Secondly it restrains the buckling of longitudinal compression steel and thirdly it confines the concrete within the core of the column.

The use of confinement in reinforced concrete building columns, particularly for earthquake resistant structures, is to enhance the strength and increase the ductility of concrete.

The effectiveness of confinement depends on details of the confining reinforcement, compressive strength of plain concrete, aggregate type and other parameters which will be explained in section 2.2.

2.2 Parameters Affecting Confinement

Many studies provide different parameters among the parameters: [7, 15, and 16]

1. The ratio of transverse reinforcement
2. The yield strength of the transverse reinforcement
3. The compressive strength of concrete
4. The spacing of hoops
5. Longitudinal reinforcement
6. Configuration
7. Effect of aggregate in confinement will be discussed here below
 1. *The ratio of transverse reinforcement:* - is defined as the ratio of the volume of hoops to the volume of the confined core¹ of the member. It is expressed as the volumetric ratio ρ_w . When ρ_w is increased both the strength and the ductility of the confined concrete increase. Unless

adequate transverse reinforcement is provided to confine the compressed concrete within the core region and to prevent buckling of the longitudinal reinforcement failure is eminent.

2. *The yield strength of the transverse reinforcement:* - It is commonly understood that the maximum effective lateral confining pressure occurs when the hoop stresses reach to their yield strength. The higher the strength of the stirrups the higher the confining pressure that can exert.

3. *The compressive strength of concrete:* - When the strength of concrete increases the behavior of concrete becomes brittle and as a result the ultimate strain of the concrete decreases. In other words, when the grade of concrete increases the ductility of the concrete decrease.

4. *The spacing of hoops:* - The efficiency of confinement increases as the spacing becomes closer. Since the regions of the members which remain without confinement is smaller the effective confined stress increases and premature buckling of longitudinal bars after the spalling of concrete cover prevented. It is also worth mentioning that spacing of stirrups favorably affects the ductility of a member subjected to compression.

5. *Longitudinal reinforcement:* - The content and size of longitudinal reinforcement increase confinement effect by preventing the lateral expansion of the core. The larger the diameter of the bars and their ratio, the larger their contribution to confinement.

6. *Configuration:* - When multiple hoops patterns and spiral configuration are used in member, the region of unconfined concrete becomes smaller and result in strength and ductility enhancement.

7. *Effect of aggregate:* -The roundness of aggregate assists to distribute the lateral confinement and helps the concrete element to experience higher stress. On the other hand, angular grains lead to stress concentration that lowers the ability of the element to experience the same high stress. Moreover the bond between the paste and aggregate tends to set the upper limit on the strength of concrete the column might fail before the transverse reinforcement reaches their yield strength.

2.3 Confinement Mechanism

The mechanism of confinement can be explained here below in fig.2.1. First assume that there is no lateral steel. Under axial compression, the plain concrete expands laterally by an amount denoted by Δ_{cr} and reaches its lateral expansion capacity when the axial load approaches the maximum value. At crushing of concrete, the lateral expansion Δ_{cr} becomes extremely large. The presence of lateral steel reduces this lateral expansion by imposing a lateral confining force F_r and lateral compression Δ_{ro} and delay the crushing of concrete.[2]

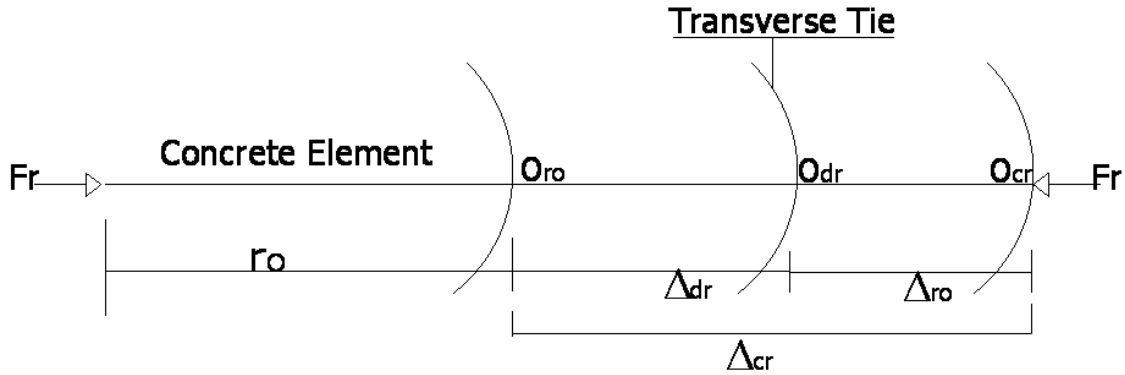


Figure 2.1 Confinement Mechanisms [2]

2.4 Confining Techniques

Many researchers have been done to investigate different confining techniques; for the purpose of this discussion some of the confining techniques are presented.

a. Confinement by spiral or circular hoops

Lateral confinement provided by spiral or circular reinforcement greatly improves the strength and ductility of concrete columns. The spirals confine concrete in circular columns much more effectively than rectangular or square ties.

Spiral or circular hoops, because of their shape are placed in hoop tension by the expanding concrete, and thus provide a continuous confining line load around the circumference as indicated in fig. 2.2. The maximum effective lateral pressure that can be induced in the concrete occurs when the spirals or circular hoops are stressed to their yield strength. [15]

For closely spaced of the spirals the behavior of the confined core is similar to that of concrete under moderate amounts of hydrostatic pressure. [15]

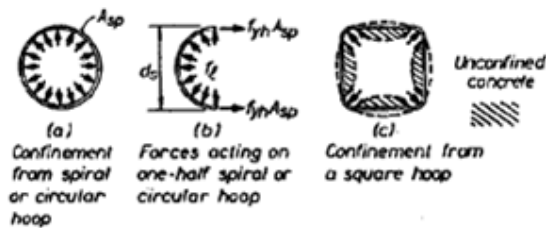


Figure 2.2 Confinement of Square and Circular Hoops [15]

b. Confinement by square or rectangular hoop

The strength and ductility of tied concrete columns was found to increase with an increase in the volumetric ratio of lateral ties.

The columns with 135° and 90° hooked cross ties were less ductile than columns with 180° hooks. Transverse reinforcement was capable of preventing spalling of concrete and delaying buckling of the longitudinal reinforcement in the concrete columns. Columns with 90° have limited confinement action, lesser strength enhancement and limited ductility. [14]

The welded stirrups ensured the lateral pressure all around the specimen until the stress passed the yield strength. Meanwhile, hooked stirrups experienced some deformation at the hook before failure. This deformation led to the loss of lateral confinement.

Square hoops can only confine reactions near the corners of the hoops because the pressure of the concrete against the sides of the hoops tends to bend the sides outward. The confinement of rectangular or square hoops can be improved by the use of overlapping hoops or by providing cross ties.

C. Fiber Reinforced Polymer (FRP) [21]

Fiber reinforced polymer (FRP) materials are generally associated with synthetic fiber materials such as fiber glass, carbon fibers, and aramids embedded in an epoxy or ester. Fiber composites generally possess higher strength to weight ratio than conventional construction materials such as steel.

Better confinement is achieved when the numbers of layers of FRP wrap is increased, this results in enhancing load carrying capacity of the column, in addition to the improvement of ductility.

Parameters affecting column confined by FRP:-

- The number of composite layers
- The corner radius for square shape and rectangular column, and
- The relation of FRP confinement with steel reinforcement.

Application of FRP

- Provide external confinement to reinforced concrete columns when the existing internal transverse reinforcement is inadequate.

Advantages of FRP as confinement

- Increase ductility; - As a result of the confinement provided the concrete will fail at a larger strain than the unconfined. Depending on the degree of confinement significant increases in ductility can be achieved.
- Increase strength: - The lateral pressure exerted by the straps will increase the compressive strength of the concrete in both the core and shell regions resulting in higher load carrying capacity. The lateral confinement provided by the straps will also provide additional support against bulking of the longitudinal bars.

c. Steel Jacketing [15]

Steel jacketing has been widely used for seismic retrofit of highway bridge columns. A deficient circular column is covered with pre-fabricated steel shells (or jacket) which are jointed together either by welding or mechanical connections. The small gap between the jacket and the column, which is usually less than 10 mm, is filled with grout to provide continuity between the jacket and the column. The new column section is much stronger and stiffer than the original column.

For circular columns, the jackets are constructed in two half-shells slightly oversized for easy installation, which are welded in situ along the vertical seams.

For rectangular columns, the jacket is usually rolled to an elliptical shape, and the gaps between the casing and the column are filled with concrete rather than grout as shown in Figure 2.3. The elliptical shape is needed to provide a continuous confining pressure by passive restraint in potential plastic hinge regions. Rectangular steel jackets for retrofitting rectangular columns also increase the strength and ductility of columns. Research results have shown that rectangular jackets are less effective than elliptical jackets.

Advantage of steel jacketing

The retrofitting of circular columns with steel circular jackets, and rectangular columns with elliptical jackets, provides a significant increase in the seismic resistance of the columns.

Application

Since this confining technique requires substantial labor and expensive material cost the use of steel jacketing might be justified for bridges or some industrial facilities where a small number of columns are needed.

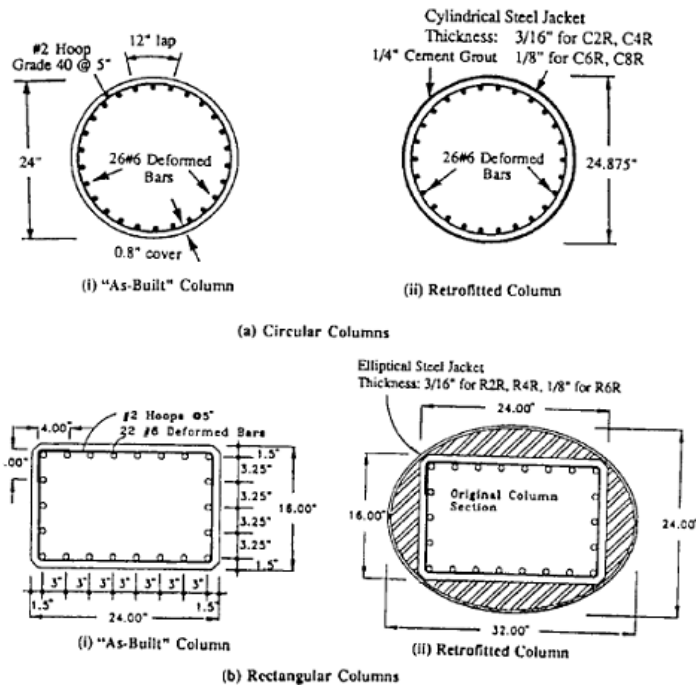


Figure 2.3 Retrofit of Circular and Rectangular Columns with Steel Jackets [15]

2.5 Code Provision on Confinement [1, 5, 6, 11]

Different design codes such as ACI, Netherland, Euro, and EBCS provide the area requirement for both circular and rectangular columns as well as minimum spacing of transversal ties. The minimum values for confinement is given in the following table.

Table 2.1 Code Provision on Confinement

ES	Circular column requirement	Angular column requirement	Minimum Spacing of transversal ties
	<p>girth ratio of circular hoop reinforcement shall not be less than</p> $0.12 \frac{f'_c}{f_{yt}}$	<p>total effective length in each of the global directions</p> <p>cross-section</p> <p>not be less than</p> $0.3 \left(\frac{s b_c f'_c}{f_{yt}} \right) \left[\left(\frac{A_g}{A_c} \right) \right]$	<p>of the minimum member dimension;</p> <p>times diameter of the longitudinal reinforcement; and</p> <p>transverse reinforcement is the need for</p> <p>ement of lap splices subjected to stress</p> <p>Als.</p>
land	<p>girth ratio of circular hoop reinforcement shall not be less than</p> <p>ger of</p> $0.4 k_p \left(\frac{f'_c}{f_t} \right)$ $0.45 \frac{f'_c}{f_{yt}} \left(\frac{A_g}{A_{ch}} - 1 \right)$	<p>total effective length in each of the global directions</p> <p>cross-section</p> <p>not be less than</p> <p>larger of</p> $0.2 k_x k_p \left(\frac{s b_c f'_c}{f_{yt}} \right)$ $0.09 \left(\frac{f'_c}{f_{yt}} \right) s b_c$	<p>the three spacing limits required by ACI</p> <p>quired by CSA.</p>

3. EXPERIMENTAL PROGRAM

3.1 General

The experimental program of this research is divided into two confining techniques confining the column by transverse reinforcement and confinement by wire mesh. Test program was designed to examine the effectiveness of confinement with different geometrical configuration of lateral reinforcement and increasing number of layers of wire mesh. Three series of lateral reinforcement were used; cross tie, normal and over lapping arrangements with square cross section. In addition, one, two and three layers of wire mesh were used for both circular and square cross sections. The yield strength of 280 Mpa for the transverse reinforcement and 80 Mpa for the wire mesh were taken.

3.2 Test Specimens

The experimental investigations were carried out on thirty three specimens of reinforced concrete column having 150 mm diameter circular column and 150mm x150mm square columns with 300 mm height.

Out of the thirty three specimens to be investigated, six specimens three from circular and three from square columns were tested without having transverse reinforcement and wire mesh. Three series of samples were tested with different geometric configuration of transversal reinforcement as shown in fig.3.1 below and six series of samples were taken for circular and square columns by varying the number of layers of the wire mesh as shown in fig 3.2 for each series three samples were taken.



a. Normal tie configuration

b. overlapping configuration

c. cross tie configuration

Figure 3.1 Different Geometrical Configurattion of Transverse Reinforcement



One layer



Two layers



Three layers

Figure 3.2a Different Layer of Wire Mesh on Circular Column



One layer



Two layers



Three layers

Figure 3.2b Different Layer of Wire Mesh on Square Column

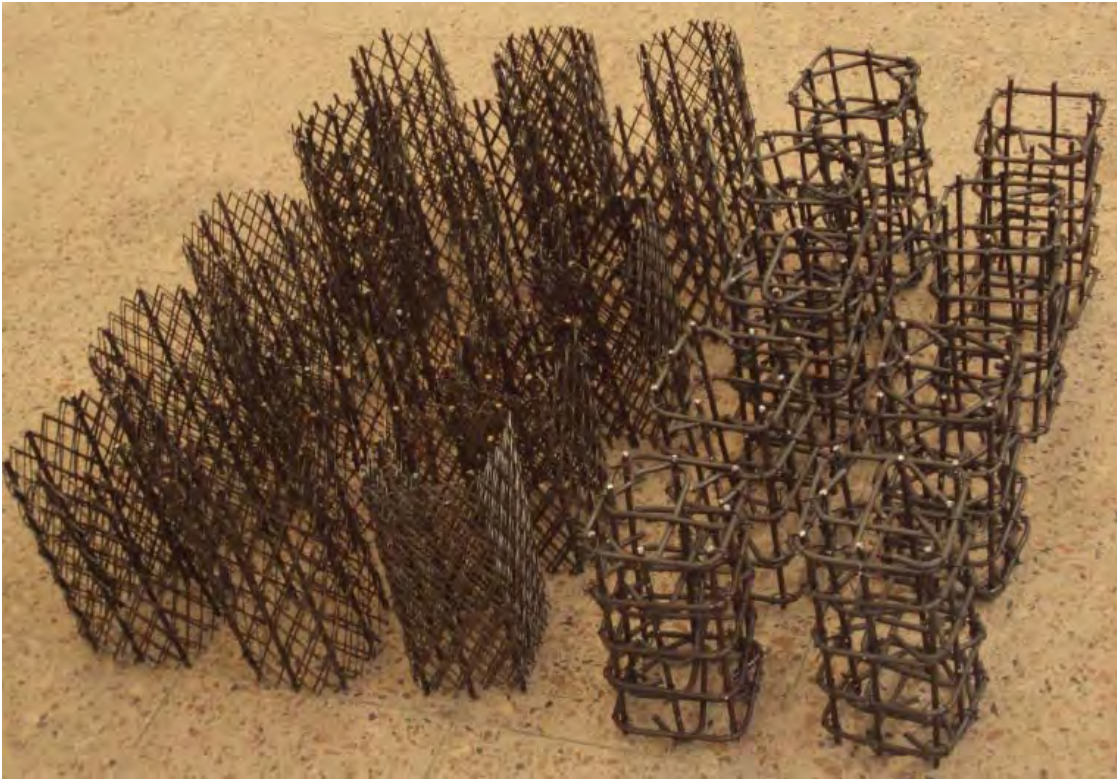


Figure 3.3 all samples

The specimen name consists of three characters; the first refers to the type of cross section (S for square, and C for circular columns), L for 1.5 mm thick wire mesh, and N,CT, OL symbols represent normal, cross tie and over lapping configuration of transverses reinforcement respectively.

For unconfined column it was designated by the word U and the last character identifies the number of layers of wire mesh (L1 for one layer, L2 for two layers and L3 for three layers). 6mm diameter steel was used for the transverse and longitudinal reinforcement and the spacing of the transverse reinforcement was 60 mm.

A cover of 15mm was provided between the ends of the longitudinal bars and 20mm for top and bottom surfaces of the specimens to prevent direct loading of the longitudinal bars.

Table 3.1 Summary of Test Specimen Designation

Test Specimen	No of sample	Designation
Unconfined square	3	US
Unconfined circular	3	UC
Normal hoop configuration	3	N
Cross tie configuration	3	CT
Overlapping configuration	3	OL
One layer square wire mesh	3	SL1
Two layer square wire mesh	3	SL2
Three layer square wire mesh	3	SL3
One layer circular wire mesh	3	CL1
Two layer circular wire mesh	3	CL2
Three layer circular wire mesh	3	CL3

3.3 Material Properties and Test Setup

Concrete- Ready mix normal strength concrete with 19mm maximum size round aggregate with a 25mm slump height was used for all the specimens. Specified 28 day compressive strength of the concrete was found as 30.7MPa. Three concrete cubes were also cast for each batch to determine the compressive strength of concrete on the day of column testing.

Concrete mix preparation

The specimens were made of three batches of concrete mix with the same proportion. The intension was to use the same batch of concrete mix for all series but the capacity of the mixer in the laboratory is small to prepare one mix for all samples at the same time. Thus, three batches of concrete mix were prepared and the cube test of each mix was conducted.

Reinforced steel – **A** 6mm diameter longitudinal and transverse reinforcement of grade 280MPa and 80MPa for the wire mesh were used.

Table 3.2 Summary of Test Result of Compressive Strength and Tensile Strength of Materials

Type of Test	Stress [Mpa]
Compressive Strength of Cube Test	30.7
Yield Strength of Transverse Steel	280
Yield Strength of Transverse Wire Mesh	80

Instrumentation

Axial deformations of columns were measured by strain gage. One strain gage with a gage length of 240mm was placed on each column face as shown in fig. 3.4.

Test setup and procedure

The columns were tested using a Universal Testing Machine shown in fig. 3.4a with a 2000kN load capacity. The load is applied by means of hydraulic pressure. When the specimen ready to be tested as shown in fig. 3.4b, the column specimen was raised in vertical position and placed in the machine. Once placed in the machine, the specimen was hanged to the head of the machine as shown in fig. 3.4 c. Special care was taken that the column specimen was directly at the center of the machine. After the specimen was installed in the machine external strain gages were installed to measure vertical displacements as shown in fig. 3.4 c after finishing preparation of specimen for test the load was applied concentrically.

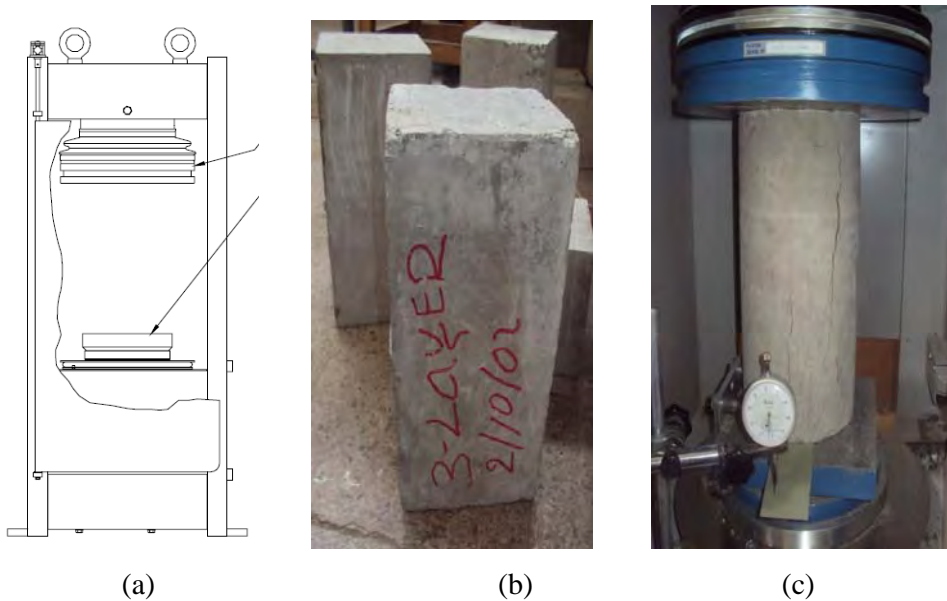


Figure 3.4 Test Setup

4. TEST RESULT AND DISCUSSION

4.1 General

The observations and results obtained from the experiments are presented in detail in this chapter. As was discussed in Chapter Three, the objective of the research is to study the effect of confinement on the strength and ductility of reinforced concrete column. Accordingly the research investigated three types of short columns, i.e

- Specimens with transverse reinforcements with normal, cross tie and over lapping arrangement;
- Specimens with one, two and three layers of wire mesh and
- Specimens without confinement.

All these three types of specimens were loaded with monotonically applied uniform axial compression load.

Peak stress and peak strain of the test results are illustrated in table 4.1. A complete list of test data for all test specimens is provided in Appendix A.

The results of the monotonic tests performed with the nine described models were analyzed taking several parameters into consideration: 1) cracking pattern; 2) maximum load, 3) contributions of the unconfined and confined column to the global strength.

4.1 Summary of test result

Table 4.1 Summary of Test Result of Peak Stress and Peak Strain

Specimen	Peak Stress(Mpa)	Peak Strain
N	25.52	0.004
CT	33.24	0.0063
OL	30.73	0.00533
US	24.6	0.00342
UC	24.45	0.0031
SL1	26.79	0.0052
SL2	34.12	0.0056
SL3	35.75	0.006
CL1	26.75	0.0075
CL2	28	0.0078
CL3	30.56	0.0087

Table 4.2 Summary of test result of compressive strength and Tensile strength of the materials

Type of Test	Stress [Mpa]
Compressive Strength of Cube Test	30
Yield of Transverse Steel	280
Yield Strength of Transverse Wire Mesh	80

4.2 Specimen Confined by Transverse Reinforcement

4.2.1 General

The plain concrete specimen, failed in a brittle manner and in the presence of a large diagonal crack approximately 30 degree to the longitudinal axis of the specimens shown in fig. 4.1.



Figure 4.1 Failure of Unconfined Concrete Column

All specimens confined by transverse reinforcement experienced similar failure modes. The failures happened at the middle third of the specimen. The failure mechanism was initiated by vertical cracks followed first by lateral deflection of the plain concrete .When the axial load increase the specimen start to show small vertical crack as shown in fig.4.2a when the axial load approach to the maximum value the extent of cracking increase as shown in fig.4.2b and c finally the loose cover concrete is spalled off and the longitudinal reinforcement experienced noticeable deformation as shown in fig. 4.2d. After the specimen reach the maximum load 135degree hook

of the stirrups become almost 90 degree due to the increasing of the lateral expansion of the core as shown in fig.4.2d.

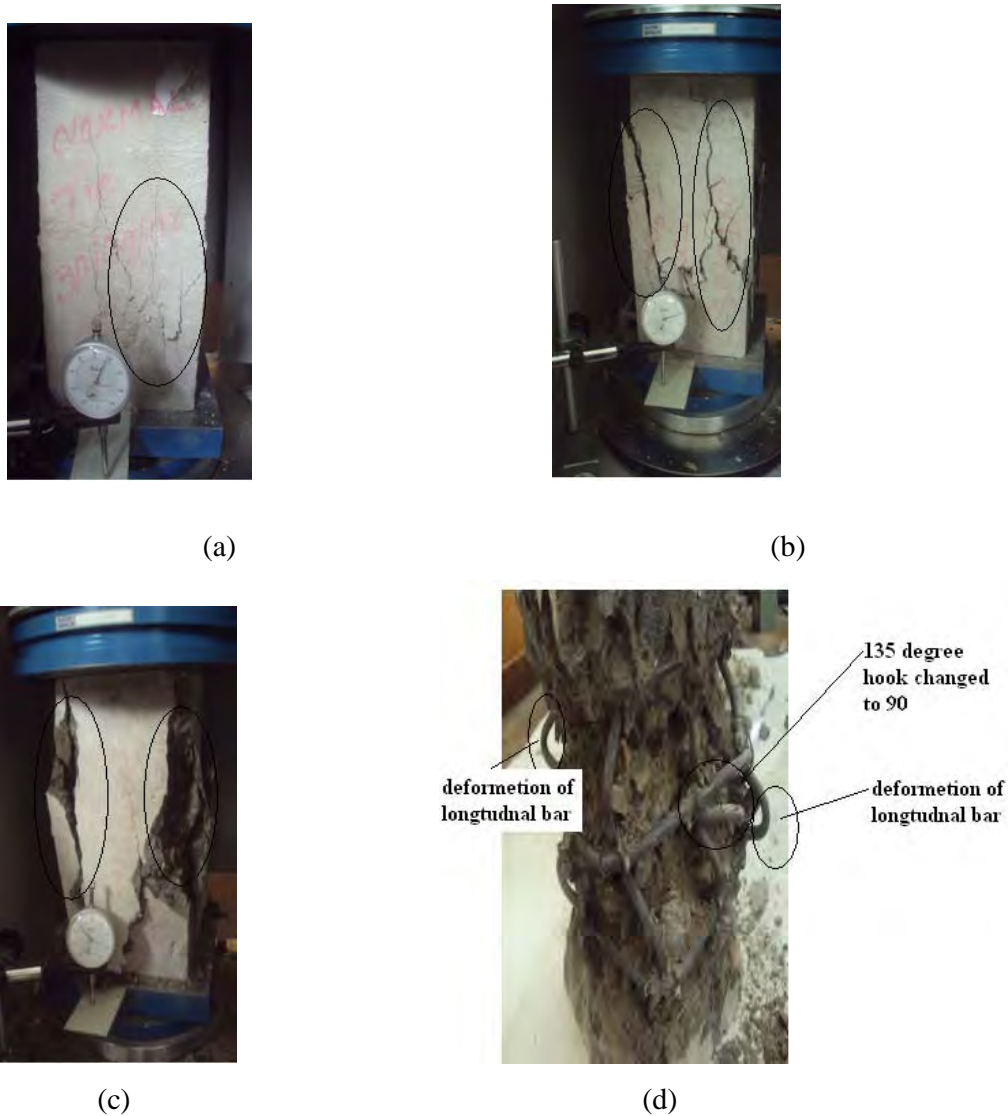


Figure 4.2 Failure Pattern of Specimen Confined by Transverse Reinforcement

4.2.2 Effect of Configuration of Transverse Reinforcement

Fig. 4.3 shows stress-strain curves, for three specimens with different geometrical configuration of transverse tie which are cross tie, normal hoop and overlapping configuration in addition to unconfined specimen.

As can be seen, the experimental initial slopes of the ascending branch resulted by all specimen agree well with the unconfined stress-strain curves. It seems that the elastic modulus is not dependent on the confinement level. This is because the confinement steel is only effective once the loading approaches a considerable value, in other words the lateral confining stress at this

stage of loading is so small to confine the concrete core. As a result, the contribution of the confinement took place at later steps of loading.

When the longitudinal bar is tied with the same spacing of transverse reinforcement but different configurations specimen with cross tie, overlapping and normal hoop shows 34.13%, 24.66% and 3.51% enhancement in peak strength when it compared with unconfined specimen respectively.

In addition a peak strain increment of 45.76%, 35.94% and 14.58% for cross tie, over lapping and normal tie are observed respectively when it compared with unconfined specimen.

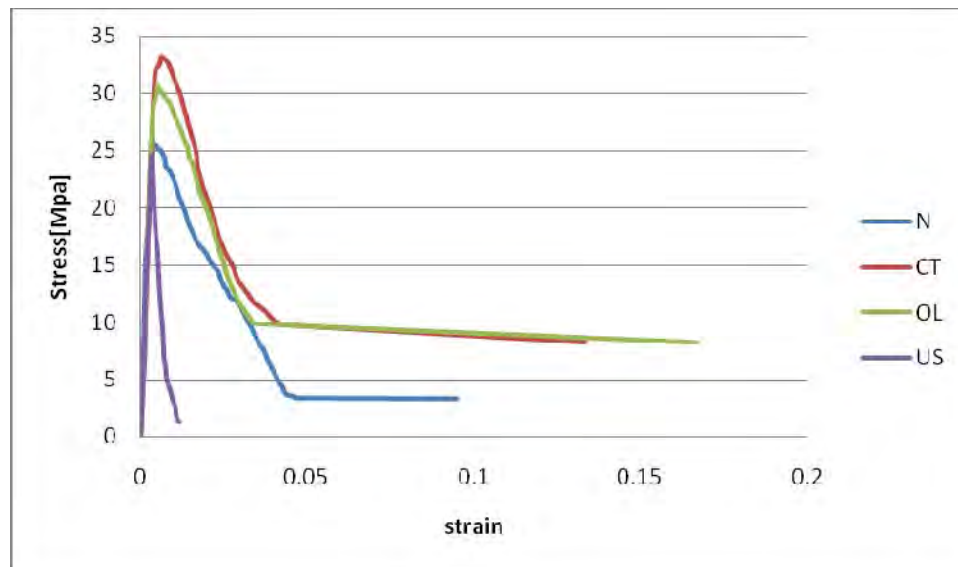


Figure 4.3 Stress-Strain Curves for Normal, Cross tie, Overlapping and Unconfined Concrete Column

The results demonstrate the significant effect of the geometrical configuration of transverse tie on the peak strength and on the descending portion of the stress-strain curve. Comparison of the test result indicate that the cross tie configuration give higher strength and ductility than others configuration.

Table 4.3 Summary of Comparison of Stress-Stain of Specimen Confined by Transverse Reinforcement with Unconfined Concrete Column

Specimen Name	Peak Stress[Mpa]	% increase	Peak Strain	% increase
N	25.52	3.51	0.0040	14.58
CT	33.24	34.84	0.0063	45.77
OL	30.73	24.66	0.0053	35.94
US	24.66		0.0034	
UC	23.71			

4.3 Specimen Confined by Wire Mesh

4.3.1 General

The tested specimens for circular and square column confined by wire mesh experienced similar failure modes as transverse tie until spalling of concrete cover. The sequence of cracking until spalling of concrete cover is shown in fig. 4.4 a & b. After spalling of concrete cover the extent of the size of lateral deformation is increased as a result of the lateral deformation of the core concrete the wire mesh start to pack together and the specimen bulged as shown in fig.4.4d when the test stopped due to the limitation of the machine.

Due to smaller yield stress of the wire mesh specimen confined by one layer (square and circular) column didn't recorded significant enhancement in strength.



(a)



(b)



(c)



(d)

Figure 4.4 Failure Pattern of Reinforced Concrete Column Confined by Wire Mesh

4.3.2 Square Specimen Confined by Wire mesh

The stress strain curves in fig.4.5 and table 4.2 shows the response of three different specimens having the same number and diameter of longitudinal bar but in different number of layers.

The results shows 7.61% , 35.62% and 37.98% increment in peak stress and 51.22% , 65.85% and 75.61% increment in peak strain when plain specimen compared with one, two and three layers wire mesh respectively.

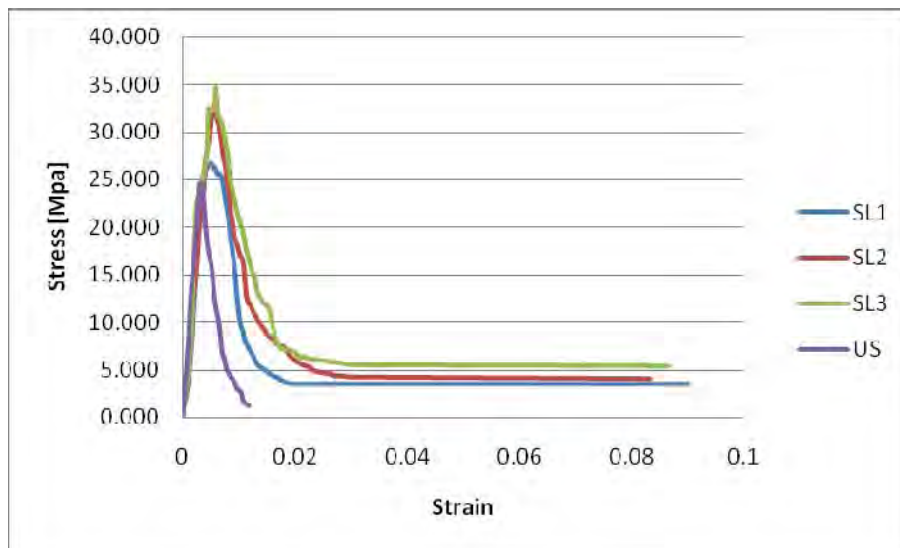


Figure 4.5 Stress Strain Curve for SL1, SL2, SL3 and US Specimen

4.3.2 Circular specimen Confined by wire mesh

The stress-strain curves in fig.4.6 and table 4.2 show the response of the three different specimens having the same circular cross section, the same number and diameter of longitudinal bar but in different number of layers.

The results shows 8.51% , 13.55%, 23.93% increment in peak stress and 119.51% , 129.27%, 154.63% increment in peak strain when plain specimen compared with one, two and three layers wire mesh respectively.

Table 4.4 Summary of Comparison of Concrete Column Confined by Wire Mesh with Unconfined Concrete

Specimen S	Number of layer	Peak Stress	Peak Stress % increase	Peak Strain	Peak Strain % increase
Square	one	26.79	8.65	0.0052	52.20
	two	34.12	38.39	0.0056	63.90
	three	35.75	44.98	0.0060	75.61
Circular	one	26.75	12.84	0.0075	119.51
	two	28.00	18.08	0.0078	129.27
	three	30.56	28.87	0.0087	154.63

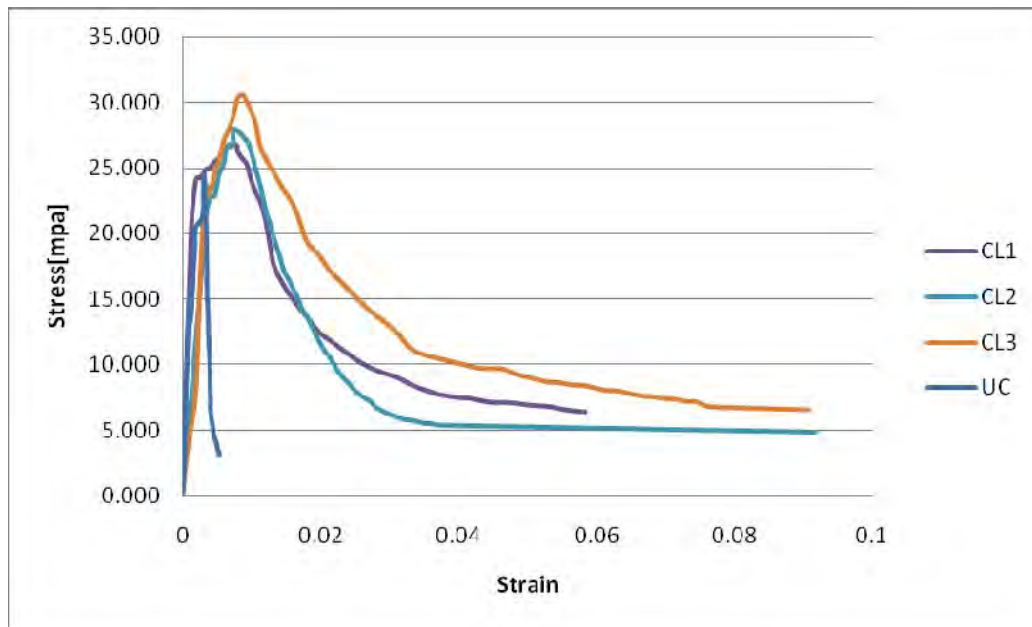


Figure 4.6 Stress-Strain Curve of CL1, CL2, CL3 of Wire Mesh

4.3.3 Effect of number of layer and shape of the cross section

As can be observed from the stress-strain curves in fig.4.7, confinement of square and circular column have no much difference in the ascending branch. However, specimen with circular cross section shows a lesser peak stress than a square cross section. This reduction in strength may be due to the size of the core area for square column is larger than circular ones. On the contrary, the descending part of the curve for the circular cross section shows ductile failure than square cross

section and the circular stress-strain curve in the descending region is more flatter than the square specimen.

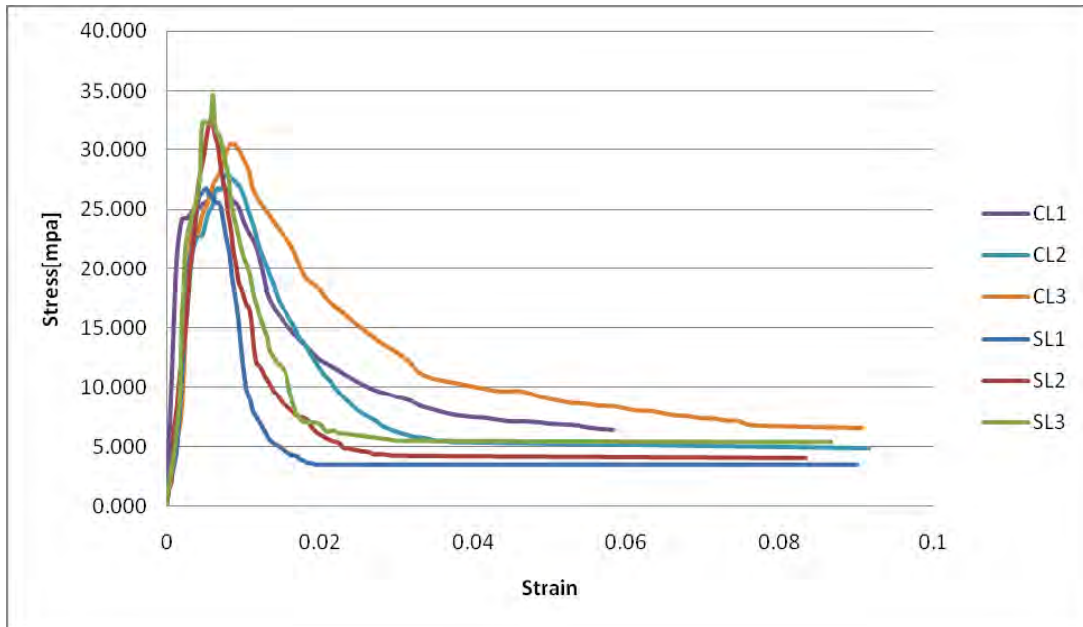


Figure 4.7 Stress-Strain Curve of Circular and Square Column Confined by Wire Mesh

4.3.4 Comparison of three layer square (SL3), three layer circular (CL3) and Cross tie configuration (CT)

The stress-strain diagram shown in fig.4.8 illustrates confinement with SL3, CL3 and CT have the same curve in the ascending region but as explained in section above specimen with circular cross section show lesser strength than SL3 and CT. But in the descending portion of the stress-strain curve CT and CL3 specimen, fig4.8 shows more ductile failures and flatter curve than SL3. CL3 and CT also preserve the strength and prevent sudden loose of strength in the descending part of stress strain curve. Significant enhancement in peak strain and ductility was observed in specimens confined by CL3 and CT configuration. Especially specimen confined by circular cross section shows an enhancement in peak strain and ductility almost twice than unconfined specimen.

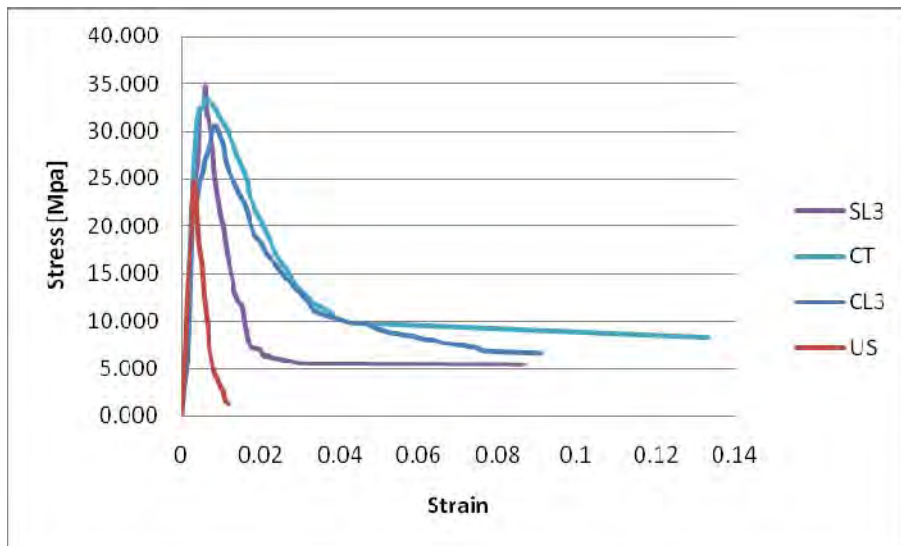


Figure 4.8 Stress Strain Curve of US, CL3, SL3 and CT

5. REVIEW OF CONFINED AND UNCONFINED MODEL

5.1 General

The earthquake resistant properties of a material can be evaluated using their stress-strain diagrams where both the strength and deformation characteristic are reflected. The determination of stress strain characteristics of confined concrete can be carried out experimentally and analytically.

A number of analytical models have been proposed by different researchers to describe the stress strain characteristics of the confined concrete. Brief detail and assumptions made for the application of models are explained below.

5.2 Unconfined Concrete from EURO Code [6]

Deformation and strength characteristics of a material can be reflected using their stress strain diagram. The relation between σ_c and ϵ_c for short term uniaxial loading is described by the expression below

$$\frac{\sigma_c}{f_{cm}} = \frac{k\eta - \eta^2}{1 + (k - 2)\eta} \dots\dots\dots (5.1)$$

Where

$$\eta = \frac{\epsilon_c}{\epsilon_{c1}} \dots\dots\dots (5.2)$$

ϵ_{c1} is the strain at peak stress according to [table 3.1 of EURO code]

$$k = 1.05 E_{cm} x \left| \frac{\epsilon_{c1}}{f_{cm}} \right| \dots\dots\dots (5.3)$$

f_{cm} is according to table 3.1 of EURO code [6]

Expression of 3.14 is valid for $0 < |\epsilon_c| < |\epsilon_{cu1}|$ where ϵ_{cu1} is the nominal ultimate strain $\epsilon_{cu1}=0.0035$,

5.3 Confined Concrete

5.3.1 Model of Kent and Park (1971) [9]

Charles Kent and Robert Park proposed stress strain curve on the basis of the existing experimental evidence. The stress strain model is illustrated in fig.5.1. It combines many of the features of previously proposed curves.

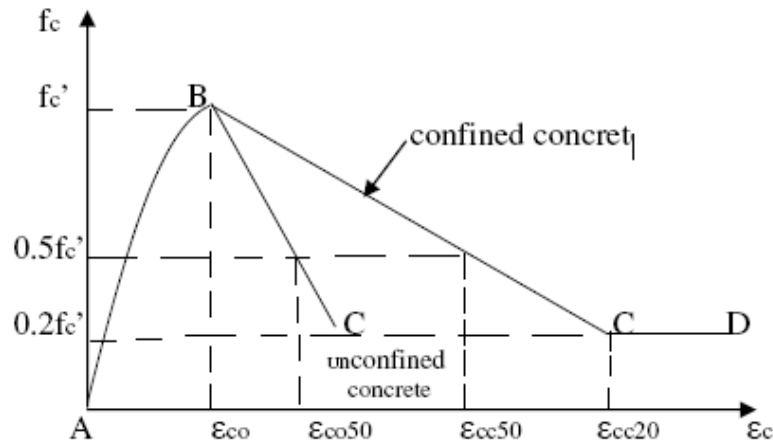


Figure 5.1 Proposed Stress-Strain Relationships for Unconfined and Confined Concrete [9]

As can be seen from Figure 5.1, the stress strain curve is divided in to three regions. Region AB of the ascending part, Region BC & Region CD on the falling apart.

Region AB: The ascending branch of the curve is represented by a second degree parabola. Transverse reinforcement has no effect on the shape of this part of the curve, as the lateral strains, which would cause the hoop to be significantly stressed, occur only when the maximum concrete stress almost reached. The maximum flexural stress reached by both confined and unconfined concrete is the same and this is referred to the cylinder strength, f_c . The strain at maximum stress is assumed to be $\epsilon_{co}=0.002$, which is a commonly accepted assumption for unconfined concrete.

In this region, the stress f_c is represented by:

$$f_c = f_c' \left(\frac{2\epsilon_c}{\epsilon_{co}} - \left(\frac{\epsilon_c}{\epsilon_{co}} \right)^2 \right) \dots\dots\dots (5.4)$$

Where $\epsilon_{co} = 0.002$

Reign BC: The falling branch of the curve is assumed to be linear and its slope is specified by determining the strain when the concrete stress has fallen to 0.5 of maximum stress. ϵ_{c050} is obtained from the results of a number of investigators. In short term loading rate, the experimental points confirm reasonably closely to:

$$\epsilon_{c050} = \frac{3 + 0.29f'_c}{145f'_c - 1000} \dots\dots\dots (5.5)$$

Where f'_c in MPa

For concrete confined by rectangular hoops, the slope of the falling branch is reduced due to the variables consisting of:

- cross sectional area of the hoop bar, A_s
- center to center spacing of hoops, S
- ratio of hoop spacing to minimum dimension of the confined core, S/B
- ratio of hoop bar diameter to core dimension D/B hoop yield stress, f_y and strength of concrete

In the calculation of ϵ_{cc50} , it was assumed that by time the strain ϵ_{cc50} is reached, all the concrete outside the core has spalled away. On this basis, if the maximum load carried by the specimen is P_m , the maximum stress will be P_m/A_g , and when the stress in the concrete core is reduced to 50% of the maximum stress, the load on the specimen is given by:

$$P_{50} = 0.5 \left(\frac{P_m}{A_g} \right) A_c \dots\dots\dots (5.6)$$

Additional strain at 50% of the maximum stress, ϵ_{c50h} on the falling branch is given by :

$$\epsilon_{c50h} = \epsilon_{cc} - \epsilon_{c050} = \frac{3}{4} \rho \sqrt{\frac{B}{S}} \dots\dots\dots (5.7)$$

In which $\rho = \frac{2(B_x + B_y)A_s}{B_x * B_y * S} \dots\dots\dots (5.7)$

Where B – width of confined core measured to outside of hoops

A_s – area of transverse reinforcement

S – Center to center spacing of transverse steel Equation for the falling branch BC may be written as:

$$f_c = f'_c (1 - Z(\epsilon_c - \epsilon_{co})) \dots\dots\dots (5.9)$$

$$Z = \frac{0.5}{\epsilon_{c50h} + \epsilon_{cc50} - \epsilon_{co}} \dots\dots\dots (5.10)$$

Where $\epsilon_{co} = 0.002$; and

ϵ_{c50h} additional strain at 50% of the maximum stress on the falling branch and is given by :

$$= \epsilon_{cc50} - \epsilon_{co50}$$

Region CD: It is assumed that the concrete can sustain a stress of $0.2f'_c$ from ϵ_{cc20} to infinity.

5.3.2 Modified Kent and Park stress strain Model (1982) [10]

Contrary to the previous model, this model takes into account the strength enhancement due to confinement. The maximum stress reached (at point B in Fig. 5.1) is changed to Kf'_c at a strain of $\epsilon_{cco} = 0.002K$

$$\text{Where } K = 1 + \frac{\rho_h f_y}{f'_c} \dots\dots\dots (5.11)$$

ρ_h – ratio of volume of rectangular hoops to volume of concrete core measured to outside of the peripheral hoop

f'_c – concrete compressive cylinder strength

f_y – yield strength of hoop

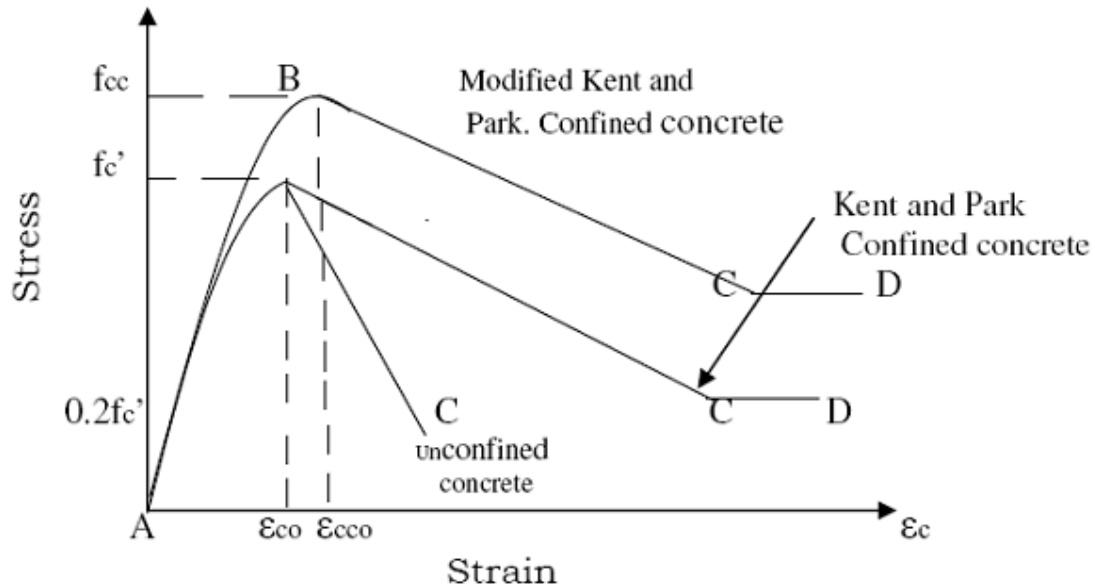


Figure 5.2 Stress-Strain Relationships for Unconfined and Confined Concrete for Modified Kent and Park [10]

Equation 5.11 assumes that rectangular hoops cause an increase of concrete strength by $\rho_h f_y$ as observed in tests conducted at the University of Canterbury on axially loaded member [7]. The concrete strain corresponding to maximum concrete stress is taken as $0.002K$, in which 0.002 is the assumed value of the strain at maximum stress of unconfined concrete. This assumed value for the strain at maximum stress enables the parabola defining the region AB of Fig. 5.1 to have the same slope at the origin, i.e., the same tangent modulus of elasticity of concrete at zero stress) as for unconfined concrete regardless of the confining steel content.

Based on this, the Modified Kent and Park stress strain curve is defined as:

For region AB; where $\epsilon_c \leq 0.002K$

$$f_c = Kf'_c \left(\frac{2\epsilon_c}{0.002K} - \left(\frac{\epsilon_c}{0.002K} \right)^2 \right) \dots\dots\dots (5.12)$$

For region BC; where $\epsilon_c > 0.002K$

$$f_c = Kf'_c (1 - Z_m (\epsilon_c - 0.002K)) > 0.2Kf'_c \dots\dots\dots (5.13)$$

$$Z = \frac{0.5}{\frac{3 + 0.29f'_c}{145f'_c - 1000} + \frac{3}{4}\rho h \sqrt{\frac{B}{S}} - 0.002K} \dots\dots\dots (5.14)$$

For region CD it is assumed that the concrete can sustain a stress of $0.2Kf'_c$ from ϵ_{cc20} to infinity.

5.3.3 Sheik and Uzumeri [20]

The analytical model proposed by Sheikh and Uzumeri assumes that the effectively confined concrete area is less than the core area and is determined by introducing the effectiveness confinement coefficient that takes in account the distribution of longitudinal steel, the tie configuration and the spacing of ties.

A complete stress strain curve shown in Fig. 5.3 is proposed. The curve represents the behavior of concrete in the core, i.e., center to center of perimeter tie. The curve consists of three parts.

Part AB and BC of the curve are straight lines. Beyond point C, the curve can be expected to continue in the same straight line until the stress is dropped to about 30% of the maximum value. Beyond point D, a horizontal line can be assumed to represent concrete behavior.

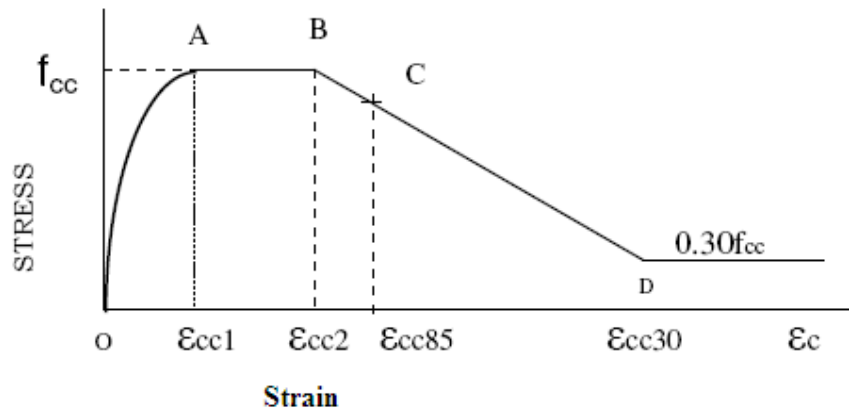


Figure 5.3 Stress-Strain Curves Proposed by Uzumeri and Sheikh [20]

In which, f_{co} – the compressive strength of concrete in plain specimen

- k_s – The strength gain factor
- $\epsilon_{cc1}, \epsilon_{cc2}$ – the minimum and maximum strain value corresponding to the maximum stress, respectively.
- ϵ_{cc85} – is the value of the strain corresponding to 85% of the maximum stress on the unloading branch of the curve.

According to this model, the relation between the concrete strength and the lateral confinement produced by rectilinear hoops can be expressed as follows:

$$f_{cc} = f_{co} + f(\rho_h, s, f_s, \lambda, \eta)$$

Where;

ρ_h – the ratio of the volume of total lateral reinforcement to the volume of the core concrete.

S – Tie spacing.

f_s – Stress in the transverse reinforcement.

λ – A factor that take in to account the configuration of the sector and distribution of longitudinal bars around the core perimeter

η – Represents the effect of the size of the section.

The increase in strength of confined concrete is calculated on the basis of the “effectively confined” concrete area. This area is less than the nominal core area bounded by the centerline of the perimeter tie and is determined by tie configuration and tie spacing. The effectively confined concrete area is then evaluated to calculate the gain in the concrete strength.

Effectively confined concrete core: the confining pressure is not uniformly applied throughout the whole volume of the core concrete. At high strains, when the cover is spalled off, a portion of the core concrete also becomes less effective in resisting the applied load. Area of the effectively confined concrete at the tie level will be primarily defined by the distribution of longitudinal steel bars fully supported by a bend of a tie, and for all practical cases, will be less than the core area. At a section midway between ties, the area of effectively confined concrete has the least volume and is determined by the tie spacing in addition to the configuration.

At a tie level, depending upon the configuration of ties and distance between the longitudinal bars, some of the concrete at the surface of the core remains unconfined. In Figure 5.4, this concrete is shown as shaded.

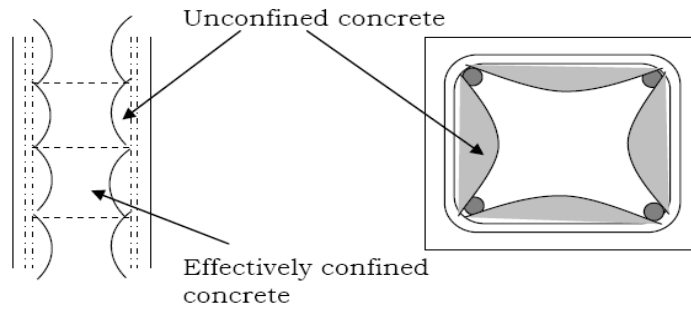


Figure 5.4 Effectively Confined Concrete Core [20]

The area of the concrete that is not confined effectively can be estimated, as shown in Figure 5.5.

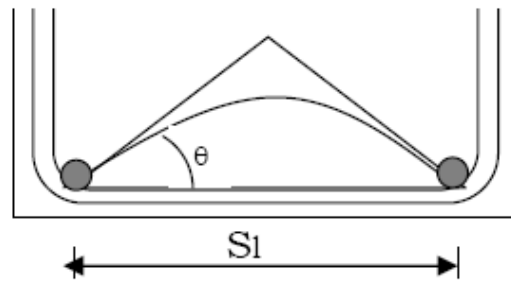


Figure 5.5 Estimation of Unconfined Concrete Core Area [20]

In this model, it is assumed that the separation between the effectively confined concrete and the unconfined concrete is in the form of a series of arcs spanning between the bars. It is also assumed that the arc may be located between triangle and a second degree parabola with the initial angle of the tangent to the horizontal as θ . The area under the curves is $S_1^2/6\cot \theta$ for a parabola and $S_1^2/4\cot \theta$ for a triangle in which S_1 is the base of the curve. As the exact shape of the arc is not known, the unconfined area can be represented by S_1^2/α , in which α is constant, the value of which is defined by the exact shape of the curves. The area of the effectively confined concrete core at the tie level may be written as:

$$A_c = \sum_{i=1}^n \frac{S_i^2}{\alpha} \dots\dots\dots (5.15)$$

Where; A_c – the core area enclosed by the center line of outer tie

n – Number of arcs

S_i – center to center distance between longitudinal bars

A_s the distance of a section from the set of ties increases, the area on which the confinement is effective further will decrease. The strength of the column is governed by the smallest area of a section that is midway between the ties.

Larger spacing would result in a smaller confined area of concrete and vice versa. In this model, the compressive strength of confined concrete in the specimen is equal to $k_s f_{co}$,

In which;

f_{co} – the compressive strength of concrete in plain specimen

k_s – Strength gain factor

$$K_s = 1 + \frac{B^2}{140P_{occ}} \left(\left(1 - \frac{nS_i^2}{5.5B^2} \right) \left(1 - \frac{S_i}{2B} \right)^2 \right) \sqrt{\rho_h f_s} \dots\dots\dots (5.16)$$

f_s – Stress in lateral reinforcement in MPa

ρ_h – the ratio of the volume of total lateral reinforcement to the volume of core

B- Center to center distance of perimeter tie of square core in millimeter.

P_{occ} – unconfined compressive strength of the concrete core f_s in Mpa and P_{occ} in kN

S – Spacing of stirrups

According to this model, when spacing of ties is twice the core size, the confinement is not effective at all in enhancing the strength of concrete.

Strains corresponding to the maximum concrete stress can be computed as :

ϵ_{cc1} , the minimum strain corresponding to the maximum concrete stress

$$\epsilon_{cc1} = 80 k_s f_c' * 10^{-6} \dots\dots\dots (5.17)$$

Where f_c' in Mpa

Similarly, ϵ_{cc2} , the maximum strain corresponding to the maximum stress is given by:

$$\frac{\epsilon_{cc2}}{\epsilon_{co}} = 1 + \frac{248}{S_i} \left(1 - 5 \left(\frac{S}{B} \right)^2 \right) \frac{\rho_h f_s}{\sqrt{f_c'}} \dots\dots\dots (5.18)$$

In which S_i in millimeters and stresses are in Mpa

where by ϵ_{co} – strain corresponding to the maximum stress in plain concrete.

The slope Z of the unloading part of the curve is obtained by modifying the equation proposed by Kent & Park and is given as;

$$Z = \frac{0.50}{\frac{3}{4} \rho_h \sqrt{\frac{B}{S}}} \dots\dots\dots (5.19)$$

The strain values corresponding to 0.85 times the maximum concrete stress calculated as:

$$\varepsilon_{cc85} = 0.225 \rho_h \sqrt{\frac{B}{S}} + \varepsilon_{cc2} \dots \dots \dots (5.20)$$

The application of this model required the knowledge of the stress in the transverse reinforcement at the time of maximum force in concrete. And since the gain in concrete strength is not very sensitive to the stress in the steel, the yield strength of the steel can be used for f_s .

5.3.4 Model of Mander, Priestly and Park [13]

The unified stress strain approach suggested by Mander et.al is based on the multi axial properties of concrete. The influence of various types of confinement is taken in to account by defining an effective lateral confining stress, which is dependent on the configuration of the transverse and longitudinal reinforcement. The model is based on experiment done on actual sized circular as well as rectangular columns with a wide range of transverse reinforcement.

The model was based on experiments done on actual sized circular as well as rectangular columns with a wide range of transverse reinforcement ratios. The stress strain model is shown in Figure 5.6

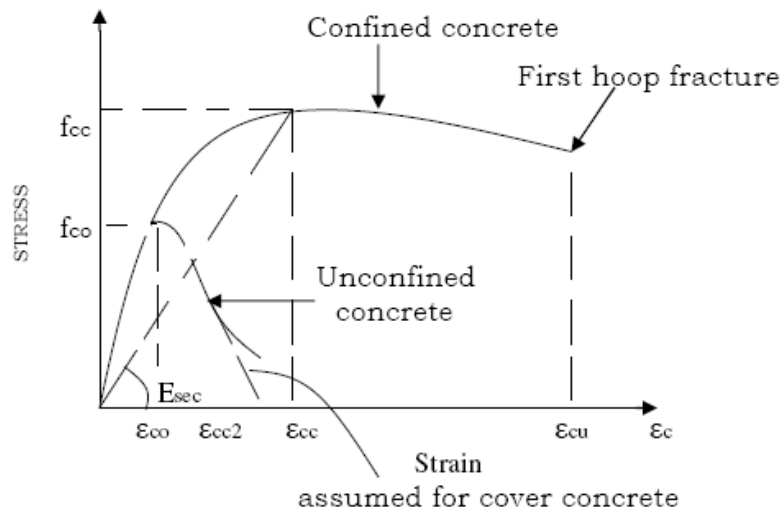


Figure 5.6 Stress-Strain Characteristic for Confined Concrete Proposed by Mander [13]

Compression strength of confined concrete: - the compression strength of confined concrete is directly related to the effective confining stress f_{le} that can be developed at yield of the transverse reinforcement.

$$f_{cc} = f_{co} \left(1.254 + 2.254 \sqrt{1 + \frac{7.94 f_{le}}{f_{co}}} - 2 \frac{f_{le}}{f_{co}} \right) \dots\dots\dots (5.21)$$

Where

f_{le} =effective confining pressure

f_{co} =unconfined concrete strength

The effective lateral confining pressure was defined following an analogous approach to that proposed by Sheikh and Uzumeri.

For circular cross section

$$f_{le} = \frac{1}{2} K_{es} \rho_s f_{yh} \dots\dots\dots (5.22)$$

Where K_{es} = confinement effectiveness coefficient

$$K_{es} = \frac{1 - \frac{s_h}{2d_c}}{1 - \rho_{cc}} \quad \text{for circular spirals} \dots\dots\dots (5.23)$$

$$K_{es} = \frac{\left(1 - \sum_{i=1}^{n_i} \frac{(w_{c,i})^2}{6b_{cx}b_{cy}} \right) \left(1 - \frac{s_{hc}}{2b_{cx}} \right) \left(1 - \frac{s_{hc}}{2b_{cy}} \right)}{1 - \rho_{cc}} \quad \text{for rectangular section} \dots\dots\dots (5.24)$$

Where

A_{sh} =cross sectional area of transverse reinforcement bar

d_c = the diameter of confined core to centerline of hoops or spirals

s_h = center to centre vertical spacing between transverse reinforcement

s_{hc} = clear vertical spacing between transverse reinforcement and

ρ_{cc} = the ratio of area of longitudinal reinforcement to the area of core section

n_i = the number of laterally supported longitudinal bars

$w_{c,i}$ = the i^{th} clear distance between laterally supported adjacent longitudinal bars

b_{cx} and b_{cy} = core dimensions to the center line of the perimeter hoop in the x and y direction respectively

ρ_s = ratio of the volume of transverse reinforcing steel to the volume of confined concrete

$$\rho_s = \frac{4A_{sh}}{d_c S_h} \dots\dots\dots (5.25)$$

f_{yh} = the yield strength of transverse reinforcement

For rectangular section which have different quantity of transverse reinforcement in the x and y direction the effective confining stress in each direction expressed using the following two equations.

$$f_{le\ x} = K_{e,s} \rho_{sx} f_{yh} \dots\dots\dots (5.26)$$

$$f_{le\ y} = K_{e,s} \rho_{sy} f_{yh} \dots\dots\dots (5.27)$$

Where

$$\rho_{sx} = \frac{4A_{shx}}{S_h b_{cy}} \quad \text{and} \quad \rho_{sy} = \frac{4A_{shy}}{S_h b_{cx}} \dots\dots\dots (5.28)$$

Mander et. al also used equation to find strain at the peak stress ϵ_{cc} .

$$\epsilon_{cc} = \epsilon_{co} \left(1 + 5 \left(\frac{f_{cc}}{f_{co}} - 1 \right) \right) \dots\dots\dots (5.29)$$

Where

f_{co} and ϵ_{co} = the unconfined concrete strength and corresponding strain respectively

The longitudinal compressive stress f_c of the confined concrete at any strain level ϵ_c is given by:-

$$f_c = \frac{f_{cc} x^r}{r - 1 + x^r} \dots\dots\dots (5.30)$$

$$\text{Where } x = \frac{\epsilon_c}{\epsilon_{cc}} \quad \text{and} \quad r = \frac{E_c}{E_c - E_{sec}} \dots\dots\dots (5.31)$$

E_c is unconfined tangent modulus of elasticity of concrete in Mpa and E_{sec} is the secant modulus of elasticity of concrete in Mpa and given by the equations:

$$E_c = 5000 \sqrt{f_{co}} \quad \text{and} \quad E_{sec} = \frac{f_{cc}}{\epsilon_{cc}} \dots\dots\dots (5.32)$$

5.3.5 Model of Saatcioglu and Razvi [18]

The model is based on the computation of equivalent uniform confinement pressure resulting from different arrangements of transverse reinforcement.

The confined strength of the concrete core confined by transverse reinforcement can be calculated from

$$f_{cc} = f_{co} + K_1 f_{le} \dots\dots\dots (5.33)$$

$$\text{Where } K_1 = 6.7(f_{le})^{-0.17} \dots\dots\dots (5.34)$$

Equivalent uniform confining pressure f_{le} for different cross section types are given by the following equations

For circular section

$$f_{le} = \frac{2 A_{sh} f_{yh}}{d_c s_h} \dots\dots\dots (5.35)$$

For the square cross section

$$f_{le} = k_2 f_1 \dots\dots\dots (5.36)$$

$$f_1 = \frac{\sum A_{sh} f_{yh} \sin \alpha}{s_h b_c} \dots\dots\dots (5.37)$$

$$k_2 = 0.26 \sqrt{\left(\frac{bc}{sh}\right) \left(\frac{1}{f_1}\right) \left(\frac{bc}{s_1}\right)} \leq 1.0 \dots\dots\dots (5.38)$$

Where α =the angle between the transverse reinforcement and core length b_c

S_1 =the spacing between laterally longitudinal reinforcement

For rectangular sections $f_{le} = \frac{f_{lex}b_{cx} + f_{ley}b_{cy}}{b_{cx} + b_{cy}}$ (5.39)

Where

f_{lex} and f_{ley} =effective lateral pressure acting perpendicular to the core dimensions b_{cx} and b_{cy} and are calculated by substituting the respective values in equation above

Saatcioglu et al also used Mander et.al equation to approximate the strain corresponding to the peak compressive stress ϵ_{cc}

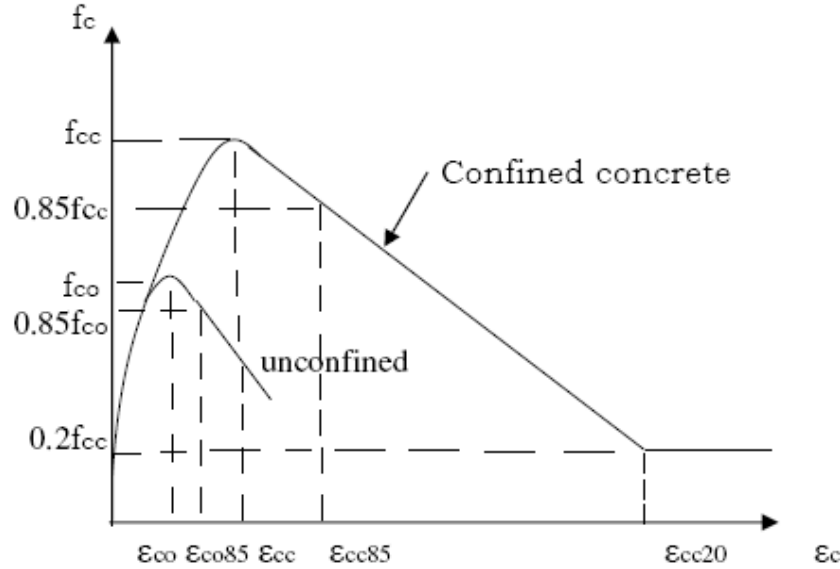


Figure 5.7 Saatcioglu’s Stress Strain Relationship for Unconfined and Confined Concrete [18]

The stress strain relationship shown above consists of a parabola in the ascending direction and linear portion for descending branch and a constant residual strength at 20% strength level.

The parabolic ascending branch use the equation

$$f_c = f_{cc} \left[2 \left(\frac{\epsilon_c}{\epsilon_{cc}} \right) - \left(\frac{\epsilon_c}{\epsilon_{cc}} \right)^2 \right]^{\frac{1}{(1+k\Delta)}} \leq f_{cc} \quad \dots\dots\dots (5.40)$$

Where $k_{\Delta} = \frac{k_1 f_{le}}{f_{co}}$ (5.41)

The descending portion is a straight line pass through the peak (ϵ_{cc}, f_{cc}) and $(\epsilon_{cc85}, f_{cc85})$

$$\epsilon_{cc85} = 260\rho\epsilon_{cc} + \epsilon_{co85} \quad \dots\dots\dots (5.42)$$

Where

$$\rho_{sx} = \frac{\sum A_{sh}}{S(b_{cy} + b_{cx})} \dots\dots\dots (5.43)$$

ϵ_{co85} = The strain at 85% strength level beyond the peak stress of unconfined concrete which can be approximate as 0.0038 in the absence of accurate data

ΣA_{sh} = the total of transverse reinforcement in two directions crossing b_{cx} and b_{cy}

5.3.6 EURO CODE [6]

1. Confinement of concrete results in a modification of the effective stress-strain relationship: higher strength and higher critical strains are achieved. The other basic material characteristics may be considered as unaffected for design.

2. In the absence of more precise data, the stress-strain relation shown in Figure 5.8 (compressive strain shown positive) may be used, with increased characteristic strength and strains according to:

$$f_{ck,c} = f_{ck} \left(1.000 + \frac{5\sigma_2}{f_{ck}} \right) \text{ for } \sigma_2 \leq 0.05f_{ck} \dots\dots\dots (5.44)$$

$$f_{ck,c} = f_{ck} \left(1.125 + \frac{2.5\sigma_2}{f_{ck}} \right) \text{ for } \sigma_2 > 0.05f_{ck} \dots\dots\dots (5.45)$$

$$\epsilon_{c2,c} = \epsilon_{c2} \left(\frac{f_{ck,c}}{f_{ck}} \right)^2 \dots\dots\dots (5.46)$$

$$\epsilon_{cu2,c} = \epsilon_{cu2} + 0.2 \left(\frac{\sigma_2}{f_{ck}} \right) \dots\dots\dots (5.47)$$

Where σ_2 ($= \sigma_3$) is the effective lateral compressive stress at the ULS due to confinement and ϵ_{c2} and ϵ_{cu2} follow from Table 3.1 of EN 1992-1-1:2004

Confinement can be generated by adequately closed links or cross-ties, which reach the plastic condition due to lateral extension of the concrete.

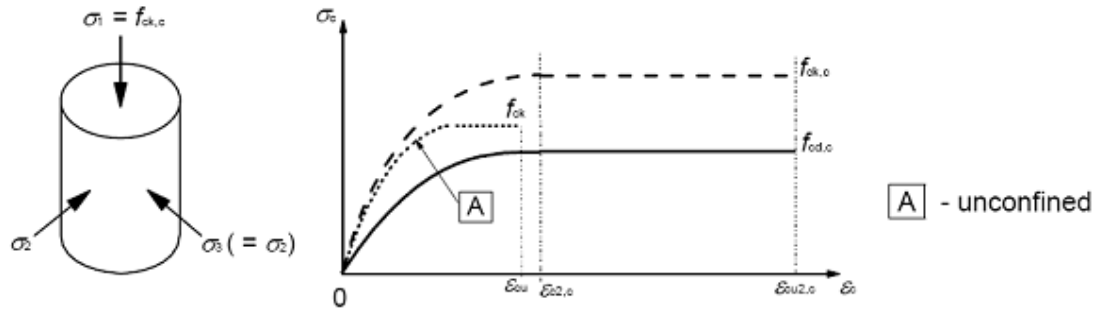


Figure 5.8 Stress Strain Relationships for Confined Concrete [6]

Based on the analytical and experimental results, the following equation was proposed to relate the amount of confining reinforcement to attainable displacement ductility, $\mu\Delta$:

For the specified value of $\mu\phi$ a concrete strain larger than $\epsilon_{cu2}=0,0035$ is needed anywhere in the cross-section, compensation for the loss of resistance due to spalling of the concrete shall be achieved by means of adequate confinement of the concrete core, on the basis of the properties of confined concrete in EN 1992-1-1:2004

The buckling of longitudinal bar and confinement of the column is

$$\alpha\omega_{wd} \geq 30\mu\phi v_d \epsilon_{sy,d} \frac{b_c}{b_o} - 0.035 \quad \dots\dots\dots (5.48)$$

Where ω_{wd} is the mechanical volumetric ratio of confining hoops within the critical regions

$$\omega_{wd} = \frac{\text{volume of confining hoops}}{\text{volume of concrete core}} \frac{f_{yd}}{f_{cd}} \quad \dots\dots\dots (5.49)$$

$\mu\phi$ is the required value of the curvature ductility factor;

v_d is the normalised design axial force

$\epsilon_{sy,d}$ is the design value of tension steel strain at yield;

h_c is the gross cross-sectional depth

h_o is the depth of confined core (to the centre line of the hoops);

b_c is the gross cross-sectional width

b_o is the width of confined core (to the centre line of the hoops);

α is the confinement effectiveness factor, equal to $\alpha=\alpha_n \times \alpha_s$, with:

- a) For rectangular cross-sections:

$$\alpha_n = 1 - \sum_n \frac{b_i^2}{6b_o h_o} \dots\dots\dots (5.49)$$

$$\alpha_s = \left(1 - \frac{s}{2b_o}\right) \left(1 - \frac{s}{2h_o}\right) \dots\dots\dots (5.50)$$

Where

n is the total number of longitudinal bars laterally engaged by hoops or cross ties; and

b_i is the distance between consecutive engaged bars (see Figure 5.9; also for b_o, h_o, s).

b) For circular cross-sections with hoops and diameter of confined core D_o (to the centre line of hoops)

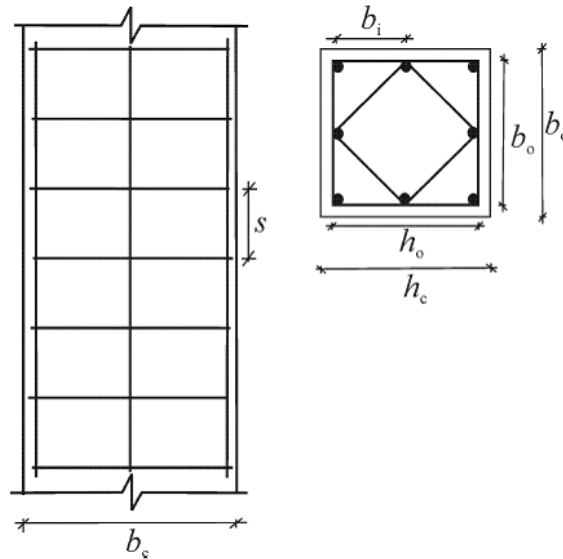


Figure 5.9 Confinement of Concrete Core [6]

5.3.7 Fafitis and Shah [22]

Fafitis and Shah's model calculate the confined strength of the concrete core confined by fiber

For $\epsilon_c < \epsilon_{cc}$, the ascending branch

$$f_c = f_{cc} \left[1 - \left(1 - \frac{\epsilon_c}{\epsilon_{cc}} \right)^A \right] \dots\dots\dots (5.52)$$

For $\varepsilon_c > \varepsilon_{cc}$, descending branch

$$f_c = f_{cc} \exp[-K(\varepsilon_c - \varepsilon_{cc})^{0.5}] \dots\dots\dots (5.53)$$

Where

$$A = \frac{E_c}{E_{sec}} \dots\dots\dots (5.54)$$

$$E_c = 4700\sqrt{f_{co}} \quad [\text{Mpa}] \dots\dots\dots (5.55)$$

$$E_{sec} = \frac{f_{cc}}{\varepsilon_{cc}} \dots\dots\dots (5.56)$$

In order to calibrate the descending branch of the stress strain curve a regression analysis was performed and empirical relation was derived for parameter K as:

$$K = \frac{1}{2.64 \frac{f_{li}}{f_{co}} + 0.027} \dots\dots\dots (5.57)$$

Where f_{li} =effective confining pressure, f_{co} =unconfined concrete strength

5.2.8 Zekaria Model [22]

Based on experimental result of confined concrete cylinder and prisms, a simple analytical model is proposed for the prediction of the stress- strain characteristics of confined concrete. The maximum confined strength due to the fiber f_{cc} is to be calculated from equation 5.32 which was derived from the regression analysis performed on these test results.

$$f_{cc} = kf_{co} = f_{co} \left[1 + 2 \left(\frac{f_{li}}{\varepsilon_{co}} \right)^{0.52} \right] \dots\dots\dots (5.59)$$

The effective lateral confining pressure provided by the jacket is computed following the concept forwarded by Mander et al. It assumes that the jacket has reached its yield strength and the equilibrating stress on the section is uniformly distributed. Thus, the radial confining pressure for a circular section due the confinement provided by the jacket is calculated using Equation below

For circular cross section

$$f_{lj} = \frac{1}{2} \rho_j f_{yj} \dots\dots\dots (5.60)$$

$$\rho_s = \frac{4t_j}{d} \dots\dots\dots (5.61)$$

d= the diameter of confined concrete section

t_j and f_{yj}= thickness and tensile yield strength of the jacket, respectively

$$f_{yj} = \frac{n_{fl} n_{xs} A_{sf} f_{yf}}{h_j t_j} \dots\dots\dots (5.62)$$

Where

n_{fl}= number of layers of the fiber mesh

A_{sf} and f_{yf}= area and yield strength of individual fibers respectively

h_j and t_j height and thickness of the jacket respectively

For square and circular cross section

$$f_{ljx} = K_{e,j} \rho_{jx} f_{yj} \dots\dots\dots (5.63)$$

$$f_{l jy} = K_{e,j} \rho_{jy} f_{yj} \dots\dots\dots (5.64)$$

Where

$$\rho_{sx} = \frac{2t_j}{b_y} \dots\dots\dots (5.65)$$

$$\rho_{jy} = \frac{2t_j}{b_x} \dots\dots\dots (5.66)$$

b_x and b_y= dimensions of the confined concrete section in the x and y directions respectively to the center line of the perimeter hoop in the x and y direction respectively

ρ_{sx} and ρ_{sy} = the ratio of area of Fiber reinforcement to the area of core section

For a reinforced concrete cross section, the effectiveness coefficient K_{ej} due to the jacket confinement is defined as:

$$K_{es} = \left(1 - \frac{(w_{j,x})^2 + (w_{j,y})^2}{3A_{cc,j}} \right) \text{ for rectangular section} \dots\dots\dots (5.67)$$

$w_{j,x}$ and $w_{j,y}$ = the relatively unconfined portion of the inside length

$$w_{j,x} = [b_x - 2 * (0.2b_x)] = 0.6b_x \dots\dots\dots (5.68)$$

$$w_{j,y} = [b_y - 2 * (0.2b_y)] = 0.6b_y \dots\dots\dots (5.69)$$

Once the value of $f_{lj,y}$ and $f_{lj,x}$ are determined from the above equation, the overall equivalent lateral confining pressure can be evaluated as:

$$f_{vj} = \frac{f_{lj,x}b_x + f_{lj,y}b_y}{b_y + b_x} \dots\dots\dots (5.70)$$

The strain corresponding to the peak stress, ϵ_{cc} is to be calculated from the equation suggested by mander et al

$$\epsilon_{cc} = 1 + 5 \left(\frac{f_{cc}}{f_{co}} - 1 \right) \dots\dots\dots (5.71)$$

6. COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

6.1 General

The various confinement models established are used to compare the experimental test results of the confined column. In this chapter a stress-strain model of Kent et al, Saatcioglu et al, Uzumeri, Mander et al. Fafitis et al and model of Zekaria were considered to compare the results. The results were carried out in tabular form and the discussions were on an average percentage difference of the three type of configuration for the transverse reinforcement and for specimen confined by wire mesh an average percentage were taken on one, two and three layer.

Table 6.1 Summary of Test Result of Compressive Strength and Tensile Strength of Materials

Type of Test	Stress [Mpa]
Compressive Strength of Cube Test	30.7
Yield Strength of Transverse Steel	280
Yield Strength of Transverse Wire Mesh	80

6.2 Comparative Study of Experimental Result of Specimen Confined by Transverse Reinforcement with Confinement Model

Peak Stress and Peak Strain

The results reveal that Mander et al and Saatcioglu et al models give better predictions than Kent et al and Uzumeri model. When the models compare with the experimental results, an average percentage difference of 1.8% and 10.52% in peak stress is computed for Mander et al and Saatcioglu et al model respectively. Moreover for such models, a difference in peak strains of 25.9% for Mander et al and 56.53% for Saatcioglu et al are computed.

For Kent et al model an average percentage difference of 17 % and 155% peak stress and strain is observed respectively. It can be noticed from table 6.1-6.3 that Uzumeri model over estimates the peak stress and strain by -17.6% and -88.5% on the average respectively than the experimental result.

For all specimens Kent et al model underestimates the peak stress and strain than the experimental result. This underestimation may be related to the assumption of the model that states the peak stress and strain of unconfined and confined concrete is the same.

Post Peak Strain

The analytical initial slopes of the descending branch predicted by Kent et al, Mander et al and Saatcioglu et al models agree well with the experimental stress–strain curves fig.6.1 But approximately after 85% of peak loading none of all models except Kent et al agree with the experimental result.

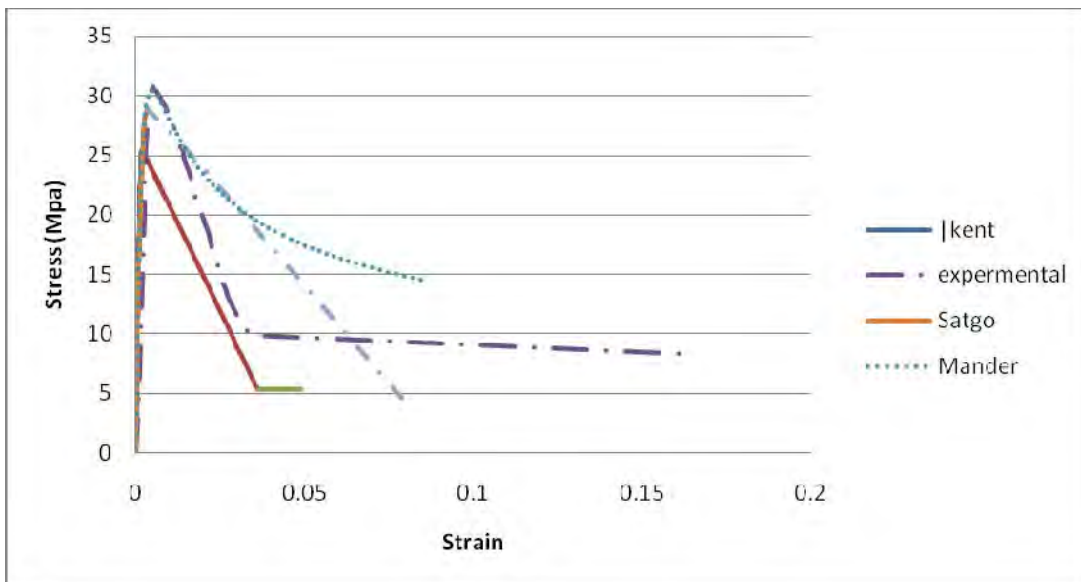


Figure 6.1 Stress–Strain Curves for Kent et al, Saatcioglu et al, Mander et al and Experimental Result of Overlapping Configuration

Table 6.2 Summary of Comparison of Confinement Model with Experimental Result for Normal Hoop Configuration

	experiment	Kent et al	Uzumeri	Mander et al	Saatcioglu et al
f_{cc}	25.52	25.5	34.52	25.56	28.31
ϵ_{cc}	0.004	0.002	0.025	0.0026	0.0031
ϵ_{c85}	0.0107	0.008	0.035	0.0065	0.0169
% f_{cc}		0.08%	-26.08%	-0.16%	-9.86%
% ϵ_{cc}		100%	-84.41%	-50.90%	28.93%
% ϵ_{c85}		33.33%	-69.75%	25.49%	-37.22%

Table 6.3 Summary of Comparison of Confinement Model with Experimental Result for Overlapping Configuration

	experiment	Kent et al	Uzumeri	Mander et al	Saatcioglu et al
f_{cc}	30.74	25.5	37.29	30.46	28.83
ϵ_{cc}	0.005	0.002	0.0679	0.0047	0.0033
ϵ_{c85}	0.0127	0.0083	0.0854	0.0138	0.0179
% f_{cc}		20.52%	-17.59%	-0.87%	6.62%
% ϵ_{cc}		150.00%	-92.64%	6.49%	-34%
% ϵ_{c85}		52.61%	-85.16%	-8.21%	-29.46%

Table 6.4 Summary of Comparison of Confinement Model with Experimental Result for Cross tie Configuration

	experiment	Kent et al	Uzumeri	Mander et al	Saatcioglu et al
f_{cc}	33.24	25.5	36.55	31.84	28.88
ϵ_{cc}	0.0063	0.002	0.0554	0.0053	0.0033
ϵ_{c85}	0.0133	0.0092	0.085	0.0155	0.0179
% f_{cc}		0.3037%	-9.05%	4.42%	15.07%
% ϵ_{cc}		216.60%	-88.57%	20.28%	91.67%
% ϵ_{c85}		44.19%	-84.32%	-13.98%	-25.31%

6.3 Comparative study of experimental result of specimen confined by wire mesh with confinement model

This section includes only models which give a better approximation with the experimental result. The summarized results of the stress-strain calculated from the analytical model and the experimental result of specimen confined by wire mesh are given in Table 6.4. The discussions were carried out on the average percentage difference of one, two and three layer wire mesh.

Peak Stress and Peak Strain

For the peak stress the results obtained from Mander et al, Saatcioglu et al, Fafitis et al and Zekaria model give better predictions than Kent et al model. When the models compared with the experimental results, an average percentage difference of -6.9%, -11.38%, -2.98% and -3.69% peak stresses are computed for Mander et al, Saatcioglu et al, Fafitis and Zekaria model respectively. Additionally for the peak strain an average percentage difference of 15.9%, -34.67%, -0.53% and

15.6% for Mander et al, Saatcioglu et al, Fafitis et al and Zekaria model are computed respectively.

On the other hand Kent et al model where the average percentage difference of 26.34 % and 182.78% peak stress and strain are analyzed respectively this model underestimate the peak stress and peak strain than the experimental result.

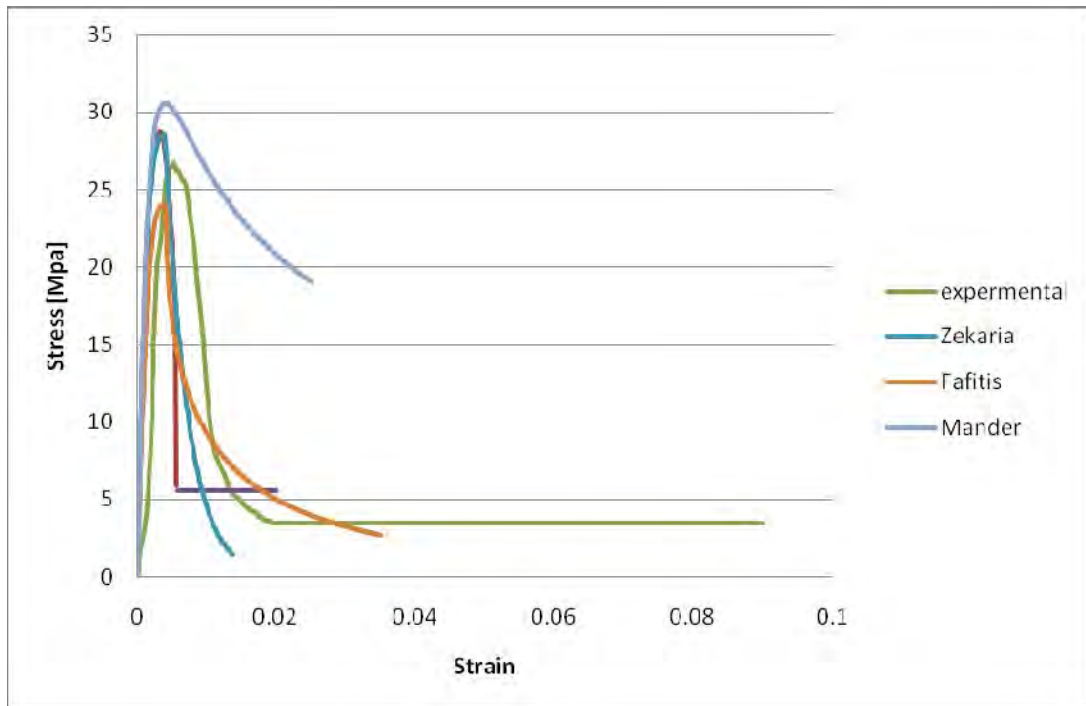


Figure 6.2 Stress–Strain Curves for Saatcioglu et al, Mander et al, Zekaria,Fafitis and Experimental Result of Specimen Confined by One Layer Wire Mesh

Post peak Strain

The results obtained from the comparison of experiment and the analytical models verify that Fafitis et al and Zekaria model give a better approximation with an average percentage difference of -20.92% and 18.56% strain at 85% of peak load respectively. More over -30.69%, -38.5%, and -77.12% of an average percentage difference of strain at 85% of peak loading are computed for Saatcioglu et al, Mander et al and Kent et al model respectively.

From the above comparison of experimental result and the analytical models of specimen confined by wire mesh verify that Fafitis et al and Zekaria model give a better approximation than the other entire model compared in this research.

Table 6.5 Summary of Comparison of Confinement Model with Experimental Result One Layer
Wire Mesh Confinement

	experiment	Kent et al	Fafitis	Mander et al	Saatcioglu et al	Zekaria
f_{cc}	26.78	25.5	28.93	30.55	28.76	28.62124
ϵ_{cc}	0.0052	0.002	0.0041	0.0039	0.0033	0.003926
ϵ_{c85}	0.0078	0.021	0.0045	0.01	0.0047	0.0058
% f_{cc} difference		5.05%	8.02%	-12.33%	7.38%	6.85%
% ϵ_{cc} difference		158.33%	-21.50%	29.75%	-36.13%	-24.02%
% ϵ_{c85} difference		-62.70%	-42.55%	-24.68%	-40.00%	-25.96%

Table 6.6 Summary of Comparison of Confinement Model with Experimental Result Two Layer
Wire Mesh

	experiment	Kent et al	Fafitis	Mander et al	Saatcioglu et al	Zekaria
f_{cc}	34.12	25.5	32.98	34.7	29.85	33.11
ϵ_{cc}	0.0058	0.002	0.0057	0.0056	0.0037	0.0058
ϵ_{c85}	0.006	0.04	0.0061	0.0127	0.0053	0.0088
% f_{cc} difference		33.81%	-3.33%	-1.70%	-12.51%	-2.96%
% ϵ_{cc} difference		190.00%	-0.99%	-3.36%	-36.21%	0.88%
% ϵ_{c85} difference		-81.67%	-16.82%	-42.26%	-27.73%	21.36%

Table 6.7 Summary of Comparison of Confinement Model with Experimental Result Three Layer
Wire Mesh

	experiment	Kent et al	Fafitis	Mander et al	Saatcioglu et al	Zekaria
f_{cc}	35.75	25.5	36.6	38.24	30.64	35.28
ϵ_{cc}	0.006	0.002	0.0072	0.0069	0.0041	0.0067
ϵ_{c85}	0.0077	0.059	0.0075	0.013	0.0058	0.0083
% f_{cc} difference		40.18%	2.42%	-6.54%	-14.26%	-1.28%
% ϵ_{cc} difference		200.00%	20.89%	-14.26%	-31.67%	11.95%
% ϵ_{c85} difference		-87.01%	-2.17%	-48.55%	-24.35%	9.57%

7. CONCLUSION AND RECOMMENDATION

7.1 Conclusion

From the test result it is observed that, there was a good enhancement in the performance of all confined columns. As stated in the literature reviews, the degree of enhancement was directly related to the number of layer wire mesh and type of configuration of transverse reinforcement.

Based on the test result and visual observation, the following conclusion are made

- The strength of column confined by cross tie, over lapping and three layers wire mesh of circular specimens give around 30% enhancement in strength. Similarly 38% enhancement in peak strength was observed for two layers & three layers square specimen as compared to unconfined specimen.
- For the other specimen confined by one layer (square and circular), for two layers circular and normal tie configuration, there was no significant enhancement in strength which have an average percentage increase of 3.15% when it compare with unconfined concrete.
- Significant enhancement in peak strain and ductility was observed in specimens confined by wire mesh and cross tie configuration. Especially specimen confined by circular cross section shows an enhancement in peak strain and ductility of almost twice than unconfined specimen.
- Comparison of the test result indicate that the cross tie configuration give higher strength and ductility than others configuration.
- For specimen confined by transverse reinforcement from all model the pre-peak and post-peak behavior of the stress–strain curves predicted by Mander et al model is in a reasonable agreement with the experimental stress-strain curve.
- The results obtained from the comparison of experiment and the analytical models of specimen confined by wire mesh verify that Fafitis and Zekaria model give a better approximation than the other entire model compared in this research.

7. 2 Recommendation

From the study that has been carried out, the followings are the recommendations drawn from the result:

1. From this research due to their higher strength and ductility, in seismic region it is recommended to use that the cross tie configuration and wire mesh with number of layer is more than two.
2. This study was carried out on small specimen with different tie configuration the influence of actual size and compressive strength has to be investigated as it has a large effect on the efficiency of confinement. Further studies should be taken which consider actual size column, shape of specimen (rectangular and circular) and compressive strength of concrete. And develop analytical model which included all the necessary parameter.

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APPENDIX-A

1. Test Results (Specimen Confined by Transverse Reinforcement)

1.1 Specimen Confined by NH (3Pcs)

Strain	Stress [Mpa] Specimen-1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen -3	Average stress [Mpa]
0.0000	0.00	0.00	0.00	0.00
0.0003	4.50	3.23	3.52	3.75
0.0007	7.72	6.94	7.63	7.43
0.0010	13.69	9.19	10.07	10.98
0.0013	16.43	13.30	14.57	14.76
0.0017	17.50	15.64	17.21	16.79
0.0020	18.38	16.82	18.48	17.89
0.0023	19.26	18.68	20.53	19.49
0.0027	21.02	20.04	22.00	21.02
0.0030	23.96	21.90	24.05	23.30
0.0033	25.72	23.17	25.32	24.74
0.0037	26.69	24.35	25.23	25.42
0.0040	26.99	24.44	25.13	25.52
0.0043	26.89	24.55	25.03	25.49
0.0047	26.99	24.44	24.84	25.42
0.0050	26.89	24.42	24.35	25.22
0.0053	26.99	24.33	24.05	25.12
0.0057	27.28	24.27	23.76	25.10
0.0065	27.18	24.06	22.98	24.74
0.0073	26.79	22.88	22.68	24.12
0.0073	26.20	22.39	22.29	23.63
0.0090	25.81	21.51	21.80	23.04
0.0098	25.23	20.63	21.41	22.42
0.0107	24.25	19.56	21.32	21.71
0.0115	23.56	18.48	20.73	20.92
0.0123	23.17	17.40	20.24	20.27
0.0132	22.68	16.72	19.75	19.72
0.0198	19.36	11.73	16.52	15.87
0.0207	18.68	11.24	16.13	15.35
0.0215	18.09	10.95	15.84	14.96

0.0223	17.70	10.66	15.74	14.70
0.0232	17.31	10.46	15.55	14.44
0.0240	16.62	10.07	14.57	13.75
0.0248	15.84	9.58	13.98	13.13
0.0373	8.98	5.58	7.15	7.24
0.0382	8.13	5.05	6.47	6.55
0.0390	7.56	4.70	6.02	6.09
0.0398	6.98	4.35	5.58	5.63
0.0407	6.44	4.00	5.13	5.19
0.0415	5.87	3.65	4.68	4.73
0.0423	5.29	3.62	4.24	4.38
0.0432	4.76	2.96	3.79	3.83
0.0440	4.40	2.84	3.62	3.62
0.0448	4.40	2.84	3.47	3.57
0.0457	4.31	2.74	3.46	3.50
0.0465	4.27	2.74	3.13	3.38
0.0947	4.18	2.61	3.13	3.30

1.2 Specimen Confined by CT Configuration (3Pcs)

Strain	Stress [Mpa] Specimen-1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen -3	Average stress [Mpa]
0.0000	0.00	0.00	0.00	0.00
0.0003	7.33	1.27	3.52	4.04
0.0007	8.80	1.86	4.40	5.02
0.0010	10.17	2.54	5.28	6.00
0.0013	15.45	4.20	8.21	9.29
0.0017	20.44	6.94	11.64	13.00
0.0020	25.42	9.48	14.86	16.59
0.0023	29.43	11.83	17.60	19.62
0.0027	31.78	13.49	19.46	21.58
0.0030	33.15	17.60	22.00	24.25
0.0033	33.64	22.00	24.44	26.69
0.0037	33.64	26.50	26.69	28.94
0.0040	34.03	30.02	28.55	30.87
0.0043	34.22	32.17	29.72	32.04
0.0047	34.32	32.36	29.82	32.17
0.0067	33.05	35.49	30.90	33.15
0.0117	28.84	33.24	28.16	30.08

0.0120	28.55	32.95	27.87	29.79
0.0123	28.26	32.27	27.38	29.30
0.0127	27.96	31.88	27.08	28.97
0.0130	27.57	31.39	26.69	28.55
0.0133	27.38	30.90	26.40	28.23
0.0137	27.18	30.70	26.20	28.03
0.0140	26.69	29.92	25.62	27.41
0.0143	26.50	29.53	25.32	27.12
0.0147	26.20	29.33	25.13	26.89
0.0150	26.01	28.55	24.64	26.40
0.0153	25.81	28.26	24.44	26.17
0.0157	25.62	27.77	24.05	25.81
0.0160	25.42	27.48	23.86	25.59
0.0163	25.03	26.89	23.37	25.10
0.0167	24.64	26.40	22.98	24.67
0.0170	24.44	24.35	21.90	23.56
0.0178	23.96	22.98	21.02	22.65
0.0187	23.17	21.80	20.14	21.71
0.0195	22.68	21.02	19.56	21.09
0.0253	16.82	16.43	14.86	16.04
0.0328	13.20	11.93	11.24	12.12
0.0337	12.91	11.54	10.85	11.77
0.0345	12.61	11.34	10.66	11.54
0.0353	12.42	11.24	10.56	11.41
0.0362	12.12	11.15	10.36	11.21
0.0370	12.03	10.85	10.17	11.02
0.0378	11.83	10.56	9.97	10.79
0.0387	11.64	10.17	9.68	10.49
0.0395	11.44	9.88	9.48	10.27
0.0403	11.24	9.68	9.29	10.07
0.0412	11.05	9.58	9.19	9.94
0.0420	10.85	9.58	9.09	9.84
0.0428	10.66	9.58	9.00	9.75
0.1333	7.43	9.58	7.72	8.25

1.3 Specimen Confined by OL Configuration (3Pcs)

Strain	Stress [Mpa] Specimen-1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen -3	Average stress [Mpa]
0.0000	0.00	0.00	0.00	0.00
0.0003	2.25	2.74	1.08	2.02
0.0007	3.42	5.87	2.74	4.01
0.0010	6.75	9.88	4.60	7.07
0.0013	10.46	13.10	7.33	10.30
0.0017	14.47	17.11	9.97	13.85
0.0020	18.09	20.73	12.61	17.14
0.0023	22.39	23.76	14.47	20.21
0.0027	26.30	27.38	15.55	23.08
0.0030	29.33	29.33	17.99	25.55
0.0033	30.90	30.31	20.34	27.18
0.0037	31.39	31.48	22.68	28.52
0.0040	31.58	31.58	24.64	29.27
0.0043	31.58	31.48	25.32	29.46
0.0047	31.29	31.39	28.55	30.41
0.0050	31.09	31.09	30.02	30.73
0.0053	30.31	30.31	30.70	30.44
0.0057	29.92	30.21	31.09	30.41
0.0060	29.72	30.12	31.00	30.28
0.0063	29.43	30.12	30.90	30.15
0.0067	29.33	30.02	30.80	30.05
0.0070	29.24	29.72	30.60	29.85
0.0073	29.14	29.33	30.41	29.63
0.0077	29.04	29.24	30.21	29.50
0.0080	29.04	28.94	30.12	29.37
0.0110	27.48	26.60	28.26	27.44
0.0113	27.28	26.50	27.77	27.18
0.0117	27.18	26.20	27.67	27.02
0.0120	26.99	25.91	27.48	26.79
0.0123	26.79	25.72	27.28	26.60
0.0127	26.50	25.23	26.89	26.20
0.0130	26.30	25.03	26.79	26.04
0.0133	26.11	24.84	25.91	25.62
0.0137	25.81	24.44	26.30	25.52
0.0140	25.52	24.25	26.20	25.32
0.0143	25.42	23.76	24.54	24.57

0.0147	25.13	23.56	24.15	24.28
0.0155	25.13	22.68	23.76	23.86
0.0163	24.54	21.02	23.17	22.91
0.0172	24.15	18.87	22.39	21.80
0.0180	23.66	17.89	21.90	21.15
0.0188	23.27	17.21	21.32	20.60
0.0197	22.78	16.52	20.44	19.91
0.0205	22.10	15.84	19.75	19.23
0.0213	21.12	15.16	19.02	18.43
0.0272	14.96	10.36	13.88	13.07
0.0280	14.37	10.36	13.15	12.63
0.0288	13.40	10.36	12.42	12.06
0.0297	13.00	10.27	11.68	11.65
0.0305	12.61	10.17	10.95	11.24
0.0313	12.32	10.17	10.22	10.90
0.0322	12.03	10.07	9.48	10.53
0.0330	11.93	10.07	8.75	10.25
0.0338	11.73	9.88	8.02	9.88
0.1667	8.21	9.19	7.28	8.23

2. Test Results (Specimen Confined by Wire Mesh)

2.1 Specimen Confined by SL1 (3Pcs)

Strain	Stress [Mpa] Specimen-1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen -3	Average stress [Mpa]
0.0000	0.00	0.00	0.00	0.00
0.0002	1.68	0.92	0.87	1.16
0.0003	1.99	1.68	1.60	1.75
0.0005	2.60	2.29	2.18	2.36
0.0007	3.06	2.31	2.19	2.52
0.0007	3.36	2.41	2.29	2.69
0.0018	9.01	9.01	8.56	8.86
0.0020	10.39	11.15	10.60	10.71
0.0022	12.07	12.83	12.19	12.36
0.0022	13.60	13.90	13.21	13.57
0.0023	16.65	14.97	14.22	15.28
0.0025	18.49	16.35	15.53	16.79
0.0037	25.82	22.92	21.77	23.50
0.0040	29.33	24.14	22.93	25.47
0.0043	31.01	24.44	23.22	26.23
0.0047	29.94	24.75	24.75	26.48
0.0052	29.33	25.21	25.82	26.79
0.0055	22.92	27.35	28.42	26.23
0.0058	22.61	27.50	28.57	26.23
0.0063	18.79	28.26	29.79	25.62
0.0067	18.33	29.03	29.49	25.62
0.0070	18.06	30.10	27.81	25.32
0.0073	17.05	28.42	27.00	24.15
0.0078	15.77	26.28	24.96	22.34
0.0082	15.03	25.06	23.80	21.30
0.0085	13.57	22.61	21.48	19.22
0.0088	12.65	21.08	20.03	17.92
0.0097	9.35	15.58	14.80	13.25
0.0100	8.07	13.44	12.77	11.43
0.0103	6.97	11.61	11.03	9.87
0.0108	6.33	10.54	10.01	8.96
0.0112	5.68	9.47	9.00	8.05
0.0115	5.41	9.01	8.56	7.66
0.0118	5.13	8.56	8.13	7.27

0.0123	4.77	7.94	7.55	6.75
0.0127	4.49	7.49	7.11	6.36

0.0130	4.22	7.03	6.68	5.97
0.0133	3.94	6.57	6.24	5.58
0.0138	3.76	6.26	5.95	5.32
0.0142	3.67	6.11	5.81	5.19
0.0145	3.58	5.96	5.66	5.06
0.0190	2.57	4.28	4.06	3.64
0.0193	2.48	4.13	3.92	3.51
0.0198	2.48	4.13	3.92	3.51
0.0900	2.48	4.13	3.92	3.51

2.2 Specimen Confined by SL2 (3Pcs)

Strain	Stress [Mpa] Specimen-1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen -3	Average stress [Mpa]
0.0000	0.00	0.00	0.00	0.00
0.0003	1.60	1.75	1.17	1.51
0.0007	2.19	2.48	1.60	2.09
0.0008	2.77	3.50	6.42	4.23
0.0010	5.10	5.98	8.60	6.56
0.0013	7.00	7.00	10.21	8.07
0.0017	9.77	8.46	13.56	10.60
0.0020	11.67	10.06	16.04	12.59
0.0023	13.13	10.94	18.08	14.05
0.0027	15.31	12.98	21.15	16.48
0.0030	17.35	17.06	24.65	19.69
0.0033	18.67	18.81	26.69	21.39
0.0037	20.56	21.00	28.58	23.38
0.0040	22.60	24.06	32.38	26.35
0.0043	24.21	26.10	33.40	27.90
0.0047	25.52	28.00	33.25	28.92
0.0050	26.25	31.35	32.81	30.14
0.0053	27.85	34.85	32.38	31.69
0.0057	29.31	37.33	31.06	32.57
0.0060	30.04	37.92	29.17	32.38
0.0063	29.17	36.31	28.00	31.16
0.0067	29.02	35.44	26.54	30.33
0.0070	28.00	32.67	25.38	28.68

0.0073	26.98	31.35	23.77	27.37
0.0077	26.25	30.33	22.60	26.40
0.0107	19.83	17.23	13.18	16.75
0.0110	16.77	16.86	12.89	15.51
0.0113	14.58	14.26	10.90	13.25
0.0117	14.29	12.40	9.48	12.06
0.0120	14.15	12.15	9.29	11.86
0.0123	13.42	12.02	9.19	11.55
0.0127	12.98	11.40	8.72	11.03
0.0130	12.69	11.03	8.44	10.72
0.0133	12.10	10.78	8.25	10.38
0.0137	11.67	10.29	7.87	9.94
0.0140	11.38	9.92	7.58	9.63
0.0143	11.08	9.67	7.39	9.38
0.0147	10.65	9.42	7.20	9.09
0.0150	10.35	9.05	6.92	8.77
0.0153	10.21	8.80	6.73	8.58
0.0157	9.92	8.68	6.64	8.41
0.0193	7.44	6.57	5.02	6.34
0.0197	7.29	6.32	4.83	6.15
0.0200	7.15	6.20	4.74	6.03
0.0203	7.00	6.07	4.64	5.91
0.0207	6.85	5.95	4.55	5.78
0.0210	6.71	5.83	4.46	5.66
0.0250	5.54	4.83	3.70	4.69
0.0253	5.54	4.71	3.60	4.62
0.0257	5.54	4.71	3.60	4.62
0.0260	5.54	4.71	3.60	4.62
0.0833	4.52	4.34	3.32	4.06

2.3 Specimen Confined by SL3 (3Pcs)

Strain	Stress [Mpa] Specimen-1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen -3	Average stress [Mpa]
0.0000	0.00	0.00	0.00	0.00
0.0002	1.02	0.73	2.19	1.31
0.0005	1.90	1.17	3.50	2.19
0.0007	2.77	1.46	5.10	3.11
0.0008	3.21	1.90	5.83	3.65
0.0010	3.79	2.33	7.00	4.38

0.0012	4.81	2.92	8.02	5.25
0.0013	5.54	3.65	9.92	6.37
0.0017	8.31	4.52	12.40	8.41
0.0018	10.35	5.69	16.77	10.94
0.0020	14.44	10.35	23.04	15.94
0.0022	14.58	13.42	24.79	17.60
0.0023	17.06	17.35	25.23	19.88
0.0027	21.29	20.85	26.25	22.80
0.0042	28.00	23.63	28.58	26.74
0.0045	33.40	27.71	30.04	30.38
0.0047	34.42	30.63	32.08	32.38
0.0057	33.40	31.21	32.81	32.47
0.0060	32.96	37.57	33.54	34.69
0.0063	32.67	31.65	31.06	31.79
0.0067	31.50	32.23	30.92	31.55
0.0070	30.04	32.52	30.33	30.97
0.0073	28.88	32.81	28.29	29.99
0.0077	27.13	33.10	26.25	28.83
0.0080	24.79	33.69	25.38	27.95
0.0083	23.04	30.63	24.06	25.91
0.0087	21.29	29.60	23.04	24.65
0.0090	21.00	28.58	21.58	23.72
0.0093	20.27	27.42	20.56	22.75
0.0097	18.96	26.69	19.69	21.78
0.0100	18.38	25.67	19.10	21.05
0.0103	17.65	25.08	18.67	20.47
0.0107	17.35	24.21	17.79	19.78
0.0110	15.60	23.63	17.21	18.81
0.0113	14.88	21.73	16.48	17.69
0.0117	14.15	20.85	15.90	16.97
0.0120	13.27	19.83	15.46	16.19
0.0123	12.69	19.10	14.88	15.56
0.0127	12.10	17.94	14.58	14.88
0.0130	11.81	16.92	14.29	14.34
0.0133	11.52	14.15	14.00	13.22
0.0137	10.94	13.71	13.71	12.78
0.0140	10.65	13.42	13.42	12.49
0.0250	5.32	6.27	6.27	5.95
0.0258	5.10	6.27	6.27	5.88
0.0267	4.86	6.27	6.27	5.80

0.0275	4.70	6.27	6.27	5.75
0.0283	4.46	6.27	6.27	5.67
0.0292	4.24	6.27	6.27	5.60
0.0300	3.97	6.27	6.27	5.50
0.0867	3.65	6.27	6.27	5.40

2.4 Specimen Confined by CL1 (3Pcs)

Strain	Stress [Mpa] Specimen-1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen -3	Average stress [Mpa]
0.0000	0.00	0.00	0.00	0.00
0.0007	8.17	12.46	10.59	10.41
0.0013	19.66	23.16	19.69	20.83
0.0020	23.94	26.27	22.33	24.18
0.0027	24.91	25.88	22.00	24.27
0.0033	26.27	26.08	22.17	24.84
0.0040	26.86	26.08	22.17	25.03
0.0047	27.44	26.47	22.50	25.47
0.0053	27.64	26.86	22.83	25.77
0.0080	27.25	27.83	23.66	26.24
0.0087	26.47	27.44	23.33	25.75
0.0093	25.69	27.05	22.99	25.25
0.0100	24.52	25.69	21.84	24.02
0.0107	23.16	24.91	21.17	23.08
0.0113	22.77	23.94	20.35	22.35
0.0120	21.21	22.77	19.36	21.11
0.0127	20.05	20.24	17.20	19.16
0.0133	18.10	18.49	15.72	17.43
0.0150	16.35	16.74	14.23	15.77
0.0167	14.79	15.57	13.23	14.53
0.0183	13.62	14.40	12.24	13.42
0.0200	12.65	13.23	11.25	12.38
0.0217	11.87	12.65	10.75	11.76
0.0233	11.29	11.87	10.09	11.08
0.0250	10.51	11.29	9.59	10.46
0.0267	9.93	10.70	9.10	9.91
0.0283	9.54	10.31	8.77	9.54
0.0300	8.95	10.12	8.60	9.23
0.0317	8.76	9.73	8.27	8.92
0.0333	7.98	9.34	7.94	8.42

0.0350	7.78	8.95	7.61	8.12
0.0367	7.59	8.56	7.28	7.81
0.0383	7.40	8.37	7.11	7.63
0.0400	7.40	8.17	6.95	7.51
0.0417	7.20	8.17	6.95	7.44
0.0433	7.01	7.98	6.78	7.26
0.0450	6.81	7.98	6.62	7.14
0.0467	6.81	7.98	6.62	7.14
0.0483	6.81	7.78	6.62	7.07
0.0500	6.62	7.78	6.42	6.94
0.0517	6.62	7.78	6.23	6.88
0.0533	6.62	7.59	6.23	6.81
0.0550	6.42	7.40	6.03	6.62
0.0567	6.23	7.20	6.03	6.49
0.0583	6.23	7.01	6.03	6.42

2.5 Specimen Confined by CL2 (3Pcs)

Strain	Stress [Mpa] Specimen-1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen -3	Average stress [Mpa]
0.0000	0.00	0.00	0.00	0.00
0.0007	3.11	3.70	5.16	3.99
0.0013	6.42	7.20	9.83	7.82
0.0020	9.54	13.43	13.53	12.16
0.0027	15.57	17.52	16.06	16.38
0.0033	23.16	23.16	17.52	21.28
0.0040	22.77	26.86	18.59	22.74
0.0047	22.97	26.27	19.36	22.87
0.0053	23.94	26.08	23.70	24.57
0.0060	24.72	27.64	23.82	25.39
0.0063	24.91	30.94	23.70	26.52
0.0067	24.52	32.50	23.35	26.79
0.0073	24.33	33.47	22.54	26.78
0.0075	23.94	36.00	24.05	28.00
0.0093	23.35	30.75	27.05	27.05
0.0100	23.16	29.19	26.18	26.18
0.0107	21.99	27.64	24.81	24.81
0.0113	21.21	25.88	23.55	23.55
0.0120	20.05	24.13	21.49	21.89
0.0127	19.27	22.67	20.44	20.79

0.0133	18.49	21.21	18.92	19.54
0.0140	17.71	19.66	17.98	18.45
0.0147	16.93	18.10	16.58	17.20
0.0153	16.93	17.32	15.41	16.56
0.0160	16.35	16.54	14.60	15.83
0.0167	15.57	15.57	14.25	15.13
0.0173	14.60	14.60	13.43	14.21
0.0180	14.21	13.92	13.08	13.73
0.0187	13.82	13.23	11.91	12.99
0.0193	13.04	12.75	11.09	12.29
0.0200	12.65	12.26	9.93	11.61
0.0207	12.07	11.77	9.23	11.02
0.0213	11.87	11.29	8.64	10.60
0.0220	10.90	10.70	8.29	9.96
0.0227	10.12	10.12	8.06	9.43
0.0233	9.34	9.83	7.82	9.00
0.0240	8.95	9.54	7.47	8.65
0.0247	8.37	9.15	7.12	8.21
0.0253	7.78	8.76	7.12	7.89
0.0260	7.40	8.47	7.01	7.62
0.0267	7.01	8.17	7.01	7.40
0.0273	6.81	7.88	6.77	7.16
0.0280	6.62	7.59	6.13	6.78
0.0287	6.42	7.49	5.79	6.57
0.0293	6.03	7.40	5.74	6.39
0.0300	5.84	7.20	5.72	6.25
0.0307	5.64	7.01	5.64	6.10
0.0313	5.45	6.91	5.64	6.00
0.0320	5.25	6.81	5.45	5.84
0.0327	5.25	6.71	5.45	5.81
0.0333	5.06	6.62	5.62	5.77
0.0340	4.87	6.62	5.62	5.70
0.0347	4.67	6.42	5.62	5.57
0.0353	4.67	6.42	5.46	5.52
0.0360	4.67	6.42	5.46	5.52
0.0367	4.67	6.23	5.46	5.45
0.0373	4.67	6.23	5.29	5.40
0.0917	4.09	5.25	5.29	4.88

2.6 Specimen Confined by CL3 (3Pcs)

Strain	Stress [Mpa] Specimen-1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen -3	Average stress [Mpa]
0.0000	0.00	0.00	0.00	0.00
0.0007	3.35	2.34	4.18	3.29
0.0013	4.18	6.81	5.23	5.41
0.0020	5.23	13.04	6.53	8.27
0.0027	15.33	17.91	19.16	17.46
0.0033	22.38	20.63	27.98	23.66
0.0040	21.41	20.82	26.76	23.00
0.0047	22.77	22.77	28.46	24.67
0.0053	23.74	23.16	29.68	25.53
0.0060	25.50	23.74	31.87	27.04
0.0067	26.47	23.94	33.09	27.83
0.0073	27.25	25.30	34.06	28.87
0.0080	29.19	25.11	36.49	30.26
0.0087	29.58	25.11	36.98	30.56
0.0093	29.00	24.91	36.25	30.05
0.0100	28.03	24.52	35.03	29.19
0.0107	27.25	23.55	34.06	28.28
0.0113	25.30	22.58	31.63	26.50
0.0130	23.35	21.99	29.19	24.85
0.0147	21.41	21.80	26.76	23.32
0.0163	19.66	21.41	24.57	21.88
0.0180	18.10	17.52	22.62	19.41
0.0197	17.32	16.35	21.65	18.44
0.0213	16.15	15.18	20.19	17.18
0.0230	15.18	14.79	18.98	16.32
0.0247	14.21	14.21	17.76	15.39
0.0263	13.23	13.82	16.54	14.53
0.0280	12.46	13.23	15.57	13.75
0.0297	11.68	13.04	14.60	13.10
0.0313	10.90	12.46	13.62	12.33
0.0330	10.31	10.61	12.89	11.27
0.0347	9.93	10.12	12.41	10.82
0.0363	9.73	9.83	12.16	10.57
0.0380	9.54	9.63	11.92	10.36

0.0397	9.34	9.44	11.68	10.15
0.0413	9.15	9.24	11.43	9.94
0.0430	8.95	9.05	11.19	9.73
0.0447	8.95	8.95	11.19	9.70
0.0463	8.95	8.95	11.19	9.70
0.0480	8.56	8.76	10.70	9.34
0.0497	8.37	8.47	10.46	9.10
0.0513	8.17	8.27	10.22	8.89
0.0530	7.98	8.08	9.97	8.68
0.0547	7.98	7.98	9.97	8.64
0.0563	7.78	7.88	9.73	8.47
0.0580	7.78	7.78	9.73	8.43
0.0597	7.59	7.69	9.49	8.26
0.0613	7.40	7.49	9.24	8.04
0.0630	7.40	7.40	9.24	8.01
0.0647	7.20	7.30	9.00	7.83
0.0663	7.01	7.10	8.76	7.62
0.0680	7.01	7.01	8.76	7.59
0.0697	6.81	6.91	8.51	7.41
0.0713	6.81	6.81	8.51	7.38
0.0730	6.62	6.71	8.27	7.20
0.0747	6.62	6.62	8.27	7.17
0.0763	6.23	6.42	7.78	6.81
0.0907	6.03	6.13	7.54	6.57

3.1 Specimen Unconfined Specimen US (3Pcs)

Strain	Stress [Mpa] Specimen -1	Stress [Mpa] Specimen-2	Stress [Mpa] Specimen-3
0.0000	0.00	0.00	0.00
0.0004	2.93	2.79	2.81
0.0008	5.57	5.29	5.35
0.0011	8.60	8.17	8.26
0.0014	12.61	11.98	12.10
0.0018	14.96	14.21	14.35
0.0021	17.11	16.26	16.42
0.0024	19.26	18.30	18.48
0.0028	21.90	20.81	21.02
0.0031	25.32	24.06	24.30
0.0034	25.42	24.15	24.39
0.0038	23.66	22.48	22.70
0.0041	20.83	19.79	19.98
0.0044	18.77	17.83	18.01
0.0048	17.60	16.72	16.89
0.0051	16.82	15.98	16.14
0.0054	14.86	14.12	14.26
0.0058	12.81	12.17	12.29
0.0061	11.54	10.96	11.07
0.0064	10.46	9.94	10.04
0.0068	9.00	8.55	8.63
0.0071	6.84	6.50	6.57
0.0074	6.45	6.13	6.19