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EXPERIMENTAL AND ANALYTICAL INVESTIGATION ON SPIRAL AND CIRCULAR HOOP CONFINEMENT OF CONCRETE

A THESIS IN STRUCTURAL ENGINEERING

BY: TEDROS KIROS

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Experimental and Analytical Investigation on Spiral and Circular Hoop Confinement of Concrete

By

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The undersigned have examined the thesis entitled '**Experimental and Analytical Investigation on Spiral and Circular Hoop Confinement of Concrete**' presented by **Tedros Kiros Medhin**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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ABSTRACT

Confining of concrete using transverse reinforcement is common trend in construction industry in order to enhance strength as well as achieving of ductility; with ductile behavior of failure mechanism. Therefore, there are two types of passive confinement techniques which are practically adopted for circular cross – section of columns; these are called spiral and circular hoop. To examine the difference between spiral and hoop confinements, forty four cylindrical concrete specimens with a size of 300mm in height and 150mm in diameter are scrutinized experimentally. The experiment embraces three groups of specimens; cylindrical concrete specimens confined by spiral, circular hoops, and unconfined cylindrical column specimens. For first and second groups vertical spacing and yield strength of transverse reinforcement are main variables, in addition to these, unconfined compressive strength of concrete is considered as variable for all groups. Supplementary to the experimental specimens, ten different combinations of concrete specimens are simulated using Finite Element Package.

About 5% increase of confined strength of concrete by circular hoops over spiral confinement at 56mm spacing of transverse reinforcement was observed. The percentage increase of confined strength of concrete by spiral over circular hoops at 94mm spacing of transverse reinforcement is about 11%. It can be concluded that spiral reinforcements offer better confined strength than circular hoops at relatively large spacing and vice versa.

Sensitivity analysis was also conducted by considering confined strength of concrete as objective function. Based on the analysis, compressive strength of concrete has largest contribution than other variables. On the other hand, spacing of transverse reinforcement has an adverse effect to confined strength of concrete in both of spiral and circular hoop confinements. The contribution of yield strength of transverse reinforcement is relatively smaller than other variables.

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Abbreviation

ACI – American Concrete Institute

CAE – Complete Abaqus Environment

CDP - Concrete Damage Plasticity

COV - Coefficient of Variance

ES –Ethiopian Standard

FE - Finite Element

LVDT – Linear Variable Differential Transducer

Latin Upper Case Letters

A_g – Gross Area of Column Cross – Section

A_s – Area of Transverse Reinforcement

A_c – Core Area of Column Cross – Section

C_i – Confinement Index

D_c – Diameter of Concrete Specimen

E – Modulus of Elasticity

E_c - Modulus of Elasticity of Concrete

E_s - Modulus of Elasticity of Steel

H_o – Null Hypothesis

H_I – Alternative Hypothesis

T –Hoop Tension

U_i – Uncertainty of Random Variable

Latin Lower Case Letters

s – Spacing of Transverse reinforcement

f_l – Lateral confining pressure

r_c – Radius of concrete specimens

f_{cco} – Confined strength of concrete

f_{co} – Unconfined strength of concrete

f_y – Yield strength of transverse reinforcement

f_2 – Lateral confining pressure

f_{bo} – Biaxial strength of concrete

f_{co} – Uniaxial strength of concrete

d_c – Compression damage variable of concrete

Greek lower Case Letters

α_i - Sensitivity factor

ε – Eccentricity

ε_{oc}^{el} – Elastic compressive strain

$\ddot{\varepsilon}_c^{in}$ – Inelastic compressive strain

$\ddot{\varepsilon}_c^{pl}$ – Plastic compressive strain

ε_c – Total compressive strain

μ – Mean value

ν – Poisson's ratio

ρ_s – Volumetric ratio of transverse reinforcement

ρ_{cc} – Area ratio of longitudinal reinforcement

σ_c – Compressive yield stress

σ_{cu} – Ultimate compressive stress

ψ – Dilation Angle

σ – Standard deviation

$\bar{f}$ - mean value of "f" objective function

χ – Random variable

$\bar{x}$ - mean value of "x" random variable

1. INTRODUCTION

1.1. Background

Columns are pillar structural members subjected to mainly axial forces with or without moment, their failure mechanism also leads to collapse of the whole structure due to lateral expansion and buckling under axial load. Excessive lateral expansion and stiffness degradation could be control by confining of core concrete using transverse reinforcement which is called confinement. Therefore; confinement technique by spiral and/or circular hoops of transverse reinforcement enhances strength of the column as well as ductility. Viz behavior of confined concrete columns is increased its section capacity due to additional lateral confining pressure induced from transverse reinforcement. Moreover this can be observed easily from the stress – stain diagram confined concrete columns.

However; there is a degree of confinement difference between spiral and circular hoops of transverse reinforcements. Researchers' mentioned that spiral (helix) reinforcements has high degree of confinement than circular hoop, the reason is due to their shape of configuration which continuously tied at a restricted vertical spacing throughout the circumference of the column. In this research, the difference between spiral and circular hoop based on confined strength of concrete is considered as dependent variable. The dependent variable has direct and/or indirect relationship to the independent variables such as unconfined strength of concrete, yield strength and spacing of transverse reinforcement. To estimate the contribution of independent variable on the objective function could be determine using sensitivity analysis.

Abaqus package (SIMULIA, 2013) provides the capability of simulating damage of concrete using either of the three crack models for reinforced concrete elements: (1) Smeared crack concrete model, (2) Ducker Prager model, and (3) Concrete Damaged Plasticity model. Out of these, concrete damaged plasticity model has the potential to represent complete inelastic behavior of concrete both in tension and compression including damage characteristics (Wahalathantri 2011). Moreover, the concrete damage plasticity model assumes two main concrete failure mechanisms are cracking under uniaxial tension and crushing under uniaxial compression.

1.2. Statement of the problem

The effectiveness of spiral reinforcement over circular hoops on the base of degree of confinement is not well emphasizing in practice. Arrangement selection of transverse reinforcement for circular column is not clearly mentioned ES - EN 1992-1-1:2015.

Confinement of concrete using transverse reinforcement (i.e. spiral and circular hoop) without the contribution longitudinal reinforcement is not yet studied.

Contribution of independent variables (i.e. concrete strength, yield strength and spacing transverse reinforcement) on the dependent variable (confined strength of concrete) is difficult to quantify and making a decision without conducting sensitivity analysis of random variables is becoming common.

1.3. Objective of the Research

Experimental investigation of confined compressive strength of concrete using spiral and circular hoop at different concrete grades, yield strengths and vertical spacing of transverse reinforcement is the core objective of this research.

Specific objective:

- To investigate and evaluate concrete specimens confined using spiral and circular hoops reinforcement.
- To conduct Concrete Damage Plasticity (CDP) Model using Finite Element package (Abaqus) and compare the outputs with experimental results.
- To evaluate the post-peak response of confined concrete both experimentally and theoretically.
- To conduct sensitivity analysis of random independent variables.

1.4. Limitation of the Research

As per the objective of the research, concrete grade, yield strength and spacing of transverse reinforcements are kept as variables. In addition to this, during experimental work the dimensions of the cylindrical concrete specimens are delineated to what is available in the laboratory.

During simulation of stress – strain model for concrete in Abaqus, softening of concrete in compression, caused by cracking due to tension in the perpendicular direction is not considered in this thesis.

1.5. Research Organization

This research encompasses of six chapters. The first chapter is an introduction part; it covers general information about behavior of columns and role of confinements. In addition to this; objective, statement of the problem and limitation of the research are stated in this chapter.

Sufficient information and guidance regarding to spiral and circular hoop type of confinements are collected as literature review which is presented under chapter two.

Chapter three comprises detail information and procedures about experimental work. Materials, test set – up and test instrumentation are depicted in pictorial form. Experimental data of stress – strain diagram for confined concrete specimens using spiral and circular hoop type of confinement are insight investigated and evaluated.

Chapter four is dealing about Finite Element analysis of confined concrete specimens using Abaqus / CAE. Output results obtained from Abaqus such as stress – strain curves and compression damage property of concrete subjected to compression load have a good agreement with experimental data. Experimental and analytical observations and discussions are presented under chapter five.

Chapter six concerns on sensitivity analysis by considering confined strength of concrete using transverse reinforcement as objective function. Chapter seven covers a detail discussion and recommendation of the research.

2. LITERATURE REVIEW

2.1. Active and Passive Confinement

Appropriate modeling of stress – strain diagram of concrete is one of the most fascinating and attractive implication on predicting mechanical behavior of concrete, when subjected to load. The property of concrete by its nature has inelastic and plastic behavior and also too relatively high compressive strength and low tensile strength. Therefore; stress – strain behavior of concrete under compression, both in the ascending and descending branches, is crucial in determining both strength and ductility of reinforced concrete members. When ductile design approach is used in seismic design, structural members are required to behave in a ductile manner, so as to absorb and dissipate the great energy transmitted from severe earthquakes. Confinement of core concrete is an effective method to provide an adequate ductility for reinforced concrete members, especially when comparatively high load is imposed. Moreover; according to previous studies confinement of core concrete can be categorized in to two groups; active and passive confinement.

The studies on active confinement were to investigate the basic behavior of concrete as a material under triaxial compressive stress condition. Active confinement is normally provided by fluid pressure or mechanical pressure in experimental studies and hence the confining stress level can be freely selected within the limit of pressure devices. Practically speaking, active confinement is covering and wrapping of concrete members by fiber materials or other. On the other hand, passive confinement is normally provided by transverse reinforcement in the form of closed stirrups, ties, hoops or spirals in practice of construction.

In the case of passive confinement, at low levels of compressive stress in concrete, the transverse reinforcement is hardly stressed and the behavior of the concrete is unaffected by the confining reinforcement. The concrete becomes confined when stresses approaching the uniaxial strength, the transverse strains become very high due to progressive internal cracking and the concrete bears out against the transverse reinforcement, which the applies a confining reaction to the concrete. Due to such action, the confinement by transverse reinforcement is referred to as passive confinement (R. Park 1974). But there is a degree of confinement discrepancy between spiral, circular hoops and lateral tie of transverse reinforcements. Many researchers' states that spiral (helix) reinforcements have high degree of confinement than others, this is due to their configuration arrangement and continuously helix at a restricted vertical spacing through the circumference of the circular column. Circular hoops and ties reinforcements have lower degree of confinement than spiral respectively.

2.2. Factors that Affect Behavior of Confined Concrete

Ductility, considered as the ability of the structure or its components of offer resistance in the inelastic domain of response, can be developed only if the constituent material itself is ductile, and this not the best characteristic concrete has. In order to improve its performance, confinement is recommended. Confinement in concrete is achieved by the suitable placement of transverse reinforcement, these results in a significant increase in the strength and ductility of concrete (Esmerald Filaj 2016).

a) Compressive Strength of Concrete

High – strength concrete exhibits less lateral expansion under axial compression than normal – strength concrete due to its higher modulus of elasticity and lower internal micro – cracking. Consequently, the confining reinforcement comes into play later in the process and the efficiency of passive confinement of high – strength concrete would be reduced (Daniel Cusson 1994) and (Shafqat A 2012).

b) Volumetric Ratio of Transverse Reinforcement (ρ_s)

The confining pressure applied on the core of concrete column is directly related to the volumetric ratio (ρ_s) of confining reinforcement. As the volumetric ratio (ρ_s) of confining reinforcement increased, the strength developed increased, the slope of the falling branch decreased (i.e. flattened) and the longitudinal strain at which hoop fracture occurred increased (J.B. Mander 1988).

c) Yield Strength of Confining Steel (f_{yt})

Yield strength of transverse steel measures the upper limit of the confining pressure applied to the concrete of column core. A higher confining pressure applied to the concrete core can result as more confinement efficiency.

d) Configuration of Transverse Reinforcement

The tie configuration determines the effectively confined concrete area, which increases with a better distribution of longitudinal bars around the column concrete core. The larger the effectively confined concrete area, the higher would be the confinement efficiency. Cyclic hoops are more effective than orthogonal ones, hoops or ties penetrate the concrete core are also more effective than orthogonal ones since in this case unconfined zones are limited (George G. Penelis 2014).

e) Spacing of Transverse reinforcement (s)

Smaller transverse reinforcement spacing increases the confined concrete area, resulting in higher confinement efficiency. In addition, tie spacing controls the buckling of the longitudinal re-bars.

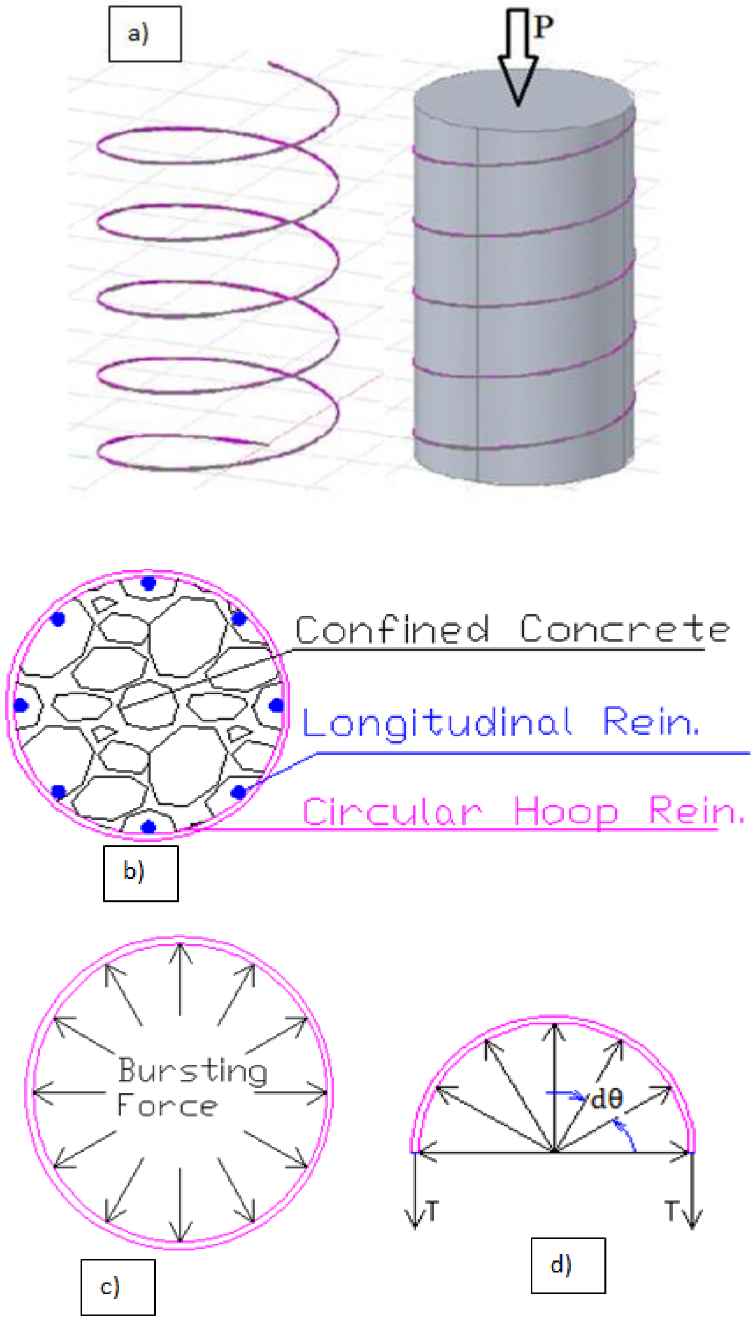
f) Volumetric Ratio of Longitudinal Reinforcement (ρ_{cc})

A lager amount of longitudinal reinforcement, provided by a larger reinforcement diameter, would prevent premature buckling of longitudinal bars.

g) Strain Rate of Axial Deformation

A high strain rate influences the increase of strength and the decrease of plastic deformation, as in the case of plain concrete.

Bursting force in a circular column due to lateral expansion of concrete subjected to axially compressive load may be considered equivalent to a system of uniformly distributed radial forces acting along the circumference of the transverse reinforcement. When confined concrete specimens are exposed to uniaxial compressive load, the spiral reinforcement subjected to hoop tension action, because of the lateral expansion of the concrete. Let's assume the lateral confining pressure is f_l, and can be express in the form of hoop tension exerts on spiral (T) and radius of the concrete specimen (r_c) as follow:-



a) Three dimensional view of Spiral reinforcement; b) Cross sectional view of Column; c) Bursting Forces; d) Exertion of Tension Hoop due to Bursting Forces.

Figure 2.1 Spirally confined concrete

Apply equilibrium equation

$$2T = \int_0^{\frac{\pi}{2}} f_l\, r_c \sin\theta\, d\theta \quad + \int_{\frac{\pi}{2}}^{\pi} f_l\, r_c \sin\theta\, d\theta \qquad (2.1)$$

$$2T = \left(-f_l\, r_c \cos\theta \,\Big|_0^{\frac{\pi}{2}}\right) + \left(-f_l\, r_c \cos\theta \,\Big|_{\frac{\pi}{2}}^{\pi}\right) \qquad (2.2)$$

$$2T = \big(-(0) - (-f_l\, r_c)\big) + \Big(\big(-f_l\, r_c\,(-1)\big) - 0\Big) \qquad (2.3)$$

$$2T = f_l\, r_c + f_l\, r_c = 2f_l\, r_c \qquad (2.4)$$

$$T = f_l\, r_c \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ per ring and } r_c = \frac{D_c}{2}$$

$$2T = f_l\, D_c\, s \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{per spacing, where 's' is vertical spacing}$$

At high lateral strain of core concrete, the hoop tension (T) of spiral or circular hoop approaching to yield strength, and can be expressed as cross –sectional area (A_s) multiplied by yield strength (f_{sh}).

$$f_l = \frac{2A_s f_{sh}}{s D_c} \qquad (2.5)$$

Where, f_l is lateral confining pressure, A_s is cross – sectional area of spiral or circular hoop, f_{sh} is yield strength of spiral or circular hoop, D_c is diameter of core concrete, and s is spacing of spiral or circular hoop.

2.3. Previous Studies on Confined Concrete

Sheikh and Toklucu (1993) tested 27 specimens to investigate the behavior of reinforced concrete circular columns confined by spiral and hoops stirrups under monotonic axial compression loads. Based on results of tests, it was reported that; strength and ductility of confined concrete increase with an increase in the amount of lateral steel and the strength enhancement have been much less sensitive than ductility, as shown in Figure 2.3. A reduction in s/D_c (spacing to core diameter) ratio results in a significant improvement of concrete behavior, specifically ductility. For lower ρ_s values, a change in s/D_c ratio did not change concrete behavior radically, since the improvements in concrete properties due to confinement were minimal, and for large ρ_s values ($\rho_s > 1.7\%$) the confinement provided by the spiral steel were very effective and change in the s/D_c ratio had not affect concrete behavior significantly.

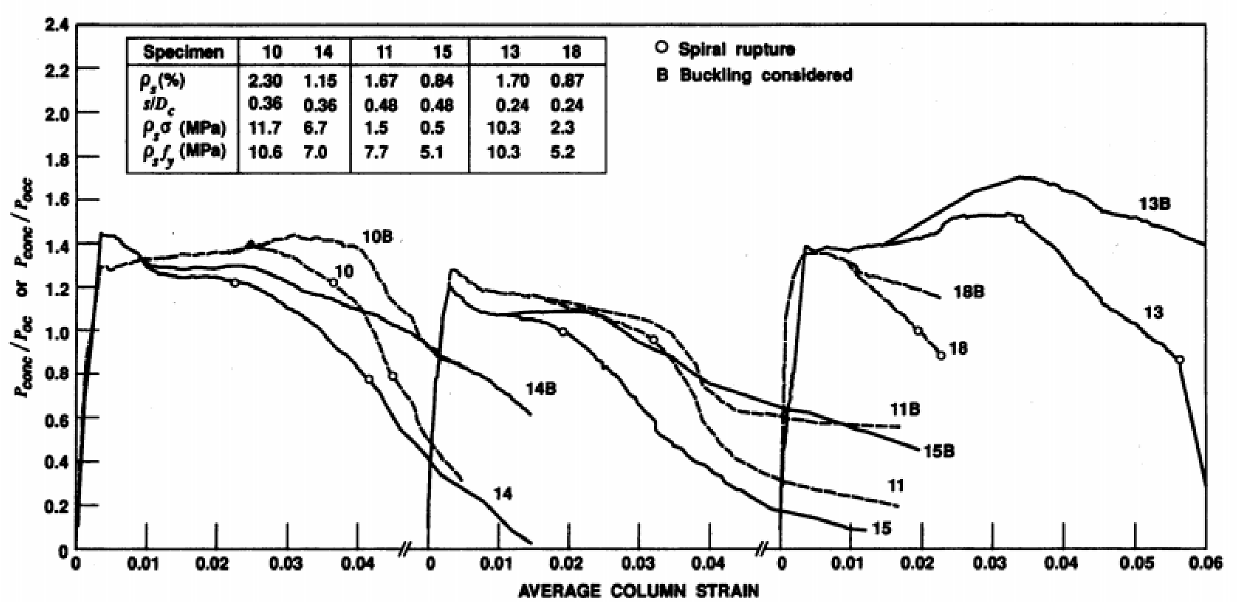


Figure 2.2 Effect of amount of Lateral Steel (Shamim A. Sheikh 1993)

In early twentieth century, researchers studied confinement effects under fluid pressure and then in spirally reinforced concrete columns, and proposed an equation to express the axial strength of spirally reinforced columns as:

$$f'_{cc} = f'_c + 4.1 f_2 \qquad (2.6)$$

Implication of confining reinforcement in reinforced concrete columns in ACI 318 – 08, especially in earthquake resistance structures is based on two conditions: 1) increase in compressive strength of concrete due to confinement should offset the strength loss due to cover spalling; and 2) columns should be able to sustain large deformations without a dramatic loss in strength.

The current ACI-318-08 code provisions for spiral reinforcement require that the volumetric ratio of spiral reinforcement (ρ_s) for non – seismic design of columns should not be less than the value given by:

$$\rho_s = 0.45\left(\frac{A_g}{A_c} - 1\right)\frac{f'_c}{f_{yt}} \qquad (2.7)$$

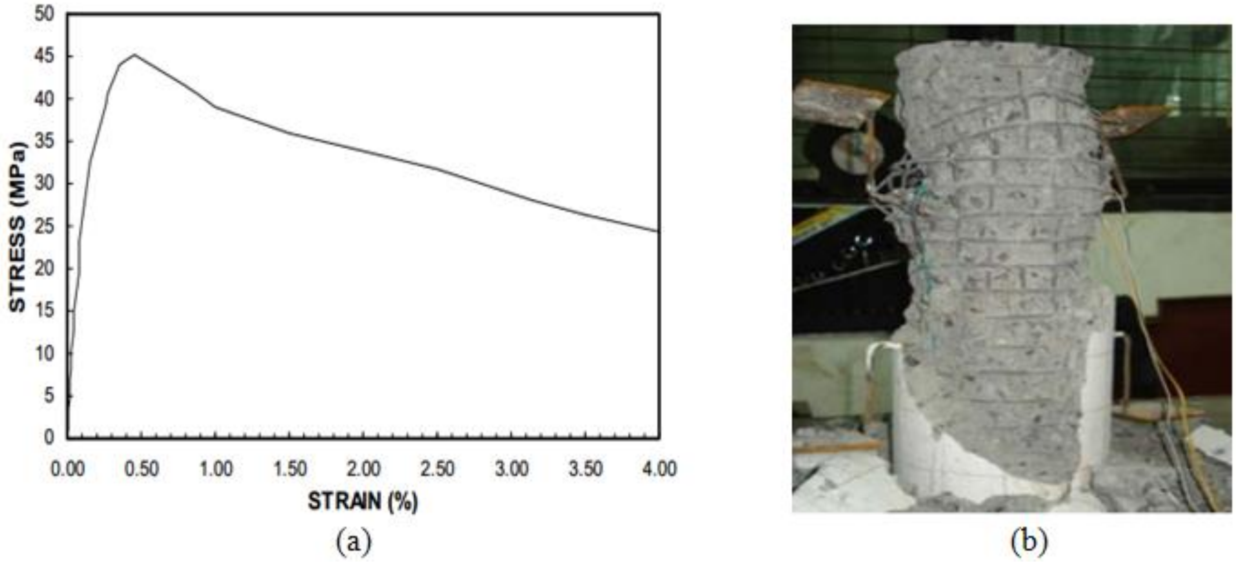
Whereas the specified yield strength of spiral steel (f_{yt}) shall not exceed 100,000 psi (667 MPa). The seismic provision require that in addition to Eq (2.7), the volumetric ratio of spiral or circular hoop reinforcement, (ρ_s), shall not be less than required by:

$$\rho_s = 0.12 \frac{f_c'}{f_{yt}} \qquad (2.8)$$

A theoretical model is developed to describe the uniaxial stress – strain relationship of spirally confined concrete by Hau Yan Leung and Chris J. Burgoyne (2005). Furthermore, it encompasses one single spiral concrete confined by two interlocking spirals is also included in their studied, using a finite element model to determine the magnification factors caused by multiple confinements. Stress – strain relationship predicted for the behavior of compression specimens with various types of reinforcement.

Behavior of circular RC columns confined with fine mesh was investigated by Tavio, R. Purwono and M.L. Ashari (2008). They were intended to conduct an experimental investigation comprised strength and ductility tests using small – scale circular concrete column specimens with different grid spacing of fine mesh and diameter of fine mesh as lateral reinforcement. The column specimens were tested under concentric loading. Their results indicate that fine mesh can be effective in confining the core concrete, resulting in significant improvements in strength and ductility of columns. These improvements were achieved even though the column specimens contained a relatively small percentage of fine mesh. Although some practical problems remain fine mesh can potentially be used in earthquake – resistant structures as confinement reinforcement, particularly for retrofitting.

Column pair (C 325) in Tavio, R. Purwono and M.L. Ashari (2008) study casted with cylinder compressive strength of concrete 26 MPa, yield strength and spacing of fine mesh with 690 MPa and 28.2 x 28.2 mm respectively including 0.95 percent of fine mesh ratio (ρ_{fm}). The observed behavior of column under uniaxial compression loading is depicted in Figure 2.3.



(a) Stress – Strain Relationship (b) Specimen after Testing

Figure 2.3 Response of column pair C 325 (Tario R. Purwono 2008)

Melat (2010) was conducted an experimental program with a total of 33 small scale concrete column with 3 different geometric arrangement of transverse tie (i.e cross tie, normal and overlapping) of square column and three different number of mesh - layer of square and circular column. For each experiment, stress – strain relationship was obtained and comparison is made with models proposed earlier. Failure modes of specimens happened at the middle third of the specimen, which was initiated by vertical cracks followed first by lateral deflection of the plain concrete. As compression load increases, the specimen start to show craze vertical cracks as shown in figure 2.4 (a), and when the axial load approach to the maximum value the extent of cracking increases radically and concrete cover was spalled off as shown in figure 2.4 (b) and (c) respectively. Longitudinal reinforcement experienced noticeable deformation (buckling) as shown in figure 2.4 (d). Finally, she recommends cross tie configuration and more than two layer of wire mesh for buildings built in seismic region.

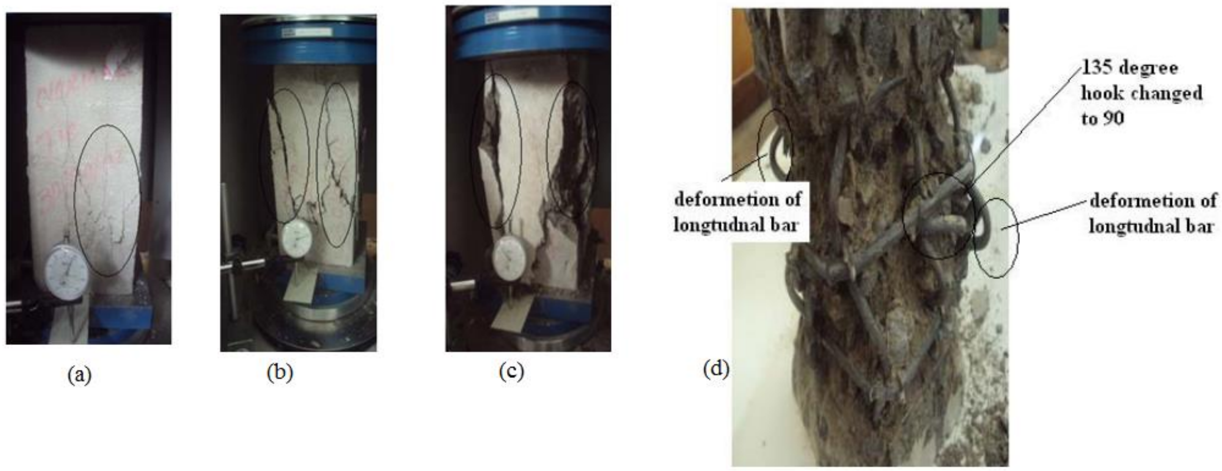


Figure 2.4 Failure Pattern of Specimen Confined by Transverse Reinforcement (Melat 2010)

Shafqat A. & Ali A. (2012) were studied an experimental investigations on reinforced concrete columns by changing the conventional lateral ties of rectangular RC column core to special confinement using the equivalent area of thin steel plates. Three columns were casted using different confining steel, and experimentation was done on these columns to check the maximum axial capacity along with study of mode of failure and toughness. Result of tied column showed that strain in confining reinforcement was only 20% of main reinforcing steel strain at first peak, and stress level in confining steel was only 28.45% of its yield stress for controlled column using normal ties. Meanwhile they agreed at results that at the time of maximum load, stresses in confining steel are significantly lesser than its capacity. So this reserve capacity can be utilized by spreading the area of lateral reinforcement over the longitudinal steel bar in order to reduce the effective length.

A total of twenty five RC cylindrical specimens were tested by Jung-Yoon LEE et al. (2013). Four parameters were considered in this investigation: compressive strength of concrete, the yield strength of transverse reinforcement, percentage of transverse steel, and spacing. Test results indicated that the structural behavior of RC cylinders confined with high strength transverse reinforcement was strongly influenced by compressive strength of concrete. The high strength lateral reinforcement in high strength concrete did not reach its yield strain and the confining effect of the high strength steel bars in high strength concrete was small compared to the effect of the high strength steel bars in normal strength concrete.

Table 2.1 Test results of Specimens (Jung - Yoon Lee 2013)

Group	Specimens	$f_c'\ (MPa)$	Spirals	
			$f_{yt}\ (MPa)$	Spacing (s),mm
C – 50	P 50	44.4	-	-
	NS 50		472	25
	NM 50		472	45
	NL 50		472	65
	HS 50		880	25
	HM 50		880	45
	US 50		1430	25
	UM 50		1430	45
	UL 50		1430	65

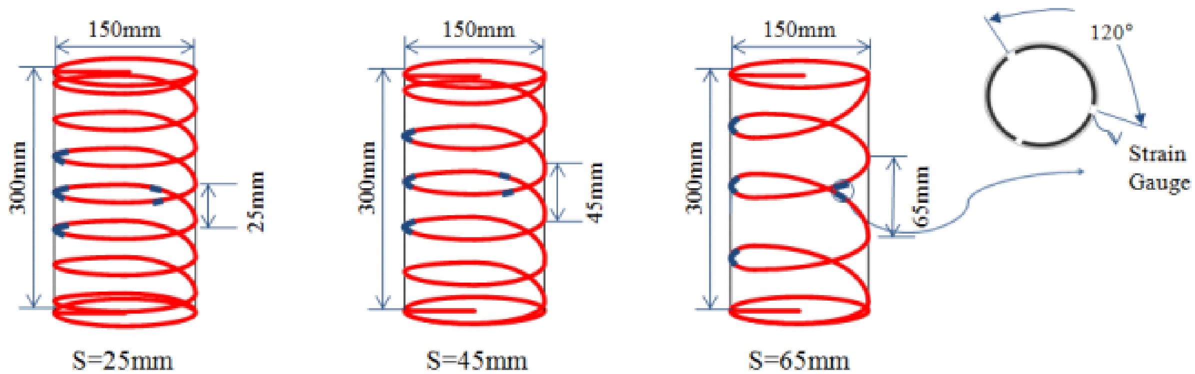


Figure 2.5 Different spiral spacing and strain gauge at spirals (Jung - Yoon Lee 2013)

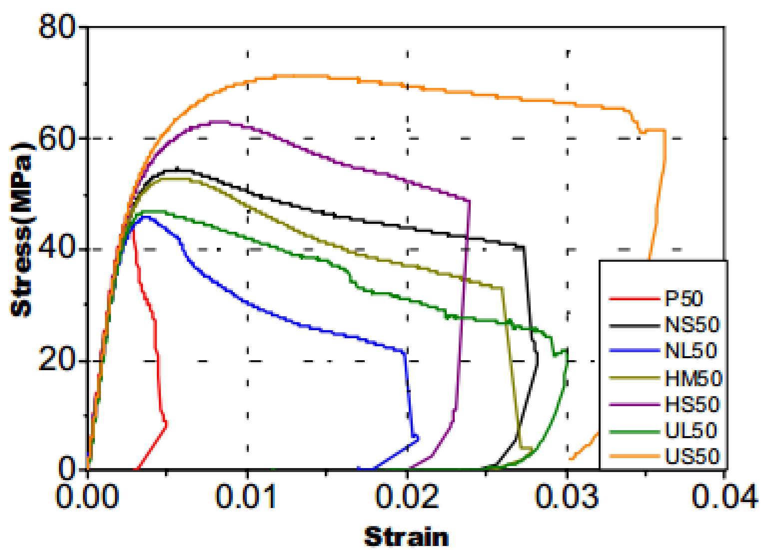


Figure 2.6 Axial stress vs. axial strain response of C – 50 specimen (Jung - Yoon Lee 2013)

Liang Huang el al. (2015) examined an experimental results and analytical modeling of the axial compressive behavior of concrete cylinders confined by both glass fiber-reinforced polymer (GFRP) tube and inner steel spiral reinforcement (SR). In this study cylinder specimens were identified by two sets of characters as follows: the first set indicated the number of GFRP layers (i.e. P1, P2, and P3 indicated one, two, and three layers, respectively); and the second set of characters indicated the pitch of SR (i.e., S1 = 25mm and S2 = 50mm). Table 2.2 summarizes the testing matrix.

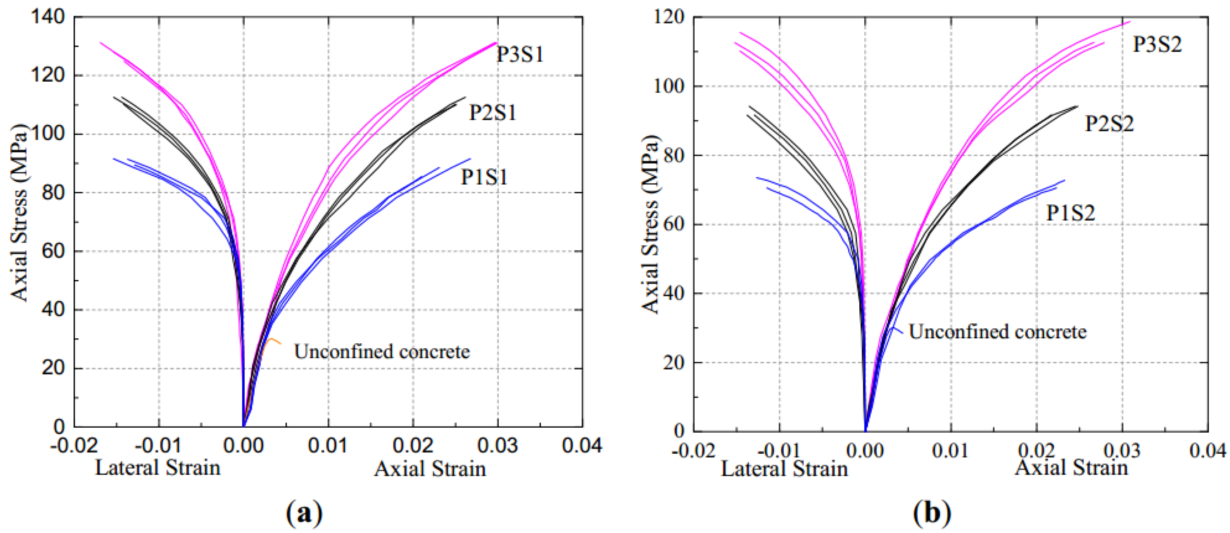
Table 2.2 Details of confined concrete cylinder specimens (Liang Huang 2015)

Specimen Designation	f_c' (MPa)	No. of Layers	E_f (GPa)	t_f (mm)	f_{lf}/f_c'	ρ_f (%)	f_{yt}	ρ_s (%)	f_{sf}/f_c'
P1S1		1		0.436	0.190	20.20			0.164
P2S1		2		0.872	0.378	25.23		3	0.164
P3S1		3		1.308	0.567	27.52			0.164
P1S2	30	1	60.8	0.436	0.190	20.20	356		0.073
P2S2		2		0.872	0.378	25.23		1.5	0.073
P3S2		3		1.308	0.567	27.52			0.073

The failure modes of GFRP – SR confined concrete cylinder specimens are shown in figure 2.7, all of the confined concrete specimens failed by tensile rupture of the GFRP tube in the hoop direction. The failure situations of all specimens were quite similar, however, for specimens with lower SR volumetric ratio more core concrete crushed and squeezed out after the rupture of GFRP compared with the higher ones.

Figure 2.7 Typical Failure Mode of Specimens (Liang Huang 2015)

According to their test results, both GFRP tube and SR confinement remarkably increase the ultimate compressive strength, energy dissipation capacity, and ductility of concrete. And finally they concluded the volumetric ratio of SR has a more pronounced influence on the energy dissipation capacity of confined concrete with more GFRP layers.



GFRP – SR Confined Cylinder Specimens with SR Volumetric ratio of (a) 3% and (b) 1.5%

Figure 2.8 Axial Stress versus Axial and Lateral Strain Curves (Liang Huang 2015)

Ming – Yang Chen el al (2017) studied on the axial compression mechanical behavior of Reactive Power Concrete (RPC) circular columns which confined by spiral hoops of yield strength 600MPa are tested, and the tie spacing and volume tie ratio were used to evaluated the RPC columns failure modes, load – displacement relationship and yield characteristics of high – strength stirrups. The results show that the peak stress of the 250mm diameter circular column with no reinforcement can be up to 144.4MPa but with brittle failure mode, and the large volume tie ratio can increase the peak stress to 180MPa and failure by ductility.

Concentric compression tests on short Aramid Fiber Reinforced Polymer (AFRP) spirally – confined concrete cylinder have been described by Hau Yan Leung and Chris J. Burgoyne. The critical variables, including the concrete compressive strength, spiral spacing, arrangement of spirals and degree of interlocking, have been considered. A promising increase in strain is obtained experimentally and theoretically for a high degree of overlap. Bulging failure was found to be the governing mode for most uniaxially compressed concrete cylinders, which is usually followed by fracture of the spiral. And it was found that the behavior of confined concrete is influenced not only by the concrete strength, but also the spiral leg spacing and the degree of interlocking. Concrete cylinders with close spacing and a high degree of interlocking usually gave higher strength and ductility.

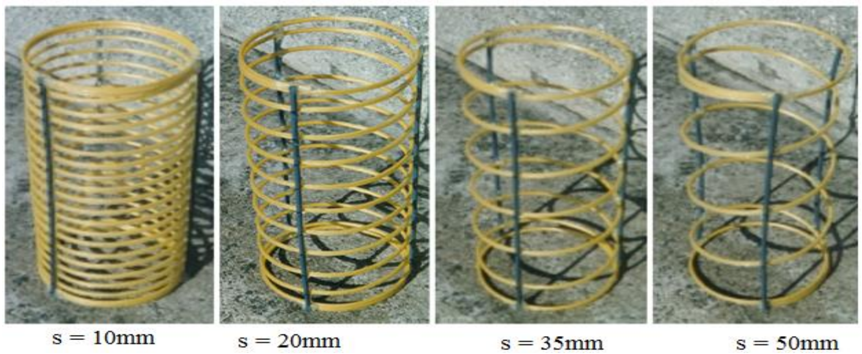


Figure 2. 9 Aramid fibre single spirals (H. Y. Leung n.d.)

Mohammad M. Zaki M. Afifi (2013) was evaluating axial performance of RC compression members reinforced with glass FRP (GFRP) and carbon FRP (CFRP) bars and stirrups through experimental and analytical investigations. A total of twenty seven full scale circular RC specimens were fabricated and tested experimentally under concentric axial load. His specimens were divided into three series; series-I contains three reference columns; one plain concrete and 2 specimens reinforced with steel reinforcement. Series-II contains 12 specimens internally reinforced with GFRP longitudinal bars and transverse GFRP stirrups, while series-III includes specimens totally reinforced with CFRP reinforcement. During his test several parameters have been studied; type of reinforcement, longitudinal reinforcement ratio, the volumetric ratios, diameters, and spacing of spiral reinforcement, confinement configuration (spirals versus hoops), and lap length of hoops. Based on the findings of experimental investigation, the GFRP and CFRP RC columns behaved similar to the columns reinforced with spiral steel. He was found that, FRP bars were effective in resisting compression until after crushing of concrete, and contributed on average 8% and 13% of column capacity for GFRP and CFRP RC specimens, respectively. The axial deformability (ductility) and confinement efficiency can be better improved by using small FRP spirals with closer spacing rather than larger diameters with greater spacing.

3. EXPERIMENTAL PROGRAM AND METHODOLOGY

3.1. Introduction

The experimental program focuses on the behavior of circular concrete specimens confined by spiral and circular hoops without longitudinal reinforcement, subjected to concentric axial loads. Moreover, the experimental work consciously focused and intended to distinguish and emphasize the contribution of spiral and circular hoop reinforcement on confinement.

3.2. Methodology

The primary methods and procedures accompanied in this thesis were gathering of enough and meaningful literature reviews related to the topic. To conduct experimental investigation, physical testing of materials such as particle size distribution, compacted dry density and silt content of sands are carried prior to casting of concrete. Tensile yield strength transverse reinforcement cage was check and recorded before being bending and rounding to the desire shape and arrangement. While transverse reinforcements allocated and placed inside formwork, concrete was casted and poured. After 28 days compressive strength of concrete was recorded.

Finite element simulation is also done after verified and validated Abaqus outputs with experimental results in the form of stress – strain diagram. Lastly sensitivity analysis was conducted for confined strength of concrete as objective function.

3.2.1. Materials

Concrete is a combination of coarse aggregate, fine aggregate (natural sand or fine crushed stone), cement, and water. As a result, its strength is depending on content, size, type and texture of these materials. So that, Dangote Portland Pozzolana Cement is used from the market and coarse and fine aggregates are obtained from local available site.

Transverse reinforcements are used to confined cylinder specimens concrete at different spacing with elastic – perfectly plastic type of stress – strain curve. The mechanical properties are stated as follow, yield strength of local product of transverse reinforcement (F_{y1} = 462MPa), yield strength of imported product of transverse reinforcement (F_{y2} = 618MPa).

Figure -1 demonstrates geometry of cylindrical column specimen. In this research a total of forty four small – scale cylindrical columns are investigated. The size of cylindrical column specimen is 300mm in height and 150mm diameter. Failures in concrete under compression loads are not only cone pattern and shear crack but also cover spalling too, although to protect transverse reinforcements 10mm concrete cover in all sides of the specimen adopted.

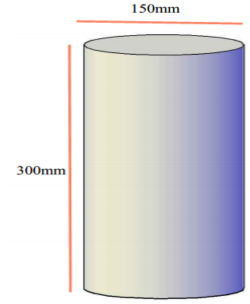


Figure 3.1 Cylindrical Column Specimen

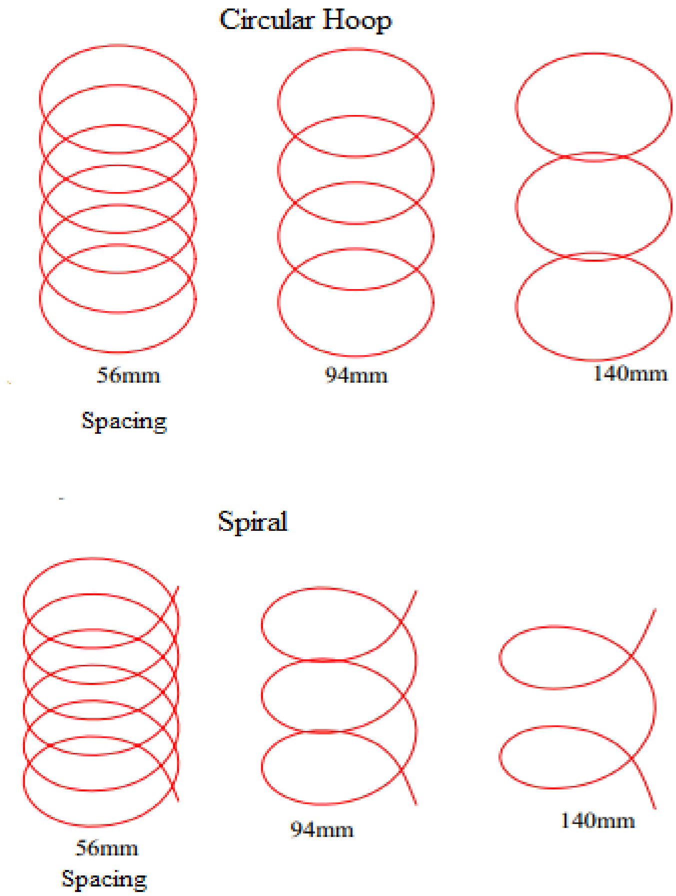


Figure 3.2 Schematic representations of spiral and circular hoop at different spacing

As pervious researchers studied (Mander et al, Saatcioglu and Razvi, Daniel Cusson and etc.) the amount of longitudinal reinforcements has great involvement on degree of confinement, however, in this experimental work its contribution is excluded, because the concrete specimen is relatively small in size. But instead of longitudinal reinforcement, 1mm diameter wire is adopted to keeping the alignment of spirals and circular hoops as shown in figure 3.3.

Figure 3.3 Spirals and Circular Hoops Cage

This experiment embraces three groups of specimens; in the first group cylindrical column specimens are confined by spiral, in the second group cylindrical concrete specimens are confined by circular hoops, and the third group is contains unconfined cylindrical concrete specimens. For first and second groups vertical spacing and yield strength of transverse reinforcement are main variable, in addition to these, compressive strength of concrete is considered as variable for all groups. Moreover, summary of test specimens and their properties are presented in Table – 3.1.

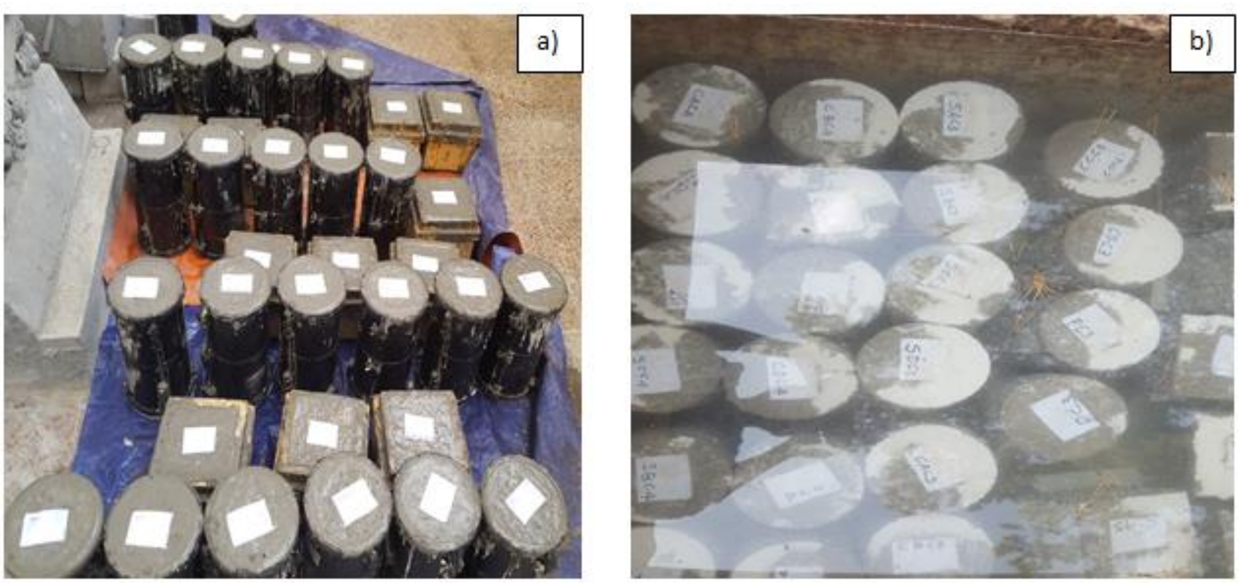
Table 3.1 Summary of specimens for experimental test

S/N	Specimen			f_{co} (MPa)	ρ_{cc} (%)	Transverse Reinforcement				
	Confining Type	Series	Designation			Dia. (mm)	f_y (MPa)	Spacing (mm)	Volumetric Ratio (ρ_s)(%)	Anchorage Type
1	Concrete	P	PC1	18.498	-	-	-	-	-	-
2			PC2	24.797						
3			PC3	27.103						
4			PC4	30.698						
5	Spiral	A	SAC2	24.797	0	8	462	56	2.76	-
6			SAC3	27.103				94	1.65	
7			SAC4	30.698				140	1.10	
8		B	SBC2	24.797			618	56	2.76	
9			SBC3	27.103				94	1.65	
10			SBC4	30.698				140	1.10	
11		C	SCC1	18.498			462	140	1.10	
12			SCC2	24.797				94	1.65	
13			SCC3	27.103				56	2.76	
14		D	SDC1	18.498			618	140	1.10	
15			SDC2	24.797				94	1.65	
16			SDC3	27.103				56	2.76	
17	Circular Hoop	A	CAC2	24.797	0	8	462	56	2.76	Weld
18			CAC3	27.103				94	1.65	
19			CAC4	30.698				140	1.10	
20		B	CBC2	24.797			618	56	2.76	
21			CBC3	27.103				94	1.65	
22			CBC4	30.698				140	1.10	
23		C	CCC1	18.498			462	140	1.10	
24			CCC2	24.797				94	1.65	
25			CCC3	27.103				56	2.76	
26		D	CDC1	18.498			618	140	1.10	
27			CDC2	24.797				94	1.65	
28			CDC3	27.103				56	2.76	

3.2.2. Casting and Curing of Concrete Specimen

Having weighed ingredient materials of concrete for each of mixing batch, the upcoming step is mixing and pouring of concrete. Small electrical table vibration also used to consolidate and compact the concrete till to achieve the maximum possible density of concrete. Almost 5 to 8% by volume of freshly placed concrete in the form of occupied by air bubbles.

Curing is the process of maintaining moisture level inside cast concrete so that hydration can continue. Practically speaking, it is a simple process of keeping the hardened concrete moist and it can continue to gain strength. Beside this, all concrete specimens are immersed to tap water for 28 days.



(a) Casting and (b) immersing to tap – water of concrete specimens

Figure 3.4 Casting and curing of concrete specimens

3.2.3. Test Set – Up and Instrumentation

Axial deformation of specimens was measured by Linear Variable Differential Transducers (LVDT). Each LVDT with a gage length of 300mm was mounted and placed on each Specimen as shown in figure 3.5. As secondary data dial gage is also used to measure total displacement of the specimen. The data were recorded using a digitalized data acquisition system known as TDS Data Logger.

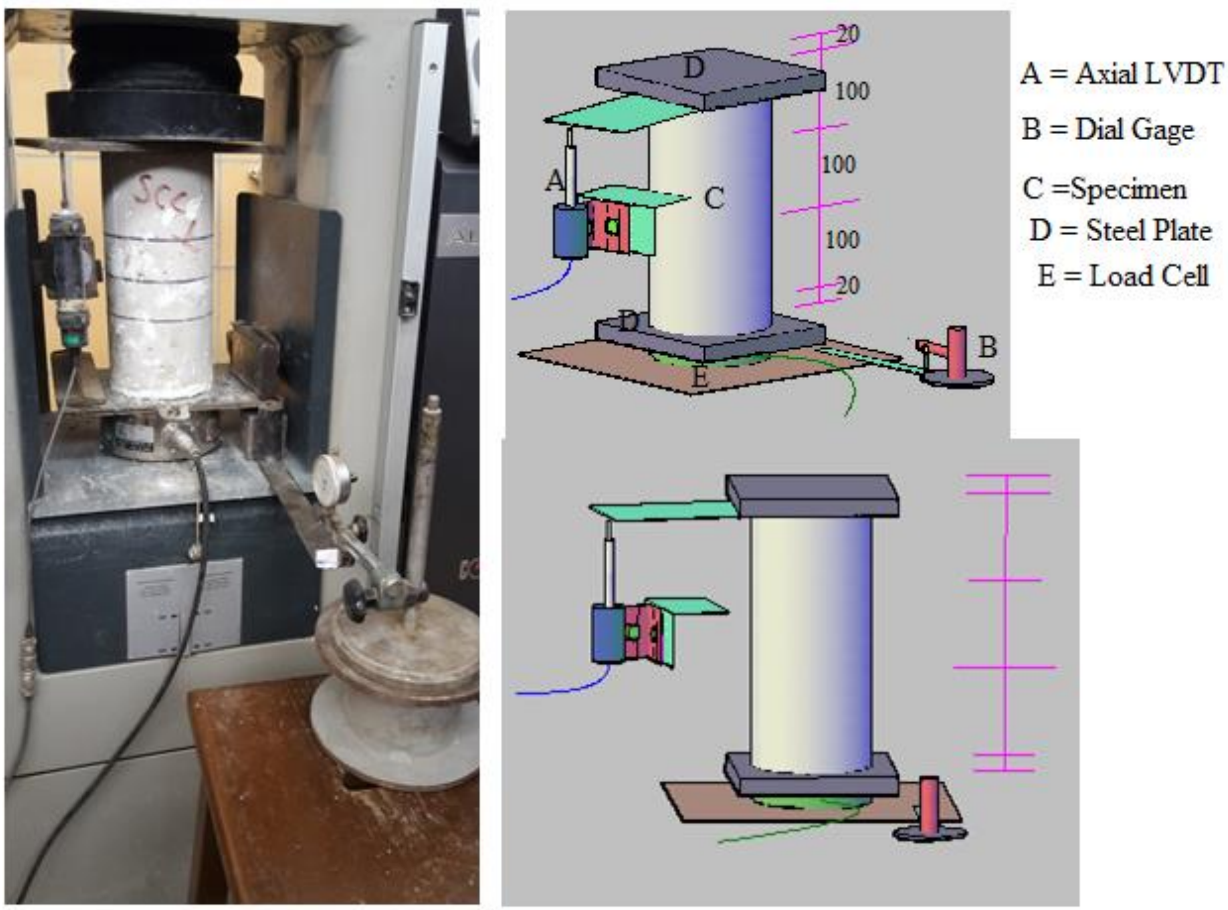


Figure 3.5 Test Set – Up and Instrumentation

3.3. Experimental Results

3.3.1. Plain Concrete

Four different grade of plain concretes are investigated as control group for each combinations of dependent variable as shown in table – 3.1 above. As the result indicates it can be concluding, lower compressive strength of concretes have relatively ductile behavior than higher strength. Graphical representations of these results in stress – strain diagram form are depicted in Figure 3.6.

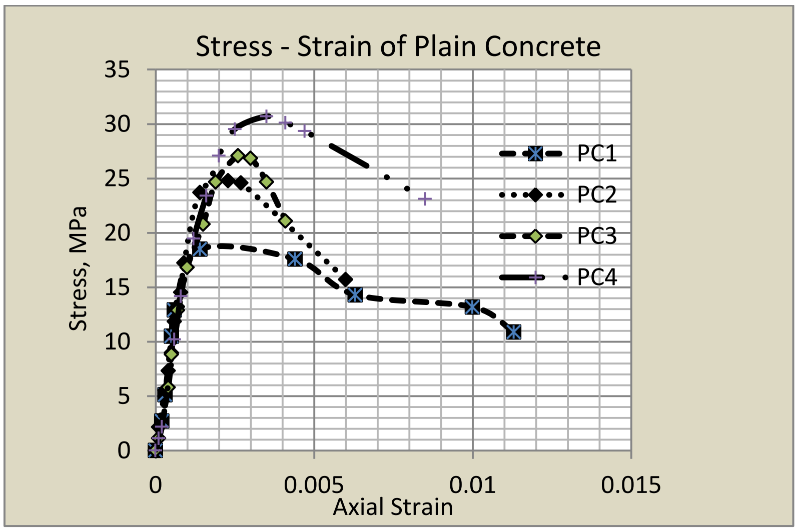


Figure 3.6 Stress – strain curve of plain concrete

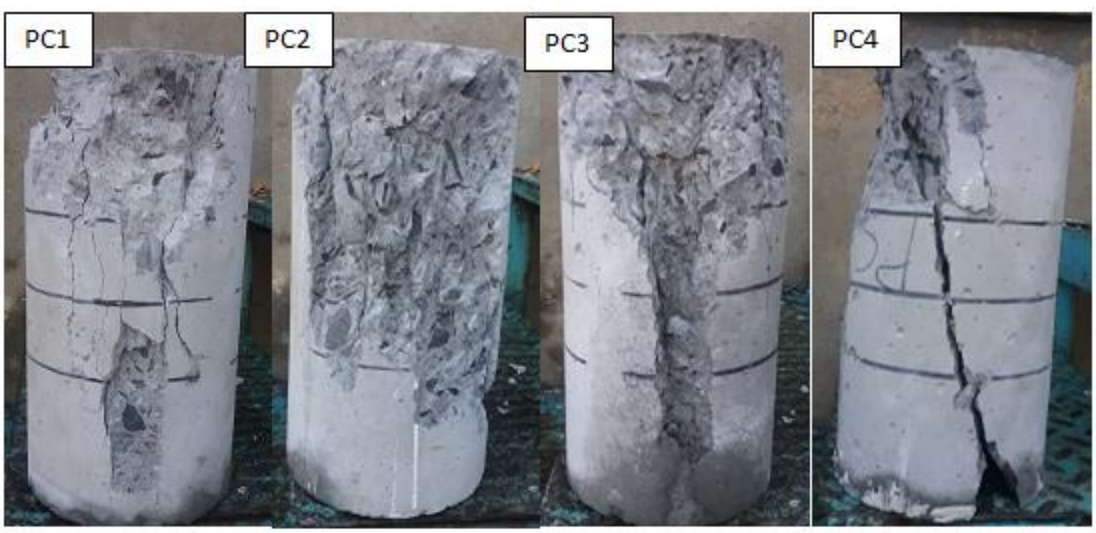
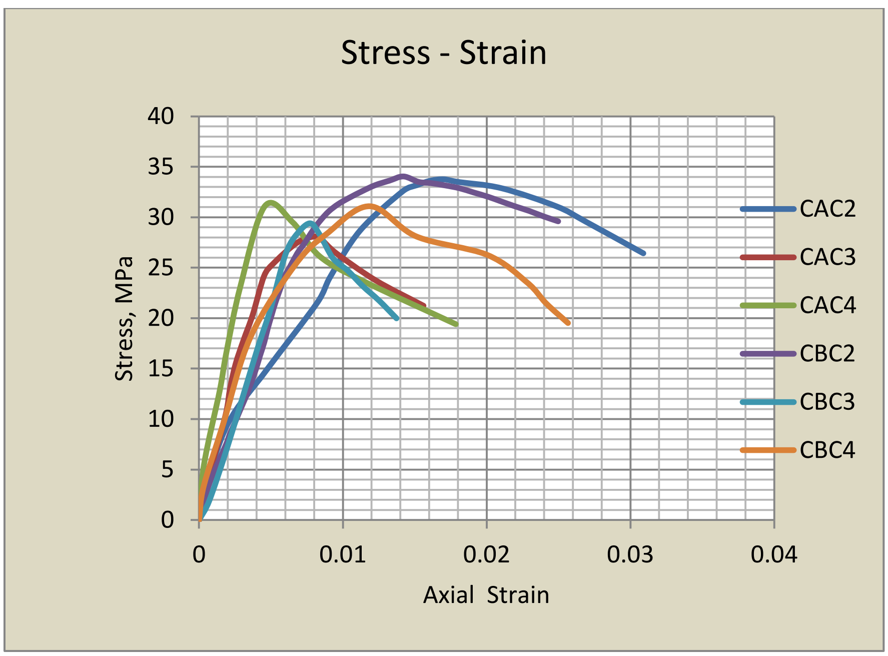


Figure 3.7 Failure pattern of plain concrete

The failure pattern of plain concrete is significantly different from one to another concrete grade. At low load stage of relatively lower strength concrete initially vertical surface micros – cracks are formed and later propagated to major crack and spalling covers. In contrary, relatively high strength of concrete have network of major cracks formed due to rapidly and swiftly development of craze cracks and eventual a critical flaw in the concrete matrix will be propagated and their failure pattern likewise different as shown above in figure 3.7 (PC4). In addition to this, post peak response of PC1 is relatively seems good and have ductile behavior than other concrete grades.

3.3.2. Specimens Confined by Circular Hoop

Confinement by circular hoop is very interesting practical trend for circular columns; hence ductility and strength are easily achieved simultaneously on well detailed column. Therefore, as mentioned in table 3.1 three different types of hoop spacing (pitch length) and two yield different yield strength of transverse reinforcement are adopted. The response of specimens under concentric axial load is showed below in figure 3.8 in the form of stress – strain curve for each case.



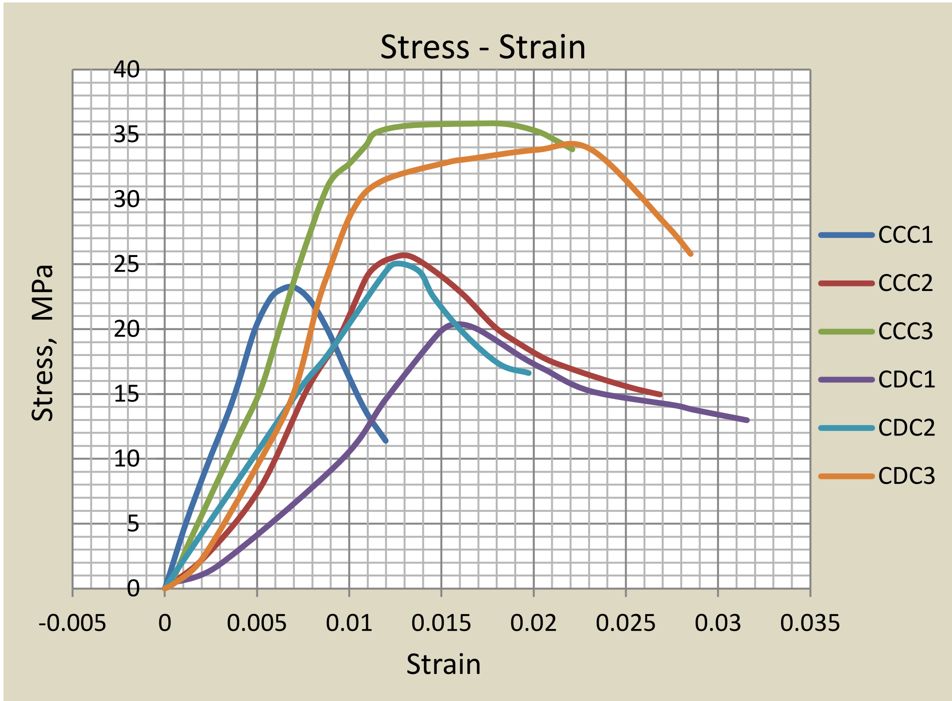


Figure 3.8 Stress – strain curve of confined concrete by circular hoops

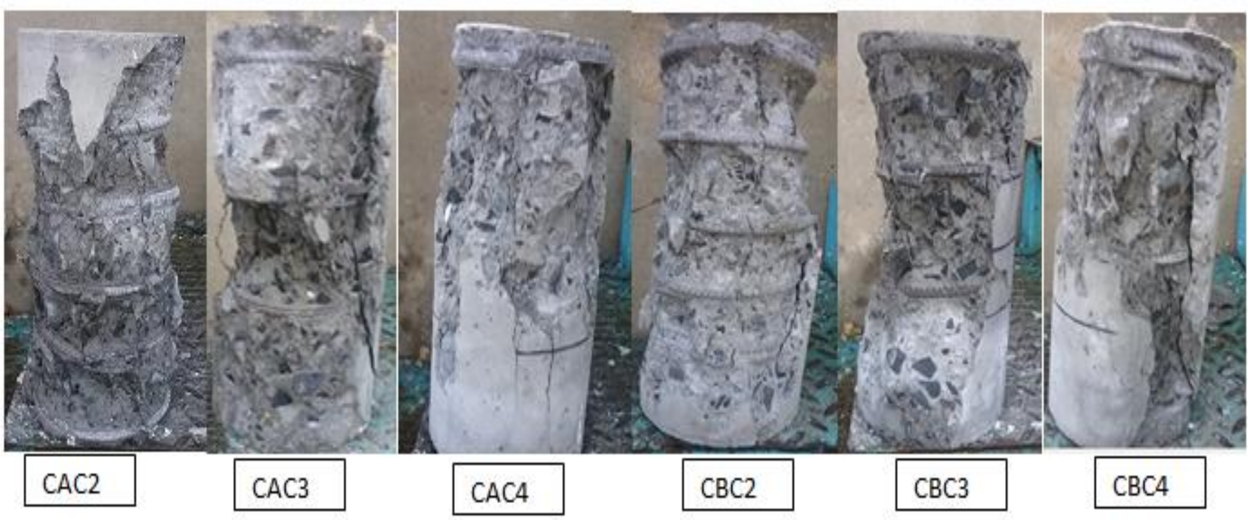


Figure 3.9 Failure pattern of confined concrete by circular hoops

Specimens which have relatively high concrete strength and spacing of transverse reinforcement are failed by surface cracks, longitudinal cracks and partially cover spalled off at stress level of around 40%, 75% and 84% of peak strength respectively (i.e. CAC4). Whereas specimens which have relatively small concrete strength and spacing of transverse reinforcement start their failure starts by initializing of cracks, propagating of networked longitudinal surface cracks and fully cover spalled at stress approximately 49%, 76% and 83% of peak strength respectively. And then core concrete also withstand the applied load even if concrete cover is spalled off because it has an additional resistance from transverse reinforcement. Later, fully – stress mobilization mechanism from core concrete to transverse reinforcement is occur and followed by concrete crushing (i.e. CAC2 and CBC2).

Table 3.2 Percentage increase of confined strength of concrete by circular hoop

Designation	f_{co} (MPa)	f_{cco} (MPa)	Percentage increase (%)	Designation	f_{co} (MPa)	f_{cco} (MPa)	Percentage increase (%)
CAC2	24.797	32.756	32.10	CCC1	18.498	23.225	25.55
CAC3	27.103	28.080	3.60	CCC2	24.797	26.331	6.19
CAC4	30.698	31.120	1.38	CCC3	27.103	35.832	32.21
CBC2	24.797	34.038	37.27	CDC1	18.498	20.324	9.87
CBC3	27.103	29.396	8.46	CDC2	24.797	25.022	0.91
CBC4	30.698	31.090	1.28	CDC3	27.103	33.822	24.79

Percentage increase of confined strength of concrete is remarkably increase with decreasing a spacing of hoops rather than increasing of concrete strength and yield strength of transverse, this illustrate spacing of hoops has significant involvement on the confined strength of concrete. Furthermore investigation about significance of random variables (i.e. concrete strength, yield strength and spacing of transverse reinforcement) is evaluated under sub – section of sensitivity analysis. Therefore, table 3.2 reveals, it is better to use relatively lower strength of concrete with relatively small spacing transverse reinforcement

3.3.3. Specimens Confined by Spiral

Spiral columns are cylindrical columns with a continuous helical bar wrapping around their circumferences. The spiral acts to provide support in the transverse direction and prevent the column from barreling. Therefore, the response of specimens confined by spiral under concentric axial load is depicted below in figure 3.10 in the form of stress – strain curve for each case.

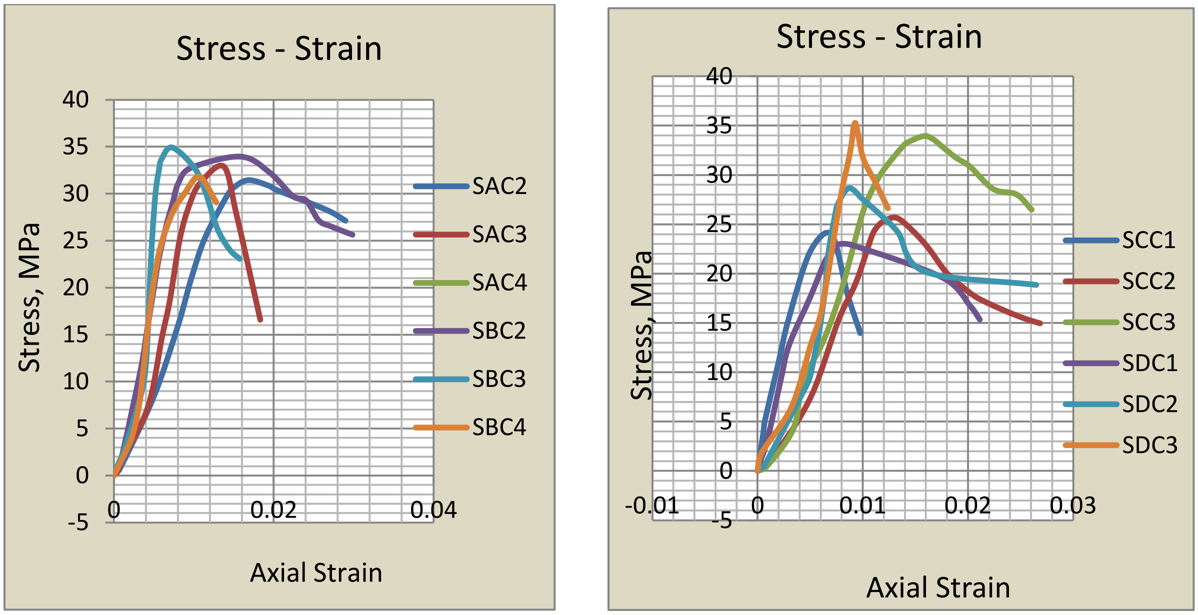


Figure 3.10 Stress – strain curve of spirally confined concrete

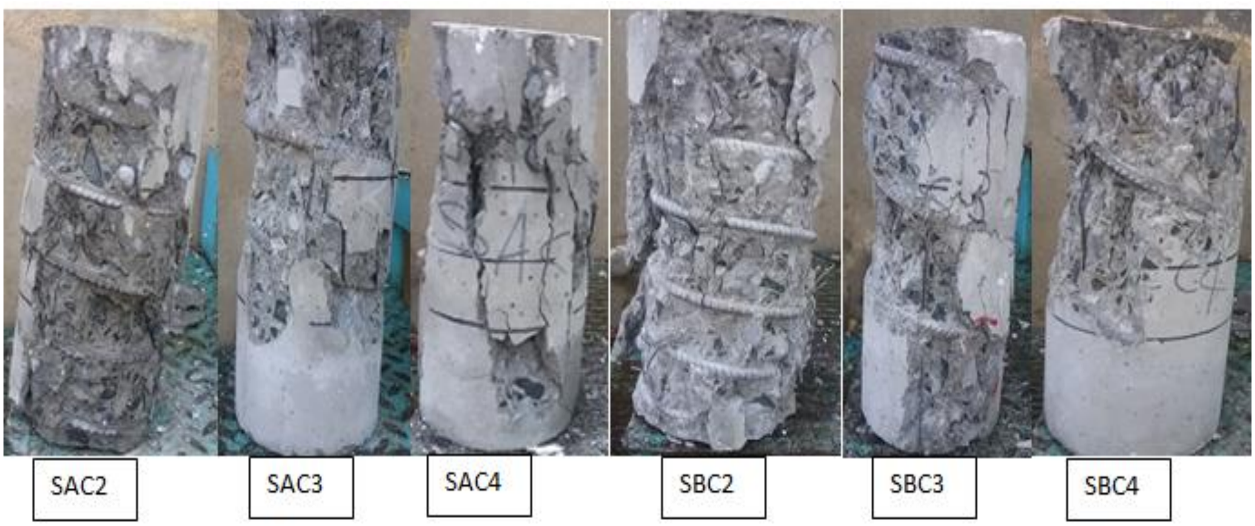


Figure 3.11 Failure pattern of spirally confined concrete

Spirally confined specimens which have relatively high concrete strength and spacing of spiral are failed by longitudinal crack failure mechanism (i.e. SAC4). Whereas concrete specimens which have relatively small concrete strength and spacing of transverse reinforcement start their failure by cover spalling. Core concrete also resist the applied load even if concrete cover is fully spalled off at approximately 87% of peak strength, because it has an additional lateral confining resistance from the spiral. Later, fully – stress mobilization mechanism from core concrete to transverse reinforcement is occur (i.e. SAC2 and SBC2).

Table 3.3 Percentage increase of spirally confined concrete

Designation	f_{co} (MPa)	f_{cco} (MPa)	Percentage increase (%)	Designation	f_{co} (MPa)	f_{cco} (MPa)	Percentage increase (%)
SAC2	24.797	31.448	26.83	SCC1	18.498	23.989	29.68
SAC3	27.103	31.092	14.72	SCC2	24.797	29.156	17.58
SAC4	30.698	31.800	3.59	SCC3	27.103	33.941	25.23
SBC2	24.797	33.95	36.93	SDC1	18.498	22.942	24.03
SBC3	27.103	30.146	11.23	SDC2	24.797	28.660	15.58
SBC4	30.698	31.800	3.59	SDC3	27.103	35.267	30.12

Percentage increase of spirally confined strength of concrete is remarkably increase with decreasing a spacing of hoops and increasing of concrete strength rather than increasing yield strength of transverse reinforcement. This illustrates spacing of hoops has significant involvement on the confined strength of concrete. Furthermore, investigation about significance of random variables (i.e. concrete strength, yield strength and spacing of transverse reinforcement) is evaluated under sub – section of sensitivity analysis.

3.3.4. Comparison of Spiral and Circular Hoops of Confinements

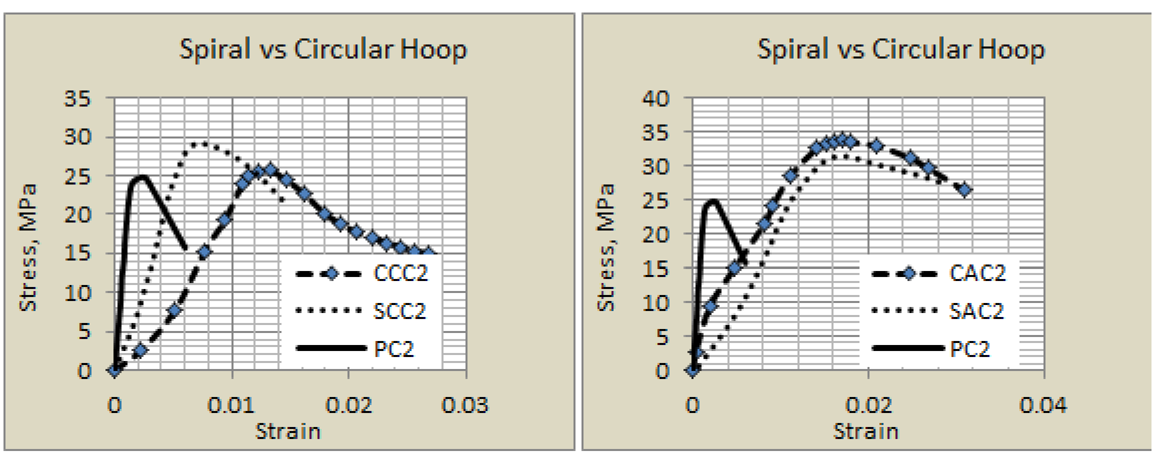
Both type of confinements are used for circular columns, and significantly increase the strength and ductility of the structure. However; the degree of confinement is different among them. So that, spiral confinement given a better strength and ductility when the spacing of transverse reinforcement is relatively became large and the difference percentage increase of confined strength of concrete spiral over circular hoop confinement is about 11.39% at same independent variables. Whilst spacing of transverse reinforcement relatively small circular hoop confinement produce good strength and the difference percentage increase of confined strength of concrete of circular hoop over spiral confinement is about 5.27 % at same independent variables. Table 3.4 below exemplifies the difference between spiral and circular hoops at same concrete strength, and yield strength and spacing of transverse reinforcement. This is due to the interaction between circular hoops and coarse aggregate, generally called concrete acts as composite structure at small spacing of circular hoop with a provision of strong anchorage bond or welded connection. The percentage increase of confined strength of concrete by spiral and circular hoop is summarized below in table 3.4.

As spacing of transverse reinforcement decreases, circular hoop type of confinement gives better confined strength of concrete than spiral, perhaps this may occur due to different anchorage type between spiral and circular hoop, which means welding of hoops may have a significant involvement on confined strength. Even though; previous research's (i.e. Mander et al) spiral confinement produce better confinement rather circular hoop, it may has some demarcations at small spacing as this research indicates.

Table 3.4 Comparison of spiral and circular hoops

Designation	f_{co} (MPa)	f_{yt} (MPa)	Spacing (mm)	f_{cco}(MPa)	% Increase	Difference of % increase
SAC2	24.796	462	56	31.448	26.825	5.27
CAC2				32.756	32.09	
SCC2			94	29.156	17.580	11.39
CCC2				26.331	6.189	

The stress – strain curve of spirally confined concrete illustrate likely second order of parabolic curve for the pre – peak response and have a smooth and plateau curve around the peak. The post – peak response of both spiral and circular hoop confinement is somewhat behave ductile. But in contrast, circular hoop have steep slope than spiral at case (a), which indicates spiral confinement has relatively ductile behavior.



a) At 94 mm spacing

b) At 56 mm spacing

Figure 3.12 Comparison of stress – strain curve of spirally and circular hoop

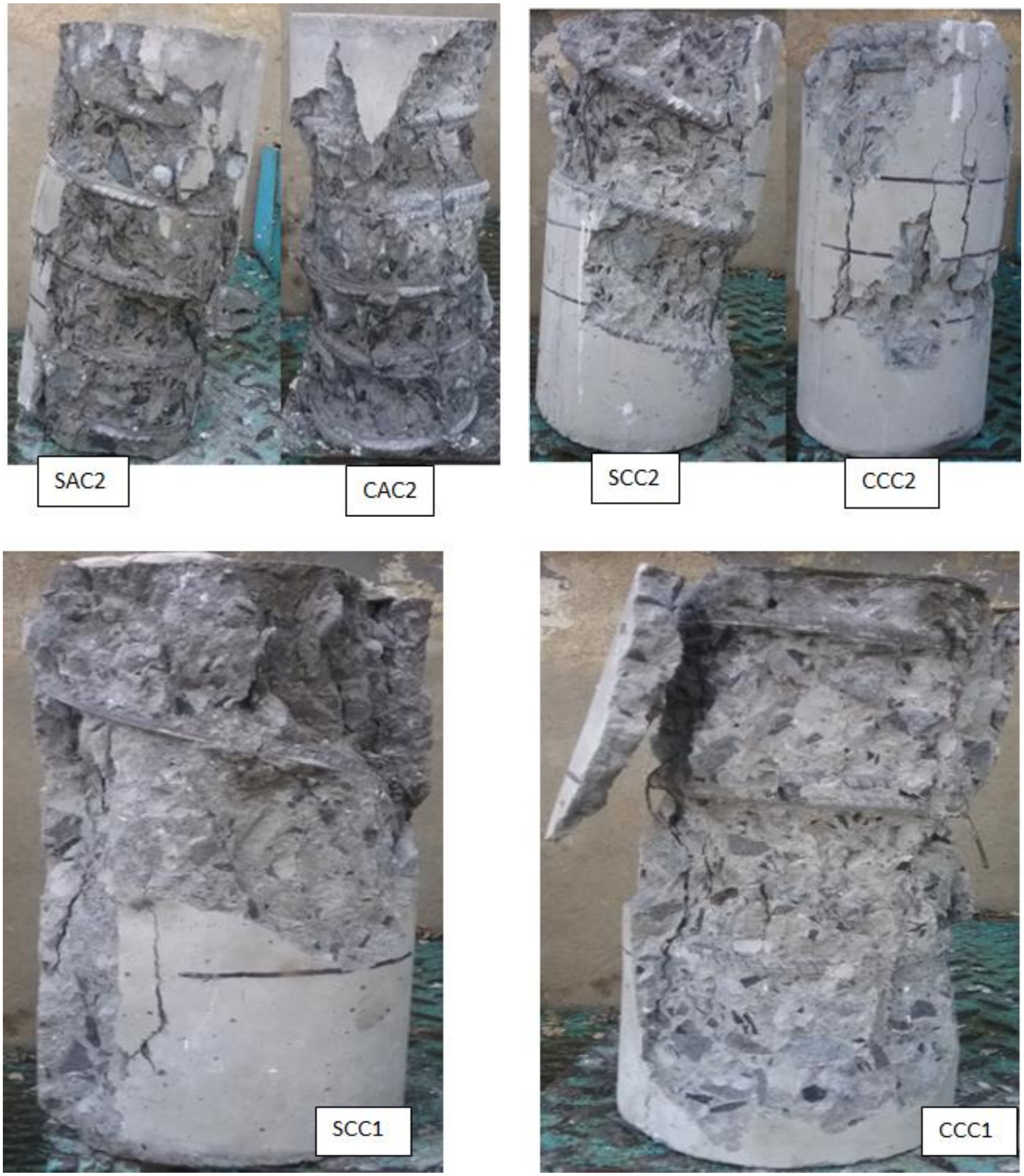


Figure 3.13 Failure pattern of spirally and circular hoop confined concrete

4. NUMERICAL SIMULATION

In addition to the experimental investigated of concrete samples, 10 specimens are numerically simulated. This helps to have a number of cases and increase its accuracy. Concrete is a complicated material to be modeled within Finite Element (FE) Packages, therefore proper material model in FE should be capable of representing both elastic and plastic behavior of concrete in compression and tension. The complete compressive behavior should include both elastic and inelastic behavior of concrete including strain softening regimes (Wahalathantri 2011).

4.1. Material Constitutive Model in Abaqus/CAE

Abaqus package (SIMULIA, 2013) provides the capability of simulating damage of concrete using either of the three crack models for reinforced concrete elements: (1) Smeared crack concrete model; which Consists of an isotropically hardening yield surface that is active when the stress is dominantly compressive and an independent “crack detection surface” that determines if a point fails by cracking, (2) Ducker Prager model; Is intended to model cohesive geological materials that exhibit pressure-dependent yield, such as soils and rocks, and (3) Concrete Damaged Plasticity model; which provides a general capability for modeling concrete and other quasi-brittle materials in all types of structures. Out of these, concrete damaged plasticity model has the potential to represent complete inelastic behavior of concrete both in tension and compression including damage characteristics (Wahalathantri 2011). Moreover, the concrete damage plasticity model assumes two main concrete failure mechanisms are cracking under uniaxial tension and crushing under uniaxial compression.

In Concrete Damage Plasticity Model (CDP), users should have to enter appropriate magnitude of various parameters. Such as, (1) parameter characterizing the performance of concrete under compound stress is known as dilation angle, (2) a parameter that describing the state of the material is the point in which the concrete undergoes failure under biaxial compression which is called ratio of the strength in the biaxial state to the strength in the uniaxial state, and (3) the plastic potential eccentricity and it is a small value which can be calculated as a ratio of tensile strength to compressive strength. As per ABAQUS user manual, default values of these parameters are presented below in Table 4.1.

Table 4.1 Default values in CDP model

Dilation Angle (Ψ)	32°
Eccentricity (ϵ)	0.1
Biaxial / Uniaxial (f_{bo}/f_{co})	1.16
κ	0.667
Viscosity parameter	0

4.1.1. Mechanical Properties of Concrete

Modulus of elasticity (E)**:-** is a substantial term (also known as elastic modulus, the coefficient of elasticity) of material property which defined by the ratio of applied stress to the corresponding strain within the elastic limit. According to ACI-318-08 code modulus elasticity of normal weight of concrete $E_c = 57{,}000\sqrt{f_c'}\ (Psi)$ or equivalently $E_c = 4{,}730\sqrt{f_c'}\ (MPa)$ and in the same manner Mander et al. (1988) suggest modulus elasticity of concrete $E_c = 5{,}000\sqrt{f_c'}\ (MPa)$. So that, in this research during simulating of concrete in Abaqus/CAE, modulus elasticity of concrete is determined according to ACI-318-08 code.

Poisson's Ratio (ν)**:-** when a material is stretched in one direction, it tends to get thinner in the other two directions, then the ratio of relative contraction strain (transverse, lateral or radial strain) normal to the applied load to the relative extension strain (longitudinal or axial strain) in the direction of applied load is called Poisson's ratio. Range of Poisson's ratio for normal concrete is 0 to 0.2, which implies 0 for fully – cracked section and 0.2 for undamaged section of concrete.

4.1.2. Compressive Stress – Strain Relationship of Concrete

To define complete stress – strain relation of concrete, user should be entering the yield stress(σ_c), inelastic strain $(\ddot{\varepsilon}_c{}^{in})$ corresponds to stress values, and damage properties (d_c) in tabular format. Therefore, total strain values should be converted to the inelastic strains using the following Eq 4.1.

$$\ddot{\varepsilon}_c{}^{in} = \varepsilon_c - \varepsilon_{oc}^{el} \qquad (4.1)$$

Where – as, $\varepsilon_{oc}^{el} = {}^{\sigma_c}/_{E_c}$ is elastic strain corresponding to the undamaged material property and ε_c is also total compressive strain. Therefore, Abaqus after detecting the inelastic strain and damage parameter, automatically calculate the plastic compressive strain of concrete using the following Eq 4.2.

$$\ddot{\varepsilon}_c{}^{pl} = \ddot{\varepsilon}_c{}^{in} - \frac{d_c}{(1-d_c)}\frac{\sigma_c}{E_c} \tag{4.2}$$

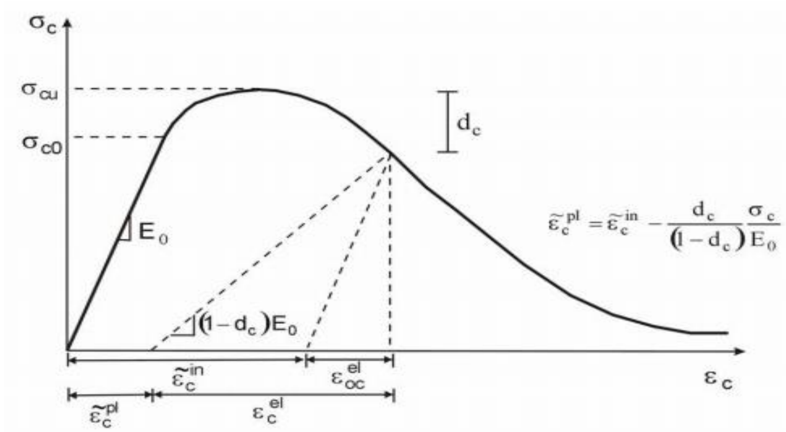


Figure 4.1 Typical compressive stress – strain relationship with damage properties

As shown in Figure 4.1 the unloaded response of concrete seems to be weakened because the elastic stiffness of the material appears to be damaged or degraded. The degradation of the elastic stiffness on the strain softening branch of the stress – strain curve is characterized by damage variable, d_c (Wahalathantri 2011). Its range is from zero for undamaged material to one for totally loss of strength, these values can also be obtained from uniaxial compression tests, by calculating the ratio of the stress for the declining part of the curve to the compressive strength of the concrete. Compression damage variable can determine by Eq 4.3.

$$d_c = 1 - \left(\frac{\sigma_c}{E_o\left(\varepsilon_c - \ddot{\varepsilon}_c{}^{pl}\right)}\right) \tag{4.3}$$

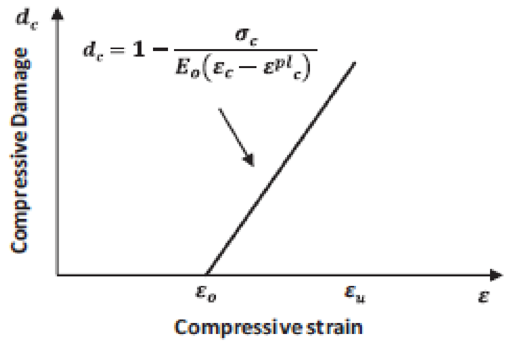


Figure 4. 2 Compression Damage Property of Concrete

Generally the stress – strain relation under uniaxial compression is taken into account by Eq 4.4 in Abaqus.

$$\sigma_c = (1 - d_c) * E_c * \left(\varepsilon_c - \ddot{\varepsilon}_c{}^{pl}\right) \quad (4.4)$$

4.1.3. Numerical Model for Compressive Stress – Strain Relationship of Concrete

The complete stress – strain diagram for concrete under compression is derived using the experimentally verified numerical method by Kent and Park (1982). This model can be used to develop the stress – strain relationship under uniaxial compression up to $0.2\sigma_{cu}$ of stress in the descending portion only using the maximum compressive strength(σ_{cu}). Additionally, a linear stress – strain relationship which obeys Hooke's law is assumed up to 30% of the ultimate compressive strength (σ_{cu}) in the ascending portion. To simulate material property of concrete in Abaqus under CDP model the following (table 4.2) tabulated data of stress, inelastic strain and compression damage property are necessarily.

Table 4.2 Compressive Stress-Strain Values of Concrete

f_{co1} =18.498MPa			f_{co2} =24.797 MPa		
Stress, MPa	Inelastic Strain	d_c	Stress, MPa	Inelastic Strain	d_c
5.549400	0.0000000	0.000000	7.439100	0.0000000	0.000000
9.668483	0.0001430	0.000000	13.543474	0.0000777	0.000000
12.847109	0.0002631	0.000000	17.594743	0.0001751	0.000000
14.881430	0.0003842	0.000000	20.187556	0.0002806	0.000000
16.183395	0.0004970	0.000000	21.846956	0.0003826	0.000000
18.498000	0.0010907	0.000000	24.797000	0.0009472	0.000000
17.831196	0.0013378	0.036047	23.417809	0.0012201	0.055619
17.259650	0.0015495	0.066945	22.235646	0.0014539	0.103293
16.769753	0.0017311	0.093429	21.222363	0.0016544	0.144156
16.349841	0.0018866	0.116129	20.353835	0.0018262	0.179182
15.989917	0.0020200	0.135587	19.609382	0.0019735	0.209203
15.681411	0.0021343	0.152265	18.971280	0.0020997	0.234936
13.830372	0.0028202	0.252332	15.142666	0.0028571	0.389335
7.584000	0.0048772	0.590010	7.584000	0.0049280	0.694157
1.000000	0.0069508	0.945940	1.000000	0.0069575	0.959673
f_{co3} = 27.103 MPa			f_{co4} = 30.698 MPa		
Stress, MPa	Inelastic Strain	d_c	Stress, MPa	Inelastic Strain	d_c
8.130900	0.0000000	0.000000	9.209400	0.0000000	0.000000
15.011796	0.0000545	0.000000	17.348809	0.0000191	0.000000
19.364630	0.0001449	0.000000	22.154518	0.0000995	0.000000
22.150443	0.0002455	0.000000	25.230171	0.0001932	0.000000
23.933364	0.0003441	0.000000	27.198590	0.0002869	0.000000
27.103000	0.0008994	0.000000	30.698000	0.0008286	0.000000
25.401357	0.0011827	0.062784	28.427745	0.0011295	0.073954
23.942805	0.0014256	0.116599	26.481812	0.0013875	0.137344
22.692618	0.0016339	0.162727	24.813869	0.0016085	0.191678
21.621029	0.0018123	0.202264	23.384204	0.0017980	0.238250
20.702524	0.0019653	0.236154	22.158777	0.0019605	0.278169
19.915235	0.0020964	0.265202	21.108411	0.0020997	0.312385
15.191496	0.0028831	0.439490	14.806213	0.0029350	0.517682
7.584000	0.0049420	0.720179	7.584000	0.0049606	0.752948
1.000000	0.0069594	0.963104	1.000000	0.0069618	0.967425

4.1.4. Tensile Stress – Strain Relationship of Concrete

The complete stress – strain curve for concrete under tension can be derived in same fashion with the compression behavior of concrete. Cracking strain and tensile damage values are determined by similar expression that defined above for inelastic strain and compressive damage variable respectively. However, this sub – section is beyond the objective and scope of the research and then detail intention is not made.

4.1.5. Mechanical Property of Transverse Reinforcement

Transverse steel reinforcements are used to confined concrete cylinder at different spacing with elastic – perfectly plastic type of stress – strain curve. Yield strength of transverse reinforcement obtained from experiment (i.e. F_{y1} = 462MPa and F_{y2} = 618MPa). And another additional two yield strengths for the purpose Abaqus simulation only adopted (i.e. F_{y3} = 300MPa and F_{y4} = 400MPa). Therefore, modules of elasticity and Poisson's ratio are quantified (E_s = 200GPa) and (v = 0.3) respectively.

4.2. Assembly and Mesh

When parts are created and assigned their section assignment, they exists in their own coordinate system, so that creating of instance under the assembly module and position them relative to each other in a global coordinate system is foremost assignment before going to analysis step. Therefore, 3D concrete cylinder specimen and spiral/circular hoops were assembled properly. The basis of every FE numerical products is the discretization of the considered model in a number of elements. A mesh is typically a network of lines that connect between each other with a certain amount of nodes used to numerically solve the problem at withstand the external loads. The key point in FE analysis is selection of appropriate element types, so that, linear hexahedral (C3D8R) type of elements are used as shown in figure 4.5.

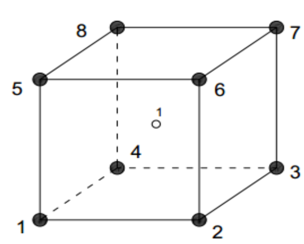
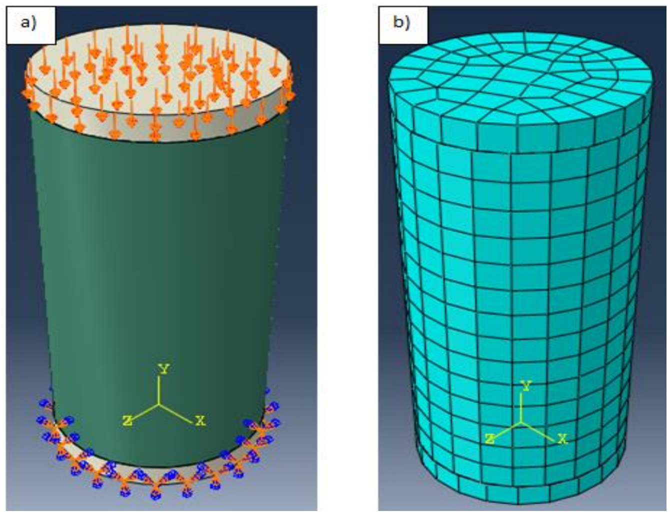


Figure 4.3 C3D8R Hexahedral Element type

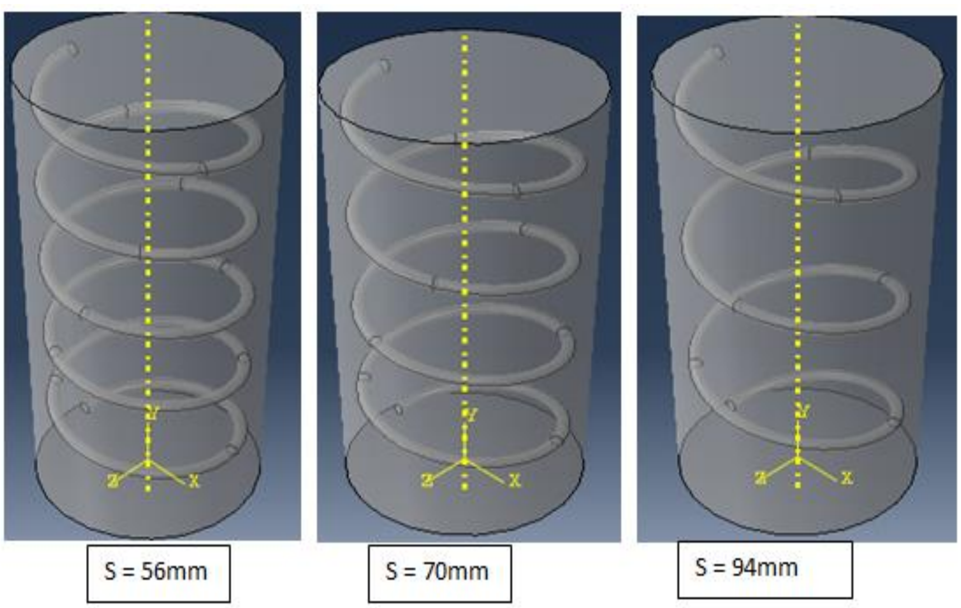
4.3. Boundary Conditions and Load

ENCASTRE (Fixed) condition type of boundary was assigned at the bottom surface of each specimen in every node and embedded type of constraints was adopted between confining reinforcements and core concrete. Axial displacement type of loading also applied at the top surface of each specimen in every node after analysis step was created. The magnitude of loads is taken from the experimental results for each specimen.



(a) Boundary Conditions and Loading system (b) Element Type and Mesh

Figure 4.4 Loading and Meshing System in Abaqus



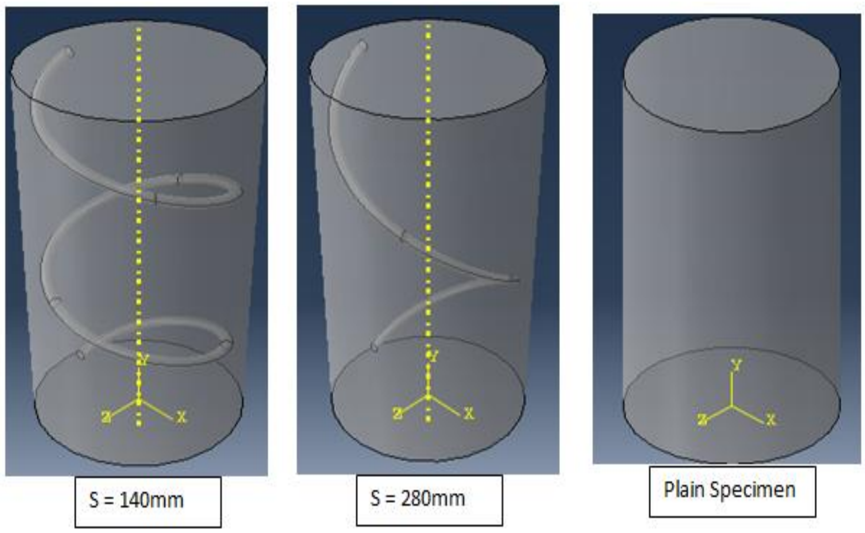


Figure 4.5 Spirally confined concrete modeled in Abaqus

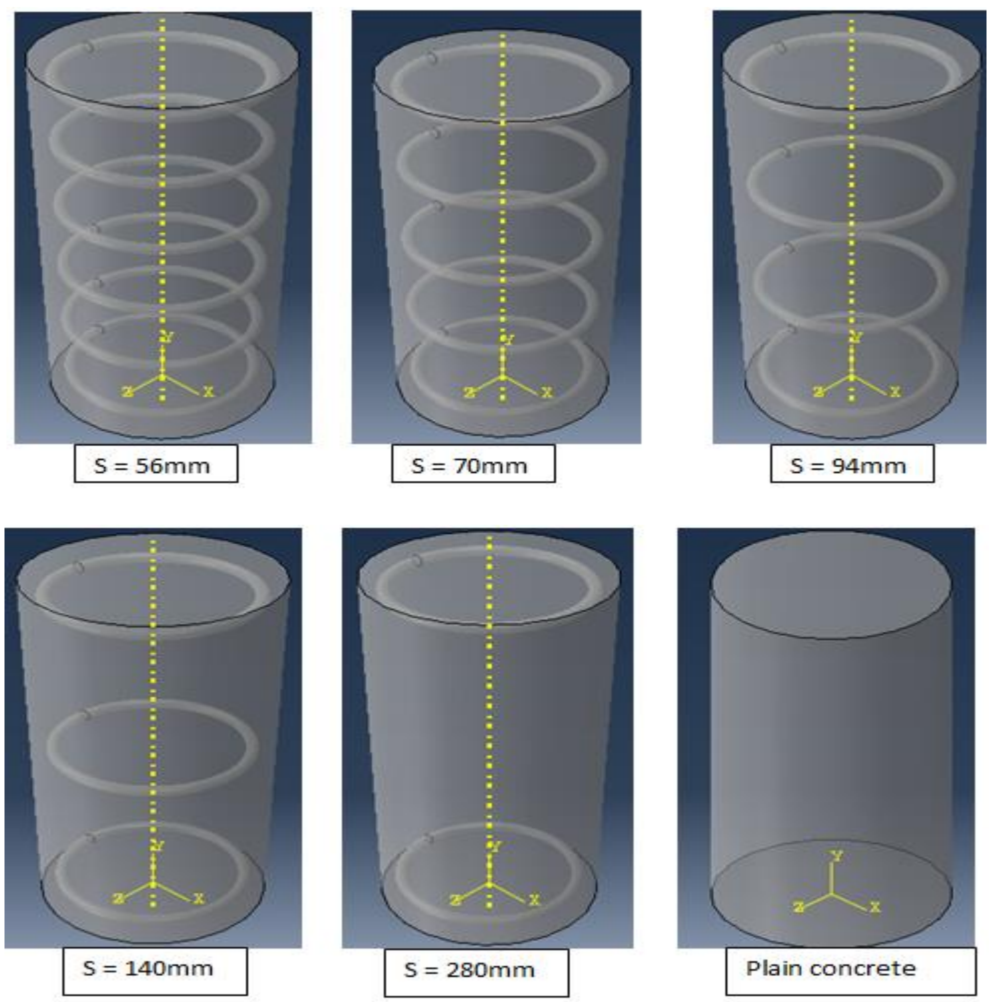


Figure 4.6 Modeling of confined concrete by circular hoop in Abaqus

4.4. Abaqus Analysis Results

Analysis was performed under job menu tool by changing initial size increment till to get suitable results of compression damage of concrete. A ratio of experimental divided by Abaqus simulation results are presented at (Table 1 of Appendix – A) and output results of some random selected specimens are depicted in the form stress – strain curve in figures 4.7 below.

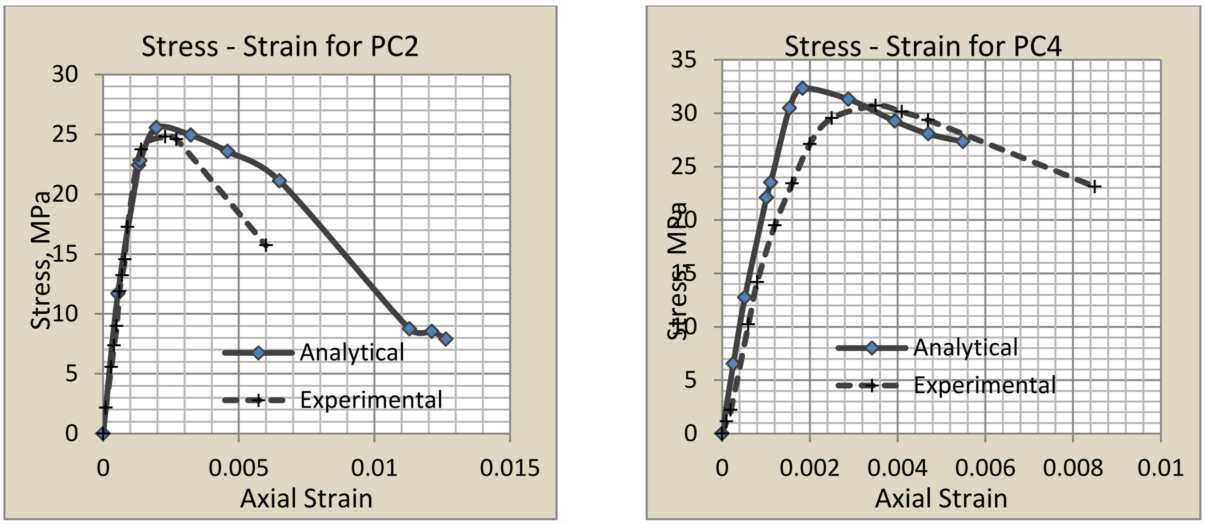


Figure 4. 7 Numerical Verifiecation of Plain Concretes

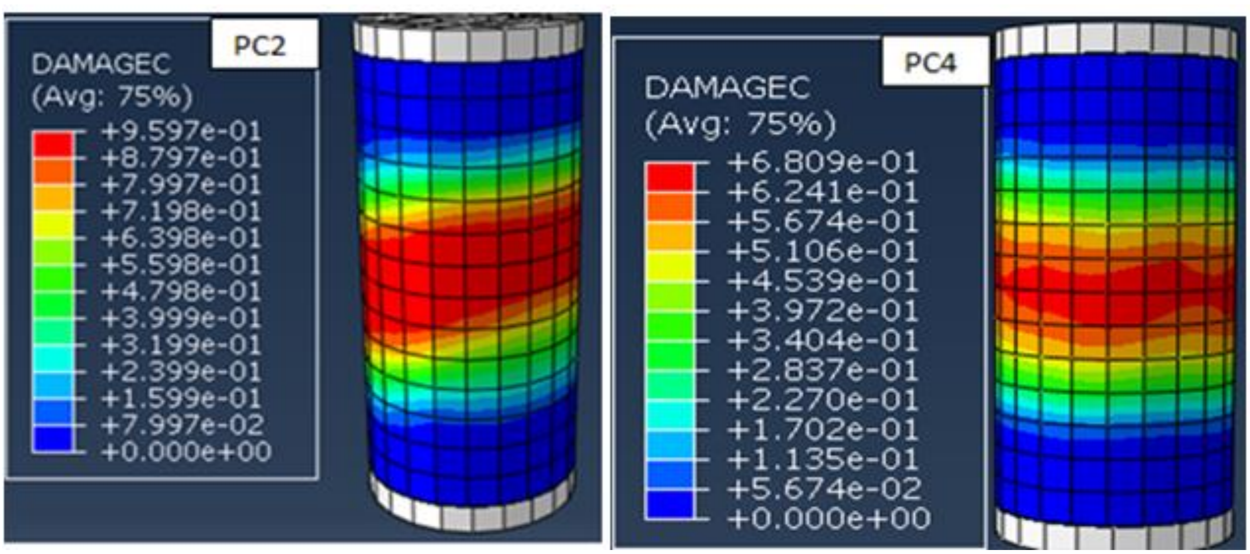


Figure 4.8 Compression Damage of Plain Concrete in Abaqus

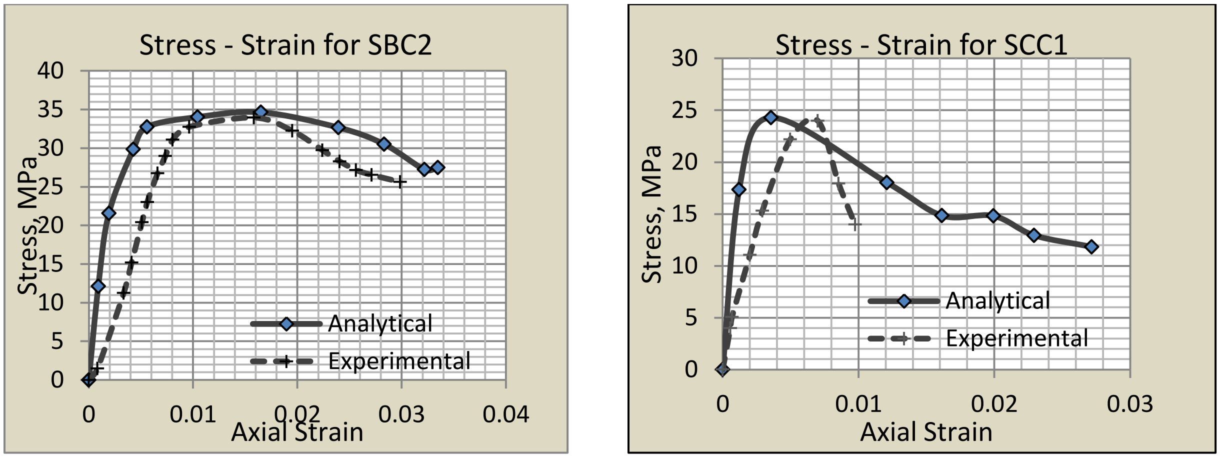


Figure 4. 9 Analytical Verification of Spiral and Circular Hoops

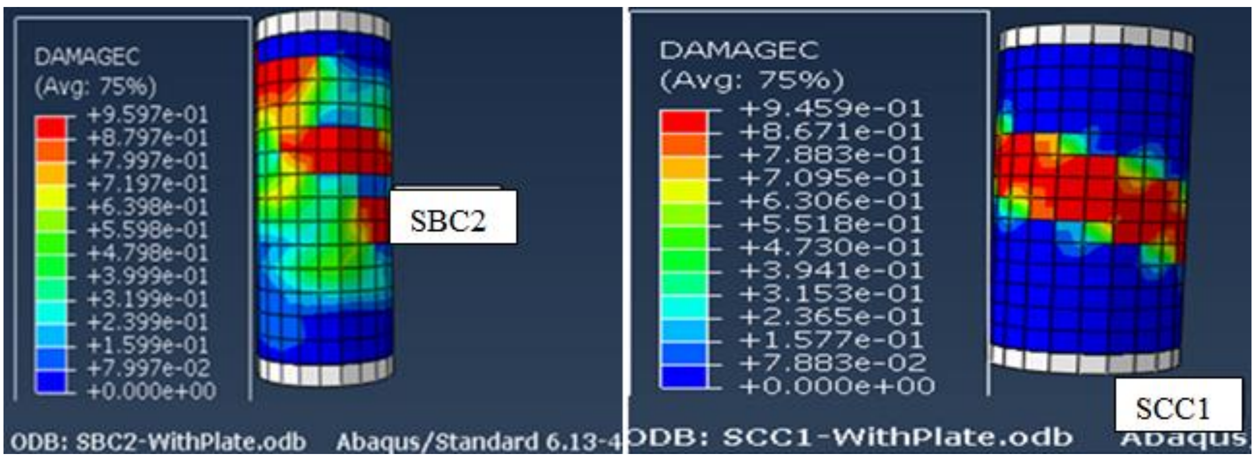


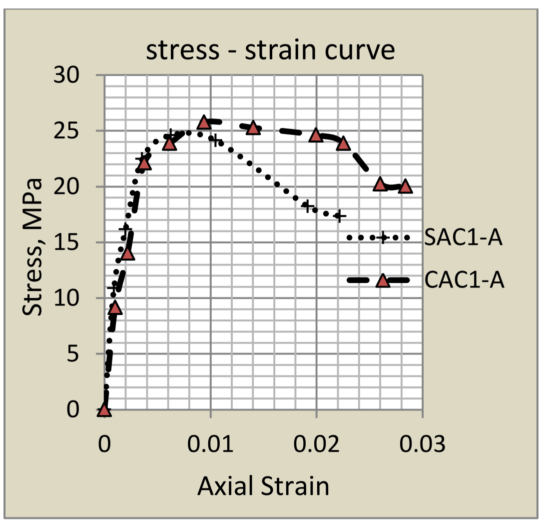
Figure 4.10 Compression Damage variable of confined Concrete in Abaqus

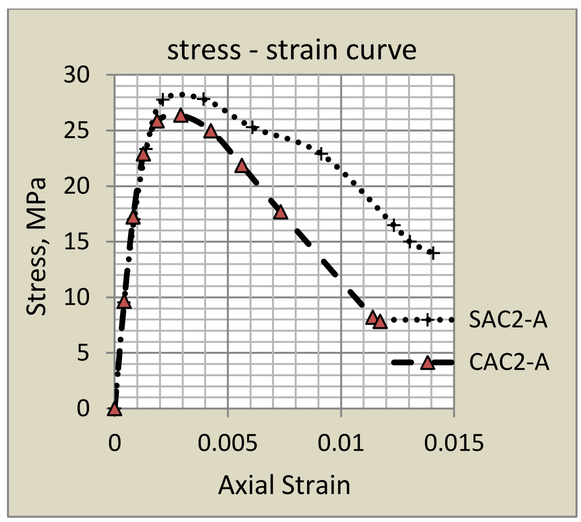
Hereafter, Abaqus simulation have been generated good results and compatible with experimental results, the following specimens stated in table 4.3 are additional specimen simulated in Abaqus only for the purpose of sensitivity analysis. Designations are also the same with table 3.1 in experimental program sub – section except the sub-script ‘A’ which indicates Abaqus, but different values of independent variables are considered.

Table 4.3 Specimens properties for Abaqus simulation

No.	Confining Type	Series	Designation	f_{co} (MPa)	ρ_c (%)	Transverse Reinforcement Dia. (mm)	f_y (MPa)	Spacing (mm)	Volumetric Ratio (ρ_s)(%)
1	Spiral	A	SAC1-A	18.498	0	8	300	70	1.91
2			SAC2-A	24.797				280	0.48
3		B	SBC1-A	18.498			400	280	0.48
4			SBC2-A	24.797				70	1.91
5		C	SCC1-A	18.497			462	280	0.48
6	Circular Hoops	A	CAC1-A	18.498			300	70	1.91
7			CAC2-A	24.797				280	0.48
8		B	CBC1-A	18.498			400	280	0.48
9			CBC2-A	24.797				70	1.91
10		C	CCC1-A	18.497			462	280	0.48

Output results obtained from Abaqus are demonstrated below in the form of stress – strain curve and compression damage property of concrete.





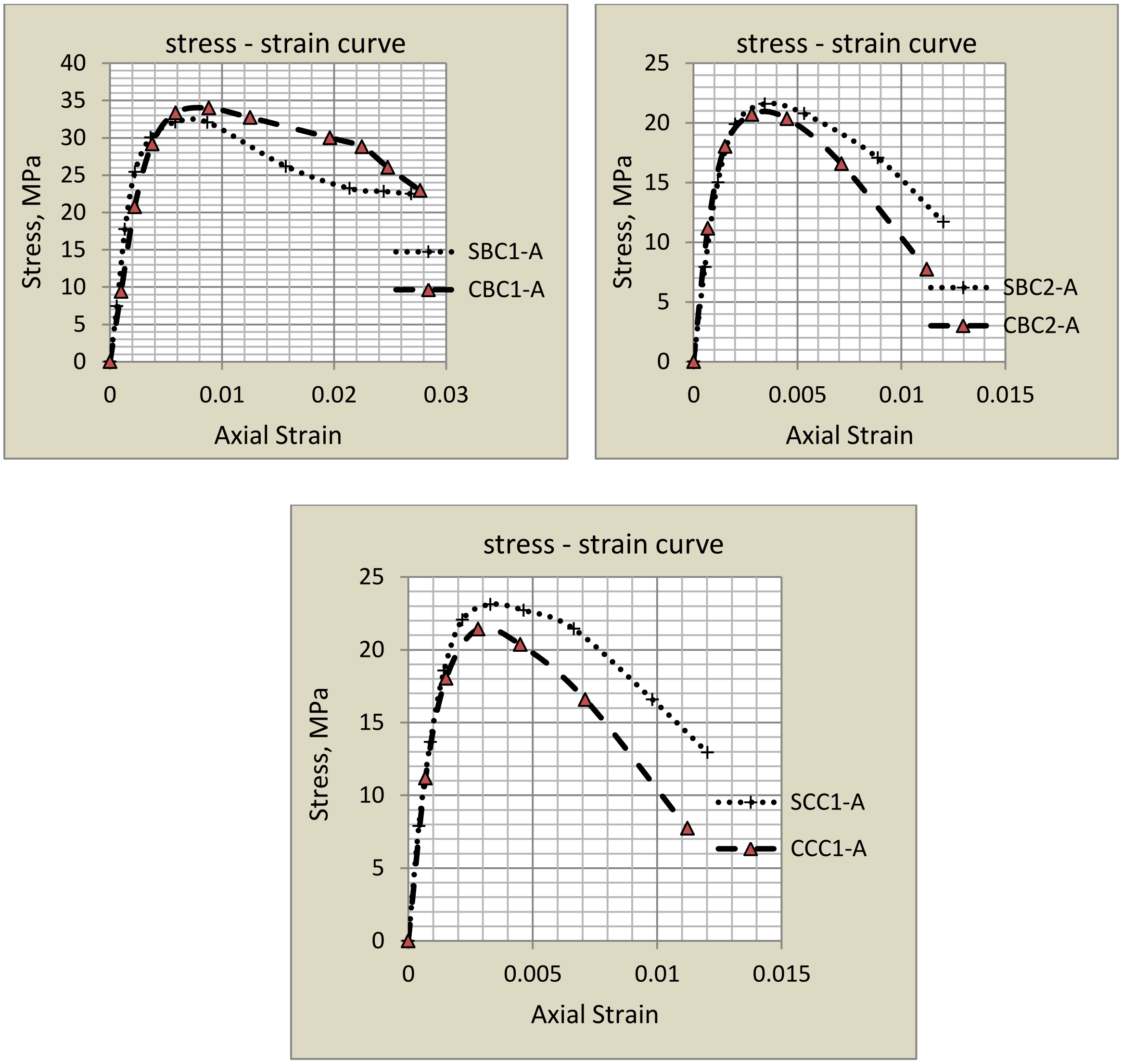
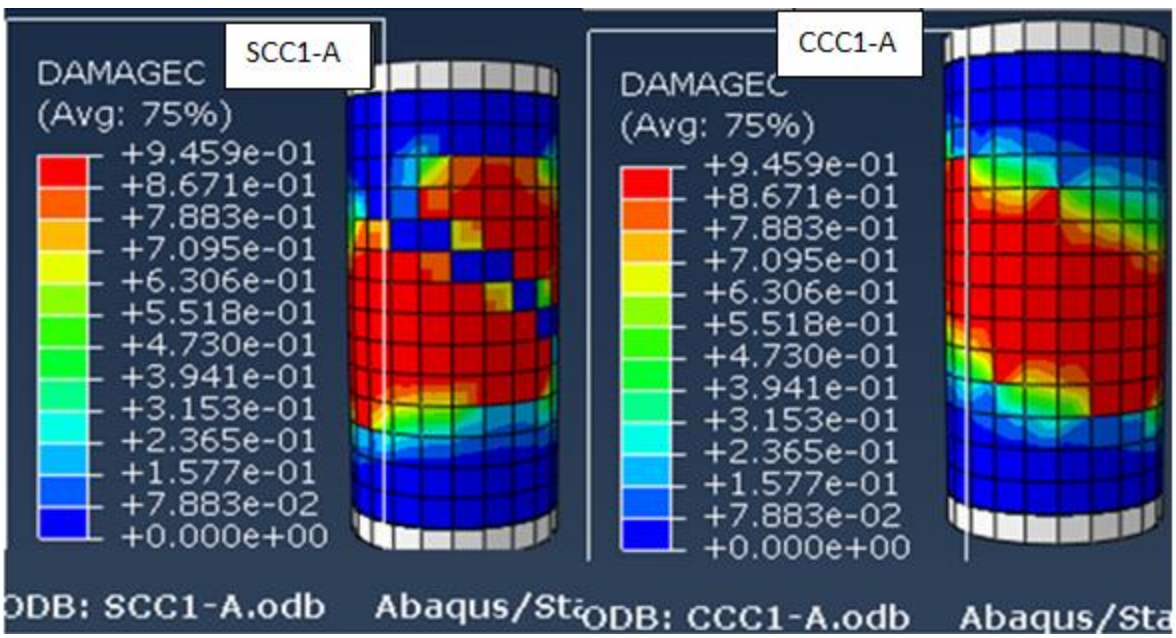


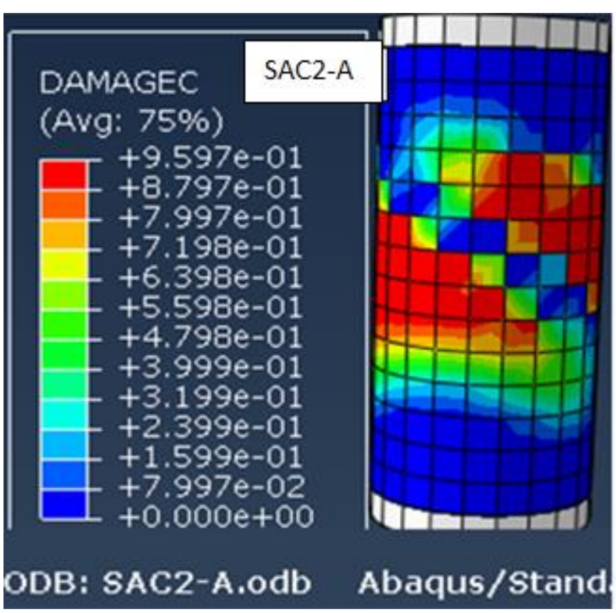
Figure 4.11 Stress – strain curve results from Abaqus

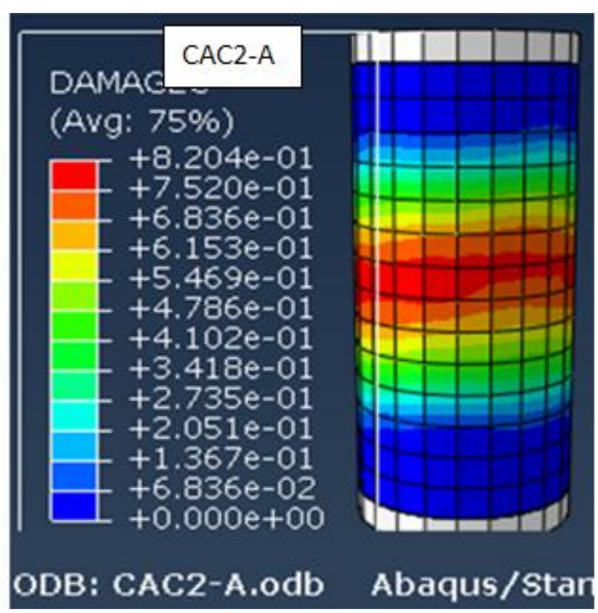
It can be simply observed from the above stress – strain curve, spirally confined concrete has less confined strength to the maximum by 6.36% than circular hoops at same concrete grade, yield strength of transverse reinforcement and at 70mm of spacing transverse reinforcement. In contrary at 280mm of spacing spirally confined concrete has greater confined strength to the maximum by 9.23% than circular hoops. The percentage increase of confined strength by spiral and circular hoops are quantified and enumerate as below in table 4.4.

Table 4.4 Abaqus results of confined strength of concrete

No.	Designation	f_{co} (MPa)	Spiral f_{cco} (MPa)	Circular Hoops f_{cco} (MPa)	% increase by Spiral	% increase by Hoop	Difference of % increase
1	SAC1-A / CAC1-A	18.498	24.608	25.784	33.030	39.389	6.359
2	SAC2-A / CAC2-A	24.797	27.817	26.355	12.177	6.283	5.893
3	SBC1-A / CBC1-A	24.797	32.109	33.983	29.487	37.045	7.558
4	SBC2-A / CBC2-A	18.498	21.592	20.721	16.728	12.015	4.713
5	SCC1-A / CCC1-A	18.498	23.119	21.412	24.982	15.755	9.227







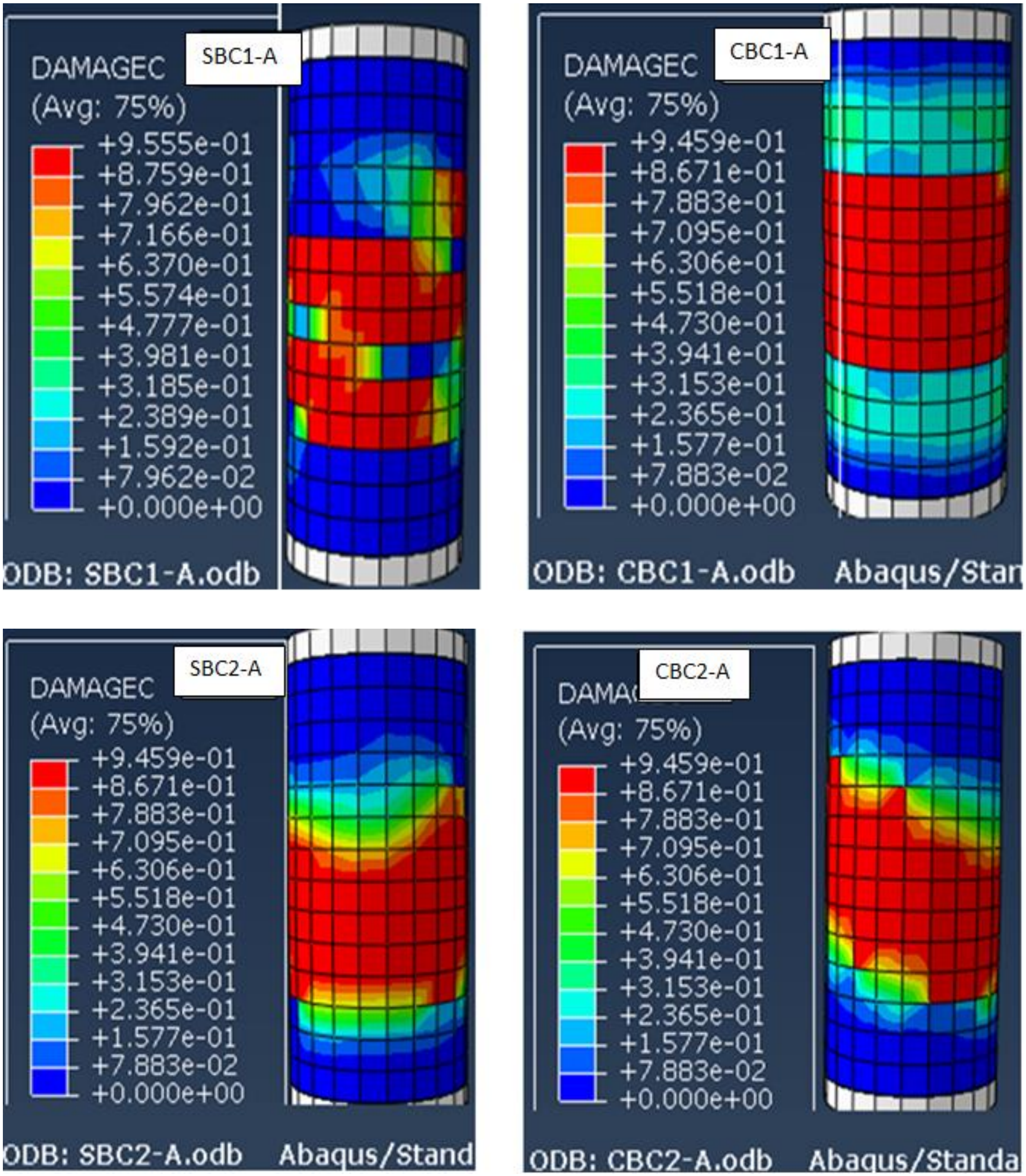


Figure 4.12 Compression Damage property of Concrete

5. OBSERVATION AND DISCUSSION

5.1. Experimental Observations and Discussion

As concrete grade increase, its obvious strength also increases, whereas ductility is decreasing and the failure mode is became suddenly brittle. Suddenly brittle failure of concrete is occurred without any sign indication of failure before damage, this is due to strong interaction between aggregates and cement paste, and at loads approaches to around peak micro – cracks are appear on surface and unexpectedly failure happened. This type of failure simply observed from figure 3.7 (PC4).

From the observed results; the difference percentage increase of circular hoops prevails over spiral confinement at spacing 56mm is about by 5.27% and difference percentage increase of spiral prevails over circular hoops confinement at spacing 94mm is about 11.39%. Which means the shape (i.e spiral or circular hoop) of transverse reinforcement of circular columns is significantly affected by their spacing. Therefore; As spacing of transverse reinforcement decreases, circular hoop type of confinement gives better confined strength of concrete than spiral, perhaps this may occur due to different anchorage type between spiral and circular hoop, which means welding of hoops may have a significant involvement on confined strength.

5.2. Discussion and Results of Abaqus Simulation

A brief discussion what studied in this sub section of the research area mentioned below:-

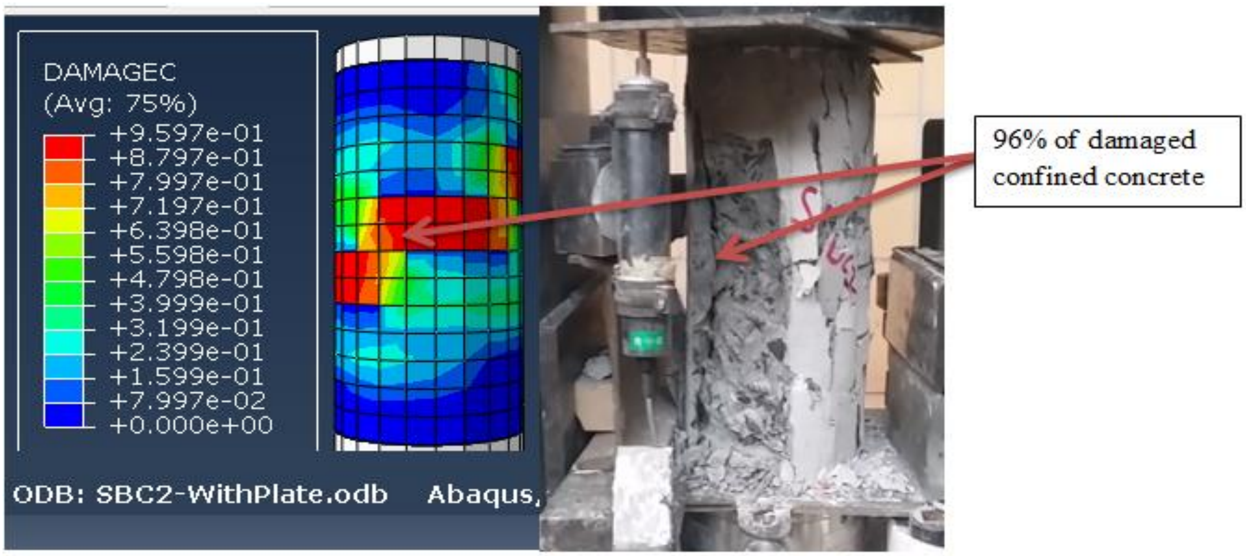
Concrete Damage Plasticity (CDP) constitutive behavior model facilitates proper values of default parameters, such as dilation angle, eccentricity, ratio of biaxial to uniaxial strength of concrete and compression damage variable have good agreement with failure mechanism of concrete under compression.

The inelastic strain and compression damage variable results obtained from the numerical study proved by CDP model can be used to simulate the concrete responses to compression; compression failure pattern obtained from FE analysis compatibility with experiments.

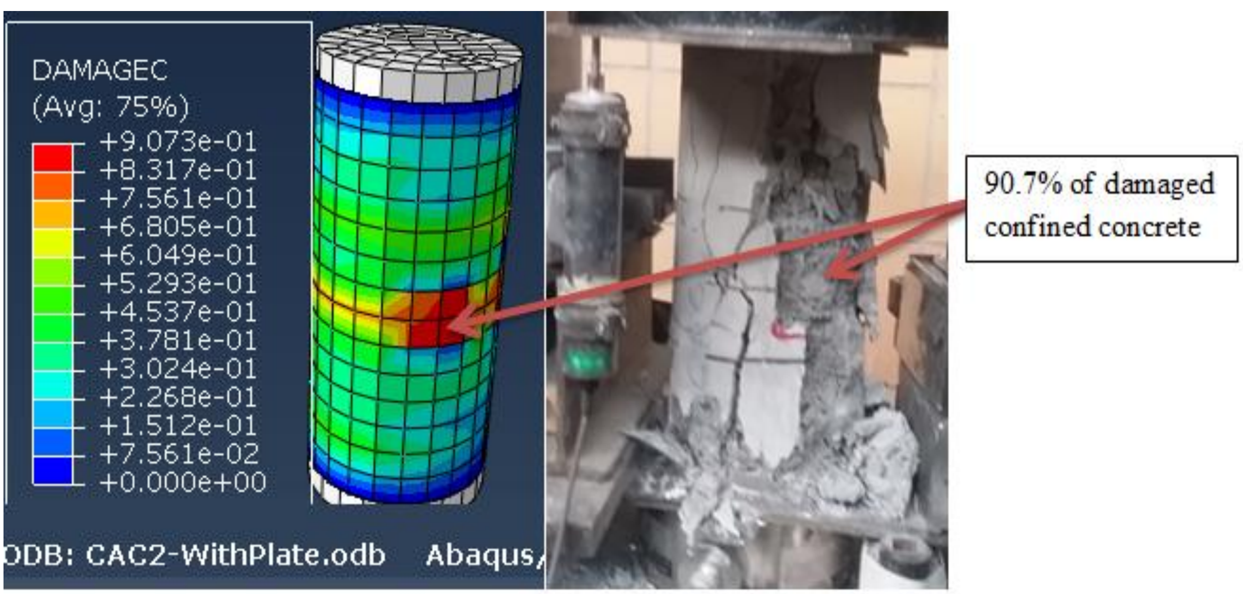
As stress – strain curve imply; post – peak response of confined concrete of both spiral and circular hoops withstand excessive deformation without significantly degradation of stiffness.

5.3. Comparison of Failure Mechanism between Experimental and Abaqus

Comparison of failure mechanism among experimental work and Abaqus simulation is mentioned below as pictorial form for confined concrete specimens of SBC2 and CAC2 designations. Detail comparison of these specimens is presented at Appendix A.



96% damaged concrete spirally confined concrete



90.7% damaged concrete circular hoop confined concrete

Figure 5.1 Comparison of Failure Mechanism of Concrete Experimental and Abaqus

6. SENSITIVITY ANALYSIS

6.1. Parametric Study

Parametric study allows investigating the effect of different random variables and their combinations of selected processing parameter values on part quality. The range of variables will depend on the molding process being used. In this study, to identify the effect of parameters affecting the confining strength of concrete, twelve different combinations are considered and sensitivity analysis of random variables has been investigated for each circular hoop and spiral confinements.

6.2. Sampling Techniques

Combinations are generated by purposive non – probability type sampling techniques. So that normal strength of concrete and available yield strength and spacing of transverse reinforcement are selected as random variables in this research. The statistical variations and the 17x3 combinations of selected random variables for spiral and circular hoops are shown in Tables 6.1 and 6.2 respectively. Out of 17x3 combinations considering two cases (i.e spiral and circular hoop), 12x3 combinations are obtained from experimental work and the rest 5x3 combinations are also acquired from Abaqus simulation for each type of confinements.

Table 6.1 Statistical variations of random variables

No	Input variables	Unit	Mean Values	Standard deviation
1	Compressive strength of concrete	MPa	24.181	4.205
2	Yield strength of steel	MPa	490.706	109.597
3	Spacing of Transverse reinforcement	mm	125.88	79.80

Table 6.2 34x3 Combinations of random Variables and Experimental output

Combination		Input Variables			Output	Type of Confinement
No	Designation	Fco (MPa)	Fy (MPa)	Spacing (mm)	Fcco (MPa)	
1	SBC2-A	18.498	400	280	21.590	Spiral
2	SDC1	18.498	618	140	22.942	
3	SCC1-A	18.498	462	280	23.119	
4	SCC1	18.498	462	140	23.989	
5	SAC1-A	18.498	300	70	24.608	
6	SCC2	24.797	462	94	25.631	
7	SAC2-A	24.797	300	280	27.817	
8	SBC4	30.698	618	140	28.476	
9	SDC2	24.797	618	94	28.660	
10	SAC2	24.797	462	56	31.448	
11	SAC4	30.698	462	140	31.800	
12	SBC1-A	24.797	400	70	32.109	
13	SAC3	27.103	462	94	32.892	
14	SCC3	27.103	462	56	33.941	
15	SBC2	24.797	618	56	33.953	
16	SBC3	27.103	618	94	34.930	
17	SDC3	27.103	618	56	35.267	
18	CDC1	18.498	618	140	20.324	Circular Hoop
19	CBC2-A	18.498	400	280	20.721	
20	CCC1-A	18.498	462	280	21.412	
21	CCC1	18.498	462	140	23.225	
22	CDC2	24.797	618	94	25.022	
23	CAC1-A	18.498	300	70	25.784	
24	CAC2-A	24.797	300	280	26.355	
25	CAC3	27.103	462	94	28.079	
26	CCC2	24.797	462	94	29.156	
27	CBC3	27.103	618	94	29.396	
28	CBC4	30.698	618	140	31.089	
29	CAC4	30.698	462	140	31.12	
30	CAC2	24.797	462	56	33.755	
31	CDC3	27.103	618	56	33.822	
32	CBC1-A	24.797	400	70	33.983	
33	CBC2	24.797	618	56	34.038	
34	CCC3	27.103	462	56	35.832	

The probabilistic distribution and the influence of random variables on the statistical variation of the estimated confined strength of concrete are investigated. Hence, median and means of the output of confined strength of concrete more or less are similar with unique mode, therefore probabilistic distribution of random variables on confined strength of concrete is used the concept of normal distribution. The formula for normal density function is given in Eq 6.1.

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \; e^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{6.1}$$

Where, *x:* random variable

μ: mean value

σ: standard deviation

In addition to this, 95% confidence interval of the mean value of confined strength of concrete is computed using student's t – distribution, since sample size is less than 30 and given in Table 6.3.

Table 6.3 Confidence intervals

Type of Confinement	Confined Strength of Concrete (MPa)		
	Mean value	Standard deviation	(95 %) Confidence intervals
Spiral	29.922	4.411	(27.57, 32.28)
Circular Hoops	30.007	6.689	(26.44, 33.58)

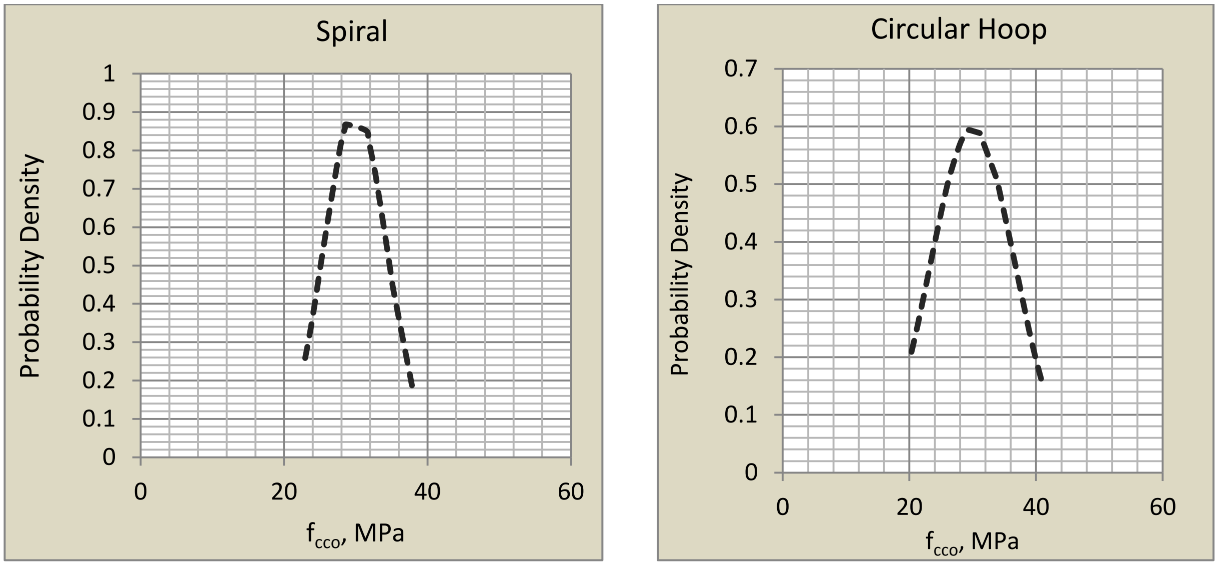


Figure 6.1 Probability distribution of Confined Strength of Concrete

6.3. Sensitivity Analyses of Confined Strength of Concrete

The sensitivity factor α_i is a kind of an index to estimate the contribution of the uncertainty of x_i to the uncertainty of the function. The confinement index (C_i) expressed by Eq 6.2 was defined to represent the degree of confinement and was used in the stress – strain model proposed (Parakash Desayi 1978). Since the objective function f is given by Eq 6.4, the effects of random variables can be determined as follows:

$$C_i = \frac{\rho_s f_{yh}}{f_{co}} \qquad (6.2)$$

$$\rho_s = \frac{4A_{sh}}{sd_s} \qquad (6.3)$$

$$\frac{f_{cco}}{f_{co}} = A + B\,\frac{\rho_s f_{yh}}{f_{co}} \qquad (6.4)$$

Where: ρ_s = volumetric ratio of spiral or circular hoop reinforcement to core concrete,

s = c/c spacing of spirals or circular hoop,

d_s = diameter of core concrete measured c/c of spirals or circular hoop,

A_{sh} = area of spirals or circular hoop,

f_{yh} = yield strength of spirals or circular hoop,

f_{co} = unconfined strength of concrete.

Constants A and B are determine by linear least square method for the data obtained from experimental and analytical separately for spiral and circular hoops.

$$\frac{f_{cco}}{f_{co}} = 1.121706 + 0.388624\frac{\rho_s f_{yh}}{f_{co}} \qquad for\ Spiral$$

$$\frac{f_{cco}}{f_{co}} = 1.023934 + 0.677369\frac{\rho_s f_{yh}}{f_{co}} \qquad for\ Circular\ Hoops$$

$$\alpha_i = \frac{\partial f}{\partial x_i}\frac{\bar{x}}{\bar{f}} \qquad (i = 1, 2, 3 \ldots n) \qquad (6.5)$$

$$U_i = \alpha_i (COV)_i \qquad (i = 1, 2, 3 \ldots n) \qquad (6.6)$$

Where, α_i: sensitivity factor of random variable i

U_i: uncertainty of random variable i

f: function with statistical variations

$\bar{f}$: mean of f

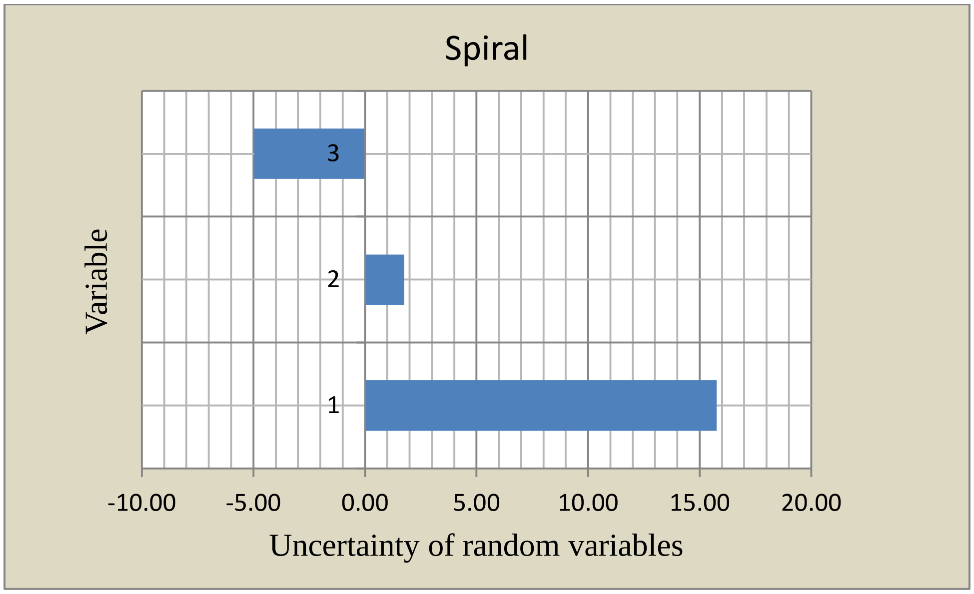
x_i : random variable i

$\bar{x}_i$: mean of x_i

COV_i: Coefficient of variation of random variable i

Table 6.4 Sensitivity factor index and uncertainty of random variables

No.	Input Variable (x)	$\bar{x}$	COV_i (%)	$\frac{\partial f}{\partial x_i}$	$\bar{f}$	α_i	U_i	Type of Confinement
1	Concrete Strength	24.181	17.39	1.121706	29.922	0.9065	15.76	Spiral
2	Yield Strength	490.706	22.33	0.004775	29.922	0.0783	1.75	
3	Spacing of Spirals	125.88	63.40	-0.0186260	29.922	-0.0783	-4.97	
1	Concrete Strength	24.181	17.39	1.02393	30.007	0.825	14.35	Circular Hoops
2	Yield Strength	490.706	22.33	0.00800	30.007	0.136	3.00	
3	Spacing of Spirals	125.88	63.40	-0.03200	30.007	-0.136	-8.63	



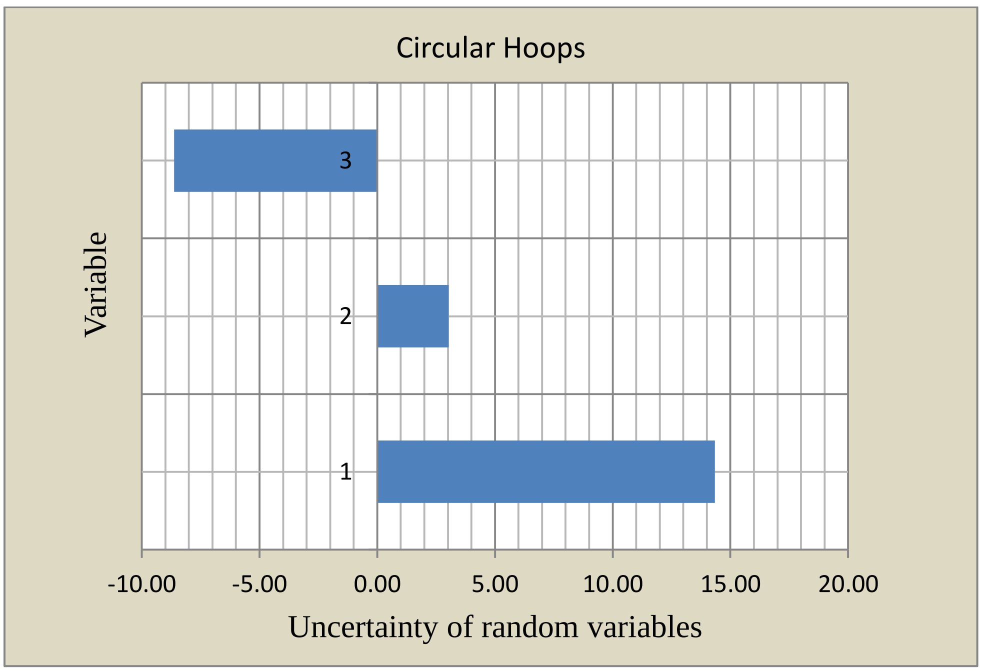


Figure 6.2 Schematic representation of Uncertainty of random variables

As shown in figure 6.2, the largest contribution to the confined strength of concrete is unconfined concrete strength. On other hand, relationship between confined strength of concrete and spacing of transverse reinforcement is inverse proportion, which means increasing spacing of transverse reinforcement significantly decrease confined strength of concrete. The contribution of yield strength of transverse reinforcement is relatively smaller than the other variables.

7. CONCLUSION AND RECOMMENDATION

7.1. Conclusion

Confining of concrete using transverse reinforcements essentially prevents local buckling and excessive lateral deformation of concrete in structural members particularly in reinforced concrete columns. Circular columns are confined either by spiral or circular hoop. In line to this, the following observations and conclusions are made.

1. Failure pattern of plain cylindrical concrete specimens is significantly different from one to another concrete grades. For relatively high strength of concrete, suddenly brittle failure is occurred without cover spalling and laterally bulging.
2. Inelastic strain and compression damage variable results obtained from the numerical study proved by CDP model used to simulate the concrete responses under compression; this compression failure pattern obtained from FE analysis compatible with experiments.
3. Around 11% increase of confined strength of concrete by spiral than circular hoops at relatively large spacing of transverse reinforcement (i.e. 94mm), and about 5% prevail of circular hoop confined concrete than spirally at relatively small spacing (56mm), refer to page 29 for further clarification.
4. Compressive strength of concrete has largest contribution to confined strength of concrete than yield strength and spacing of transverse reinforcement.
5. According to sensitivity analysis result reveals; spacing of transverse reinforcement has adverse effect to confined strength of concrete, in which increasing of spacing leads to decrease confined strength concrete.

7.2. Recommendation

This research conducts on experimenatly and analytical investigation of spirally and circular hoop confinements, the following recommendations are drawn based on out – come results.

1. Selection of transverse reinforcement arrangement (i.e spiral or circular hoop) for circular columns to some extent depends on spacing, for relatively small spacing circular hoop type of confinement gives better result than spiral. But in contrary, at high spacing of trasnverse reinforcement spiral confinement prevails over circular hoop confinement.
2. Variation due to anchorage condition (i.e welding) is not considered on this research, further studys are recommended.
3. Post peak response of structural members is not only depend on material rsponse but also structural response, viz it is size dependent. With this in line, this research conducted on restiriced dimension of concrete specimens. Therefore; highly appreciable to conduct further research by considering full size of column.
4. Effect of longitudinal reinforcement is not studied in this research, further investigation may be needed to quantify. But to consider this effect, size of specimens as much as possible large.

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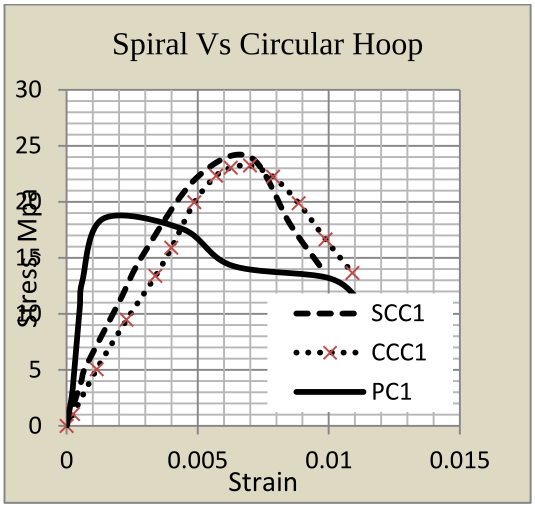
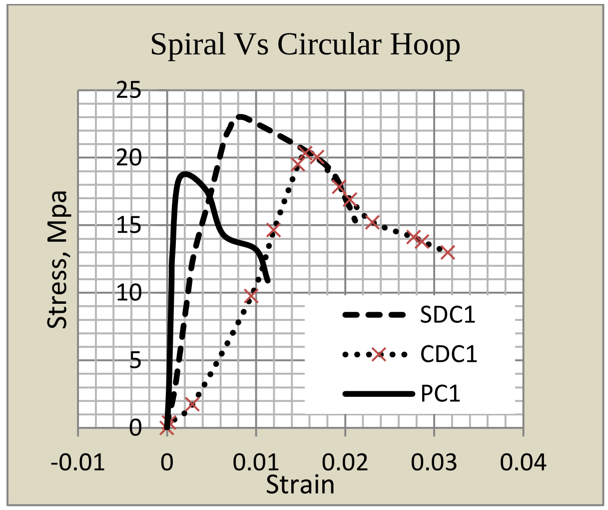
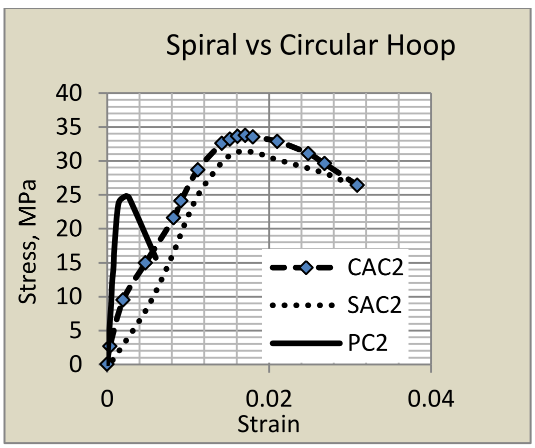
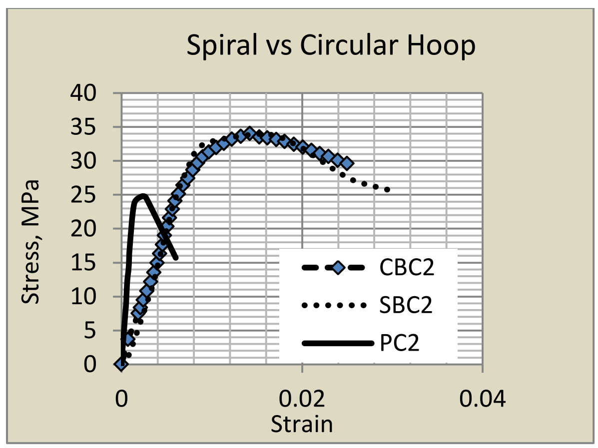
Appendix A

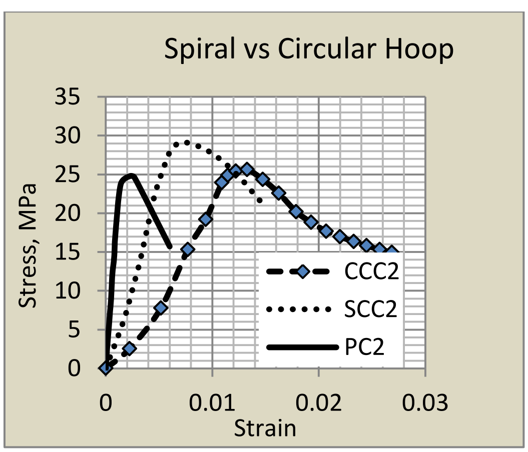
Stress – Strain Curve Obtained from Experiment

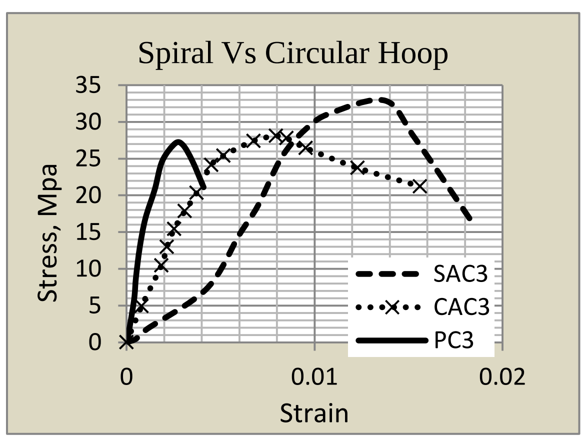


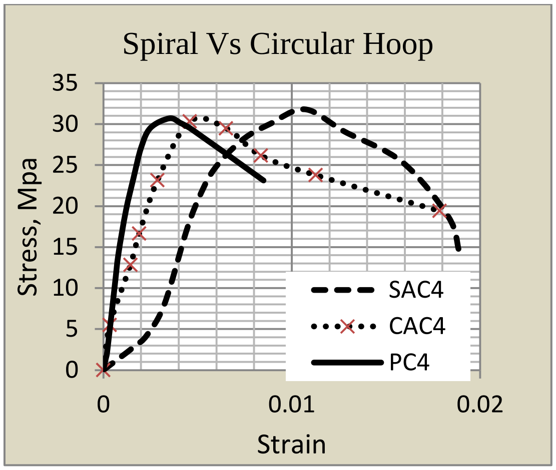


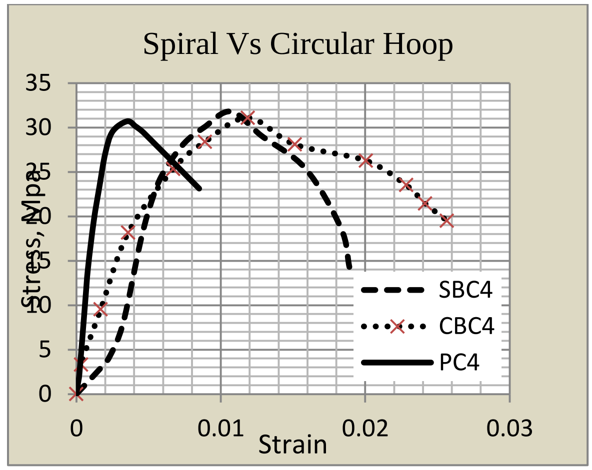


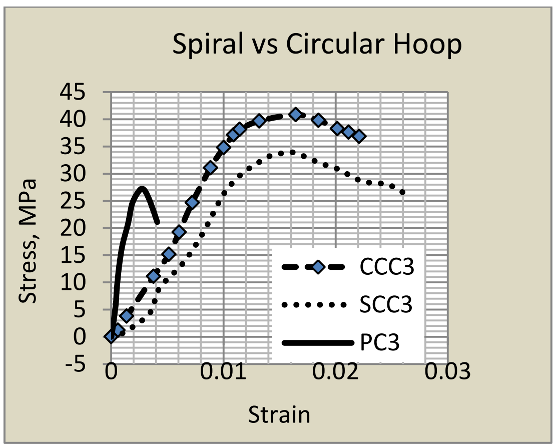


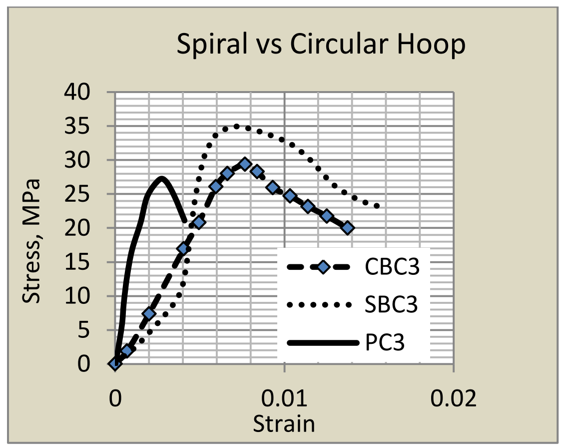





Spiral Vs Circular Hoop
Stress, Mpa
Strain
SAC4
CAC4
PC4


Spiral Vs Circular Hoop
Stress, Mpa
Strain
SBC4
CBC4
PC4


Spiral vs Circular Hoop
Stress, MPa
Strain
CCC3
SCC3
PC3

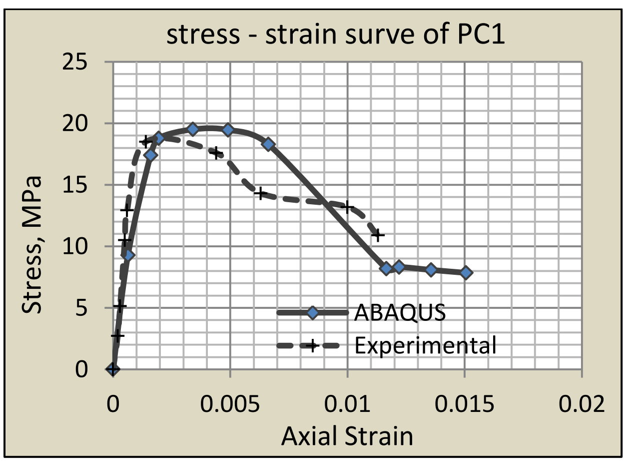

Spiral vs Circular Hoop
Stress, MPa
Strain
CBC3
SBC3
PC3

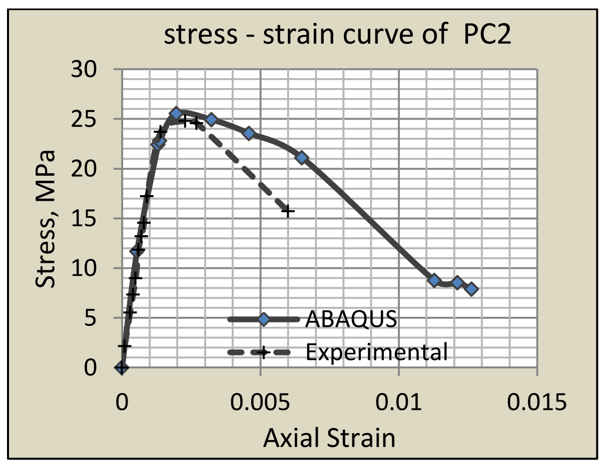
Appendix B

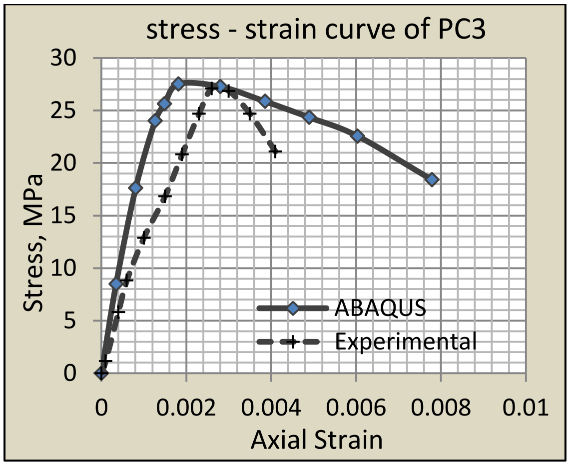
Verification of Abaqus Results with Experimental

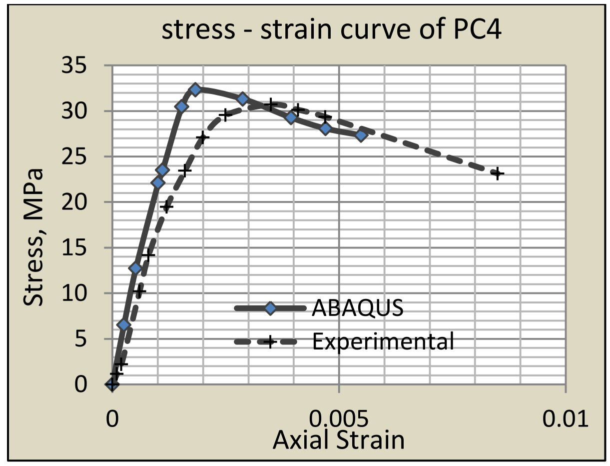
Table B.1 Verification of Abaqus results with Experimental

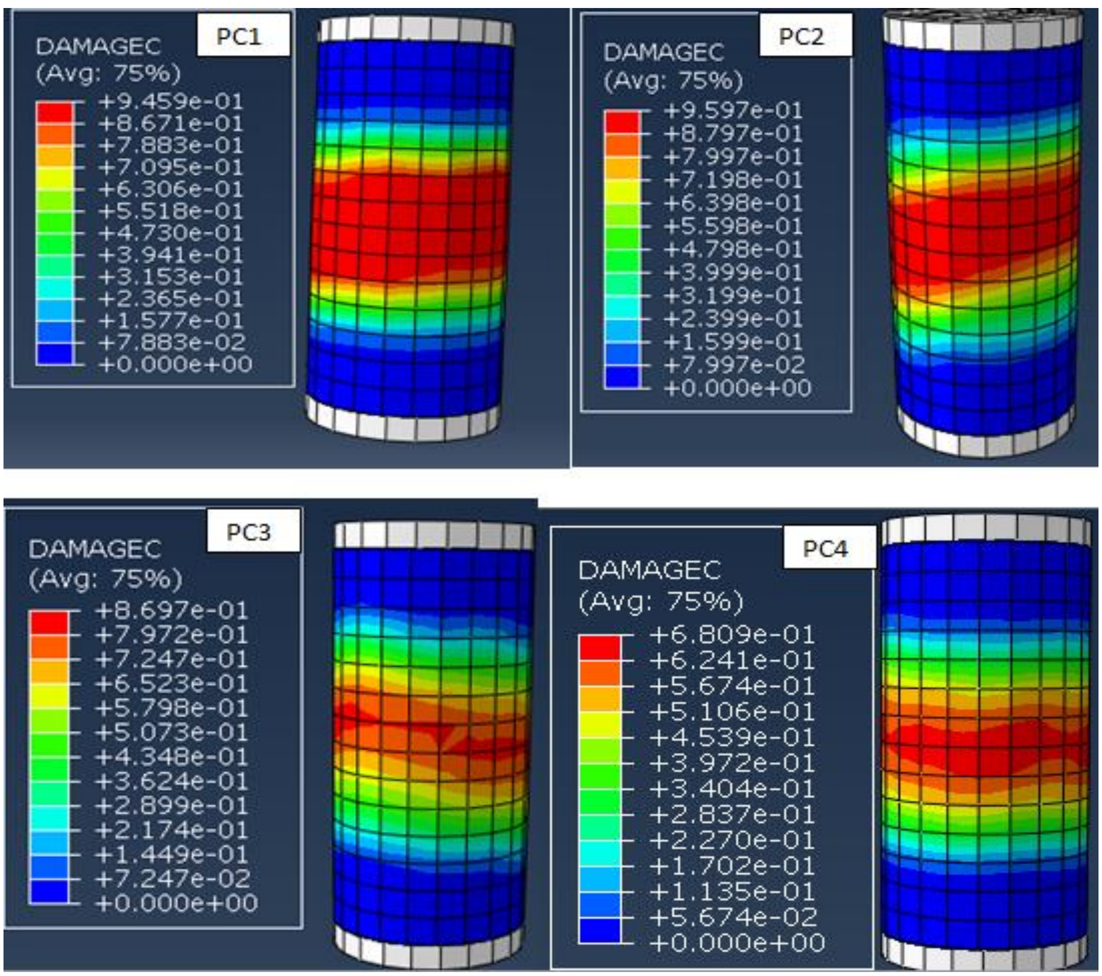
No.	Designation	Experimental f_{co} (MPa)	Abaqus f_{co} (MPa)	Experimental /Abaqus
1	PC1	18.498	19.504	0.95
2	PC2	24.797	25.544	0.97
3	PC3	27.103	27.525	0.98
4	PC4	30.698	32.313	0.95
		f_{cco} (MPa)	f_{cco} (MPa)	
5	SAC4	31.800	34.041	0.93
6	SBC2	33.953	34.639	0.98
7	SCC1	23.989	24.302	0.99
8	CAC2	33.755	35.447	0.95
9	CCC1	23.225	24.935	0.93
10	CDC3	38.822	39.828	0.97






stress - strain curve of PC3
Stress, MPa
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
Axial Strain
ABAQUS
Experimental


stress - strain curve of PC4
Stress, MPa
35
30
25
20
15
10
5
0
0
0.005
0.01
Axial Strain
ABAQUS
Experimental


PC1
DAMAGEC
(Avg: 75%)
+9.459e-01
+8.671e-01
+7.883e-01
+7.095e-01
+6.306e-01
+5.518e-01
+4.730e-01
+3.941e-01
+3.153e-01
+2.365e-01
+1.577e-01
+7.883e-02
+0.000e+00
PC2
DAMAGEC
(Avg: 75%)
+9.597e-01
+8.797e-01
+7.997e-01
+7.198e-01
+6.398e-01
+5.598e-01
+4.798e-01
+3.999e-01
+3.199e-01
+2.399e-01
+1.599e-01
+7.997e-02
+0.000e+00
PC3
DAMAGEC
(Avg: 75%)
+8.697e-01
+7.972e-01
+7.247e-01
+6.523e-01
+5.798e-01
+5.073e-01
+4.348e-01
+3.624e-01
+2.899e-01
+2.174e-01
+1.449e-01
+7.247e-02
+0.000e+00
PC4
DAMAGEC
(Avg: 75%)
+6.809e-01
+6.241e-01
+5.674e-01
+5.106e-01
+4.539e-01
+3.972e-01
+3.404e-01
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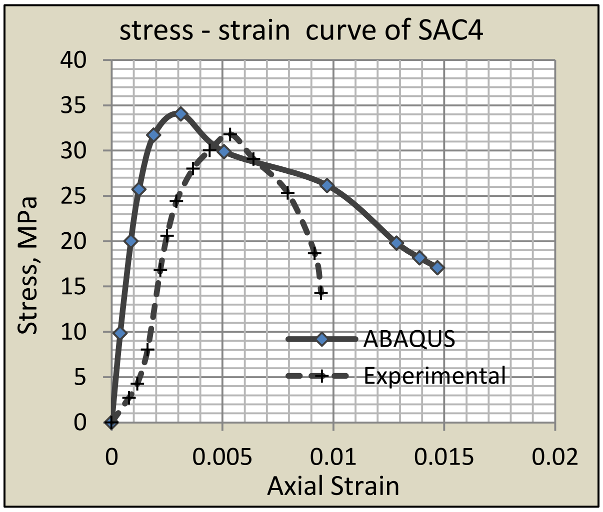
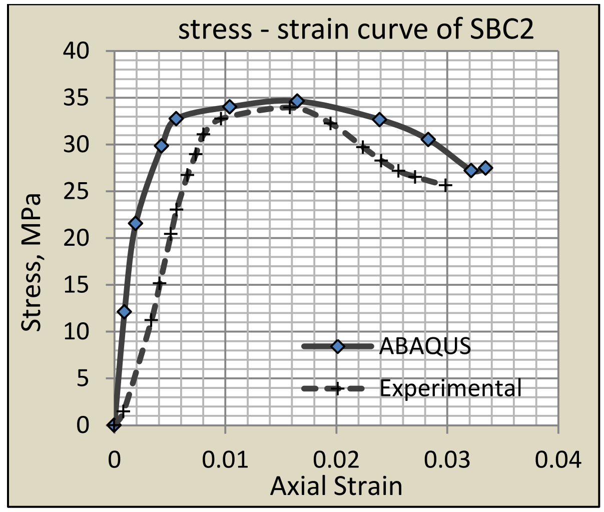
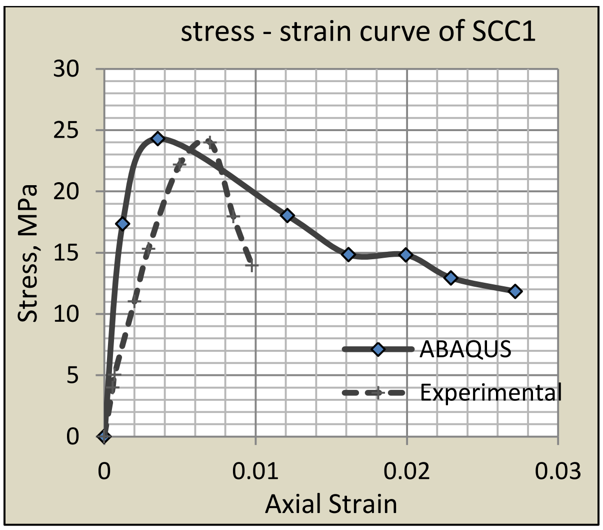
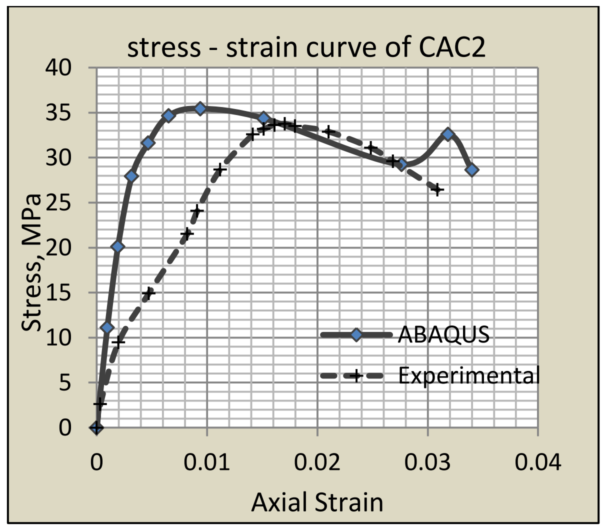
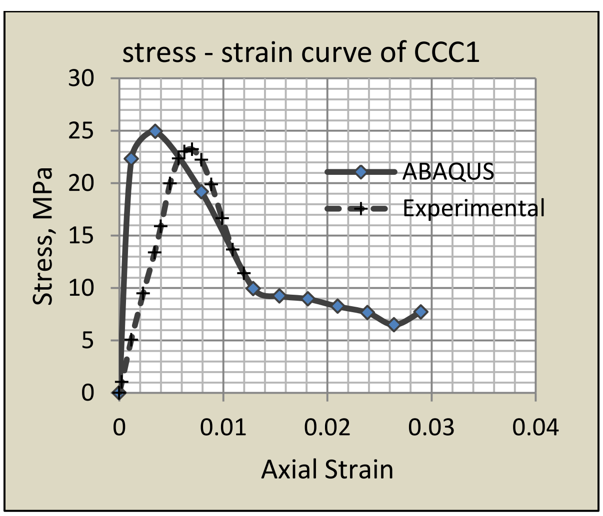
+0.000e+00

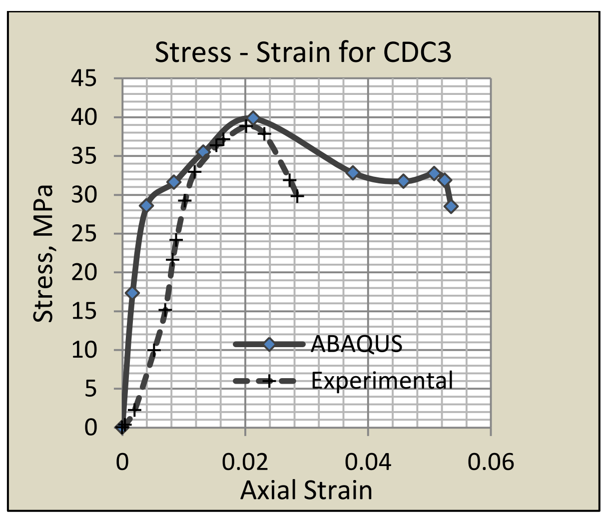

stress - strain curve of SAC4
Stress, MPa
Axial Strain
ABAQUS
Experimental

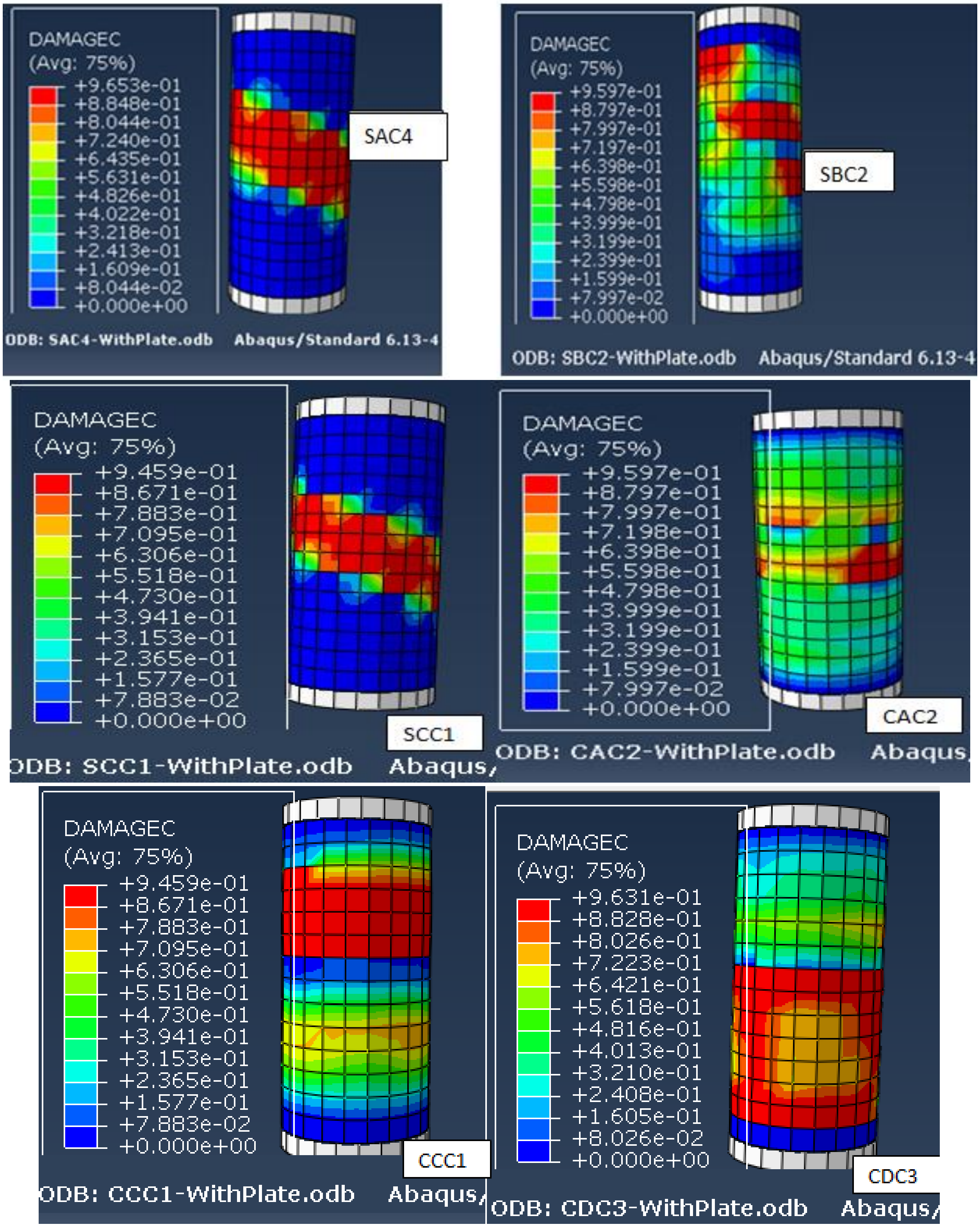

stress - strain curve of SBC2
Stress, MPa
Axial Strain
ABAQUS
Experimental


stress - strain curve of SCC1
Stress, MPa
Axial Strain
ABAQUS
Experimental


stress - strain curve of CAC2
Stress, MPa
Axial Strain
ABAQUS
Experimental

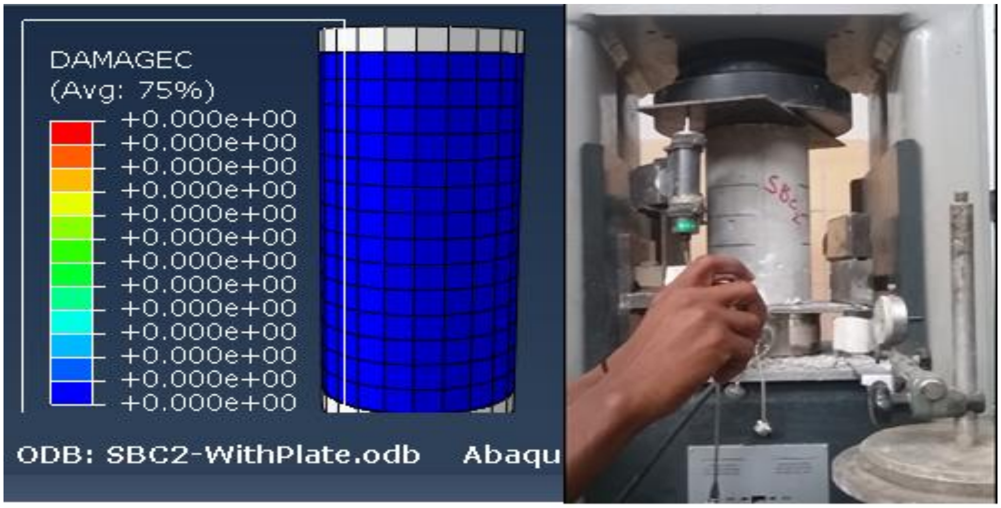

stress - strain curve of CCC1
Stress, MPa
Axial Strain
ABAQUS
Experimental


Stress - Strain for CDC3
Stress, MPa
Axial Strain
ABAQUS
Experimental

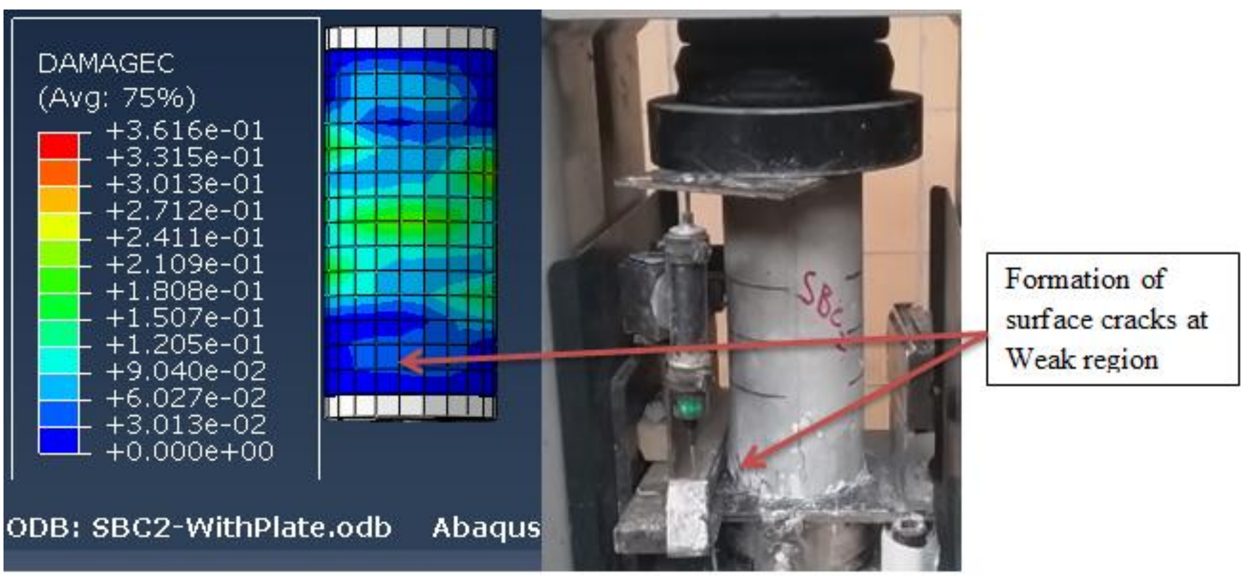

DAMAGEC
(Avg: 75%)
+9.653e-01
+8.848e-01
+8.044e-01
+7.240e-01
+6.435e-01
+5.631e-01
+4.826e-01
+4.022e-01
+3.218e-01
+2.413e-01
+1.609e-01
+8.044e-02
+0.000e+00
SAC4
ODB: SAC4-WithPlate.odb Abaqus/Standard 6.13-4
DAMAGEC
(Avg: 75%)
+9.597e-01
+8.797e-01
+7.997e-01
+7.197e-01
+6.398e-01
+5.598e-01
+4.798e-01
+3.999e-01
+3.199e-01
+2.399e-01
+1.599e-01
+7.997e-02
+0.000e+00
SBC2
ODB: SBC2-WithPlate.odb Abaqus/Standard 6.13-4
DAMAGEC
(Avg: 75%)
+9.459e-01
+8.671e-01
+7.883e-01
+7.095e-01
+6.306e-01
+5.518e-01
+4.730e-01
+3.941e-01
+3.153e-01
+2.365e-01
+1.577e-01
+7.883e-02
+0.000e+00
SCC1
ODB: SCC1-WithPlate.odb Abaqus/
DAMAGEC
(Avg: 75%)
+9.597e-01
+8.797e-01
+7.997e-01
+7.198e-01
+6.398e-01
+5.598e-01
+4.798e-01
+3.999e-01
+3.199e-01
+2.399e-01
+1.599e-01
+7.997e-02
+0.000e+00
CAC2
ODB: CAC2-WithPlate.odb Abaqus
DAMAGEC
(Avg: 75%)
+9.459e-01
+8.671e-01
+7.883e-01
+7.095e-01
+6.306e-01
+5.518e-01
+4.730e-01
+3.941e-01
+3.153e-01
+2.365e-01
+1.577e-01
+7.883e-02
+0.000e+00
CCC1
ODB: CCC1-WithPlate.odb Abaqus/
DAMAGEC
(Avg: 75%)
+9.631e-01
+8.828e-01
+8.026e-01
+7.223e-01
+6.421e-01
+5.618e-01
+4.816e-01
+4.013e-01
+3.210e-01
+2.408e-01
+1.605e-01
+8.026e-02
+0.000e+00
CDC3
ODB: CDC3-WithPlate.odb Abaqus/

Appendix C

Comparison of Failure Mechanism between Experimental and Abaqus

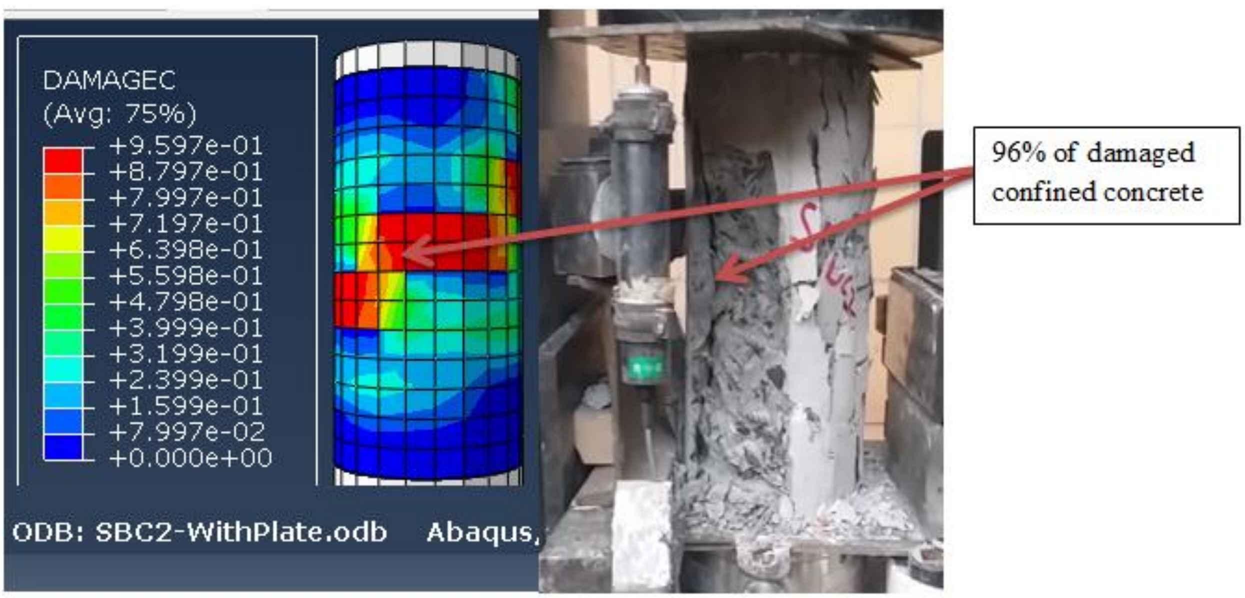


Undamaged spirally confined concrete specimen

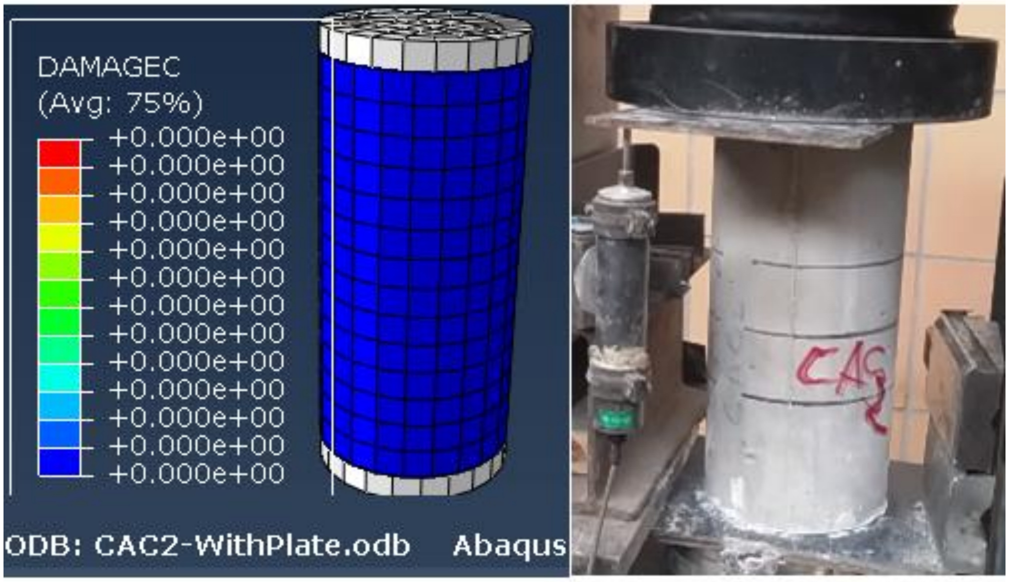


Propagation of a network surface cracks

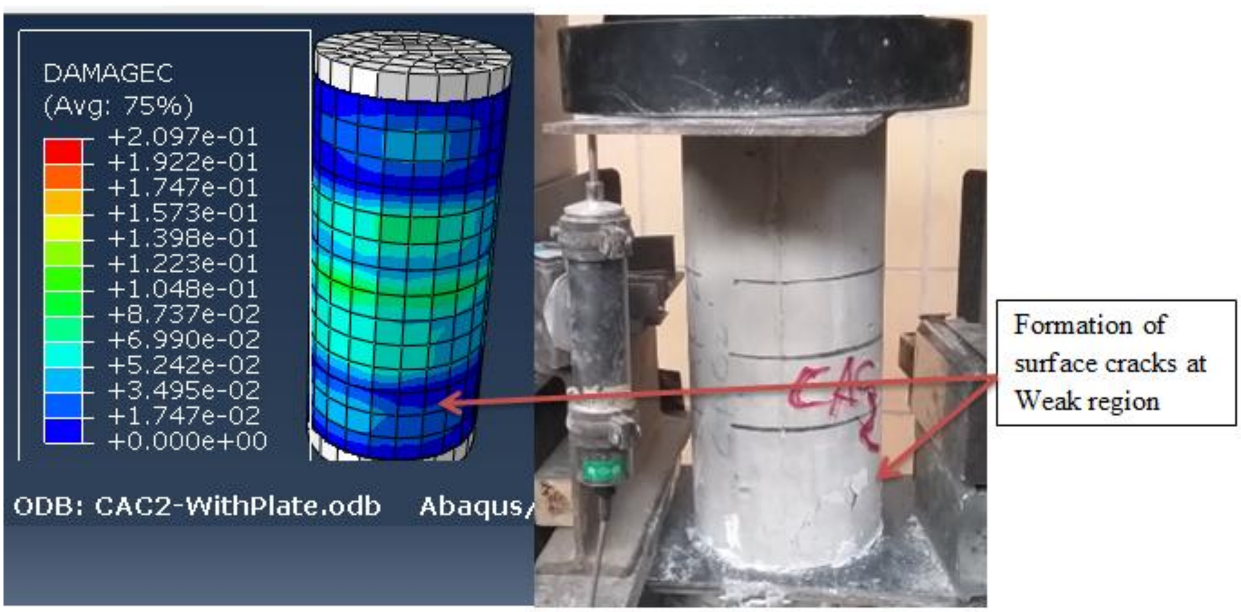
Concrete cover spalling stage



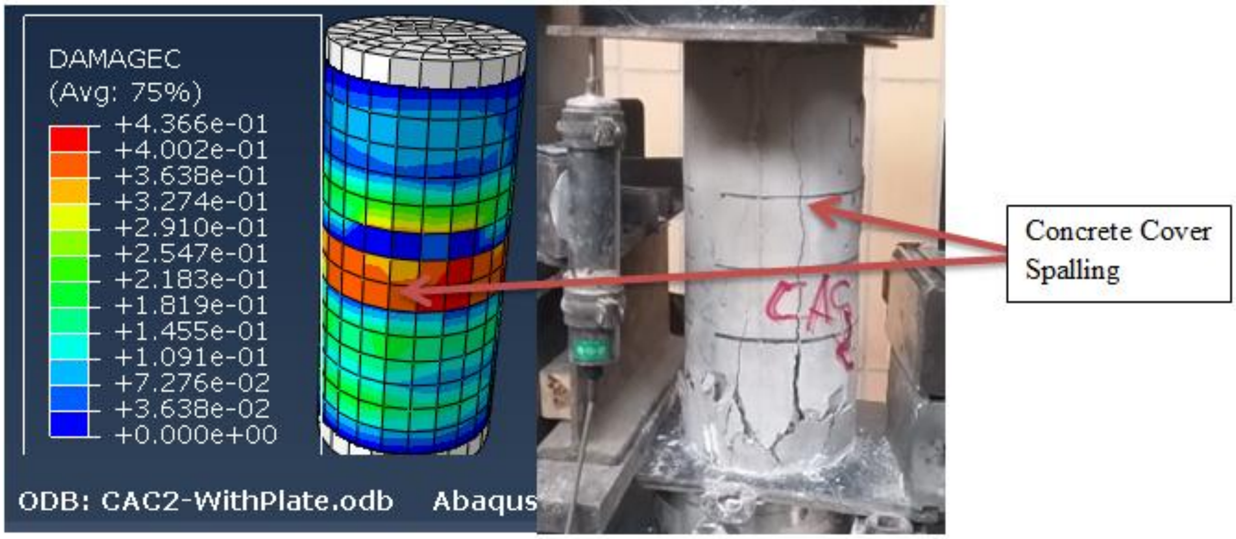
96% damaged concrete spirally confined concrete



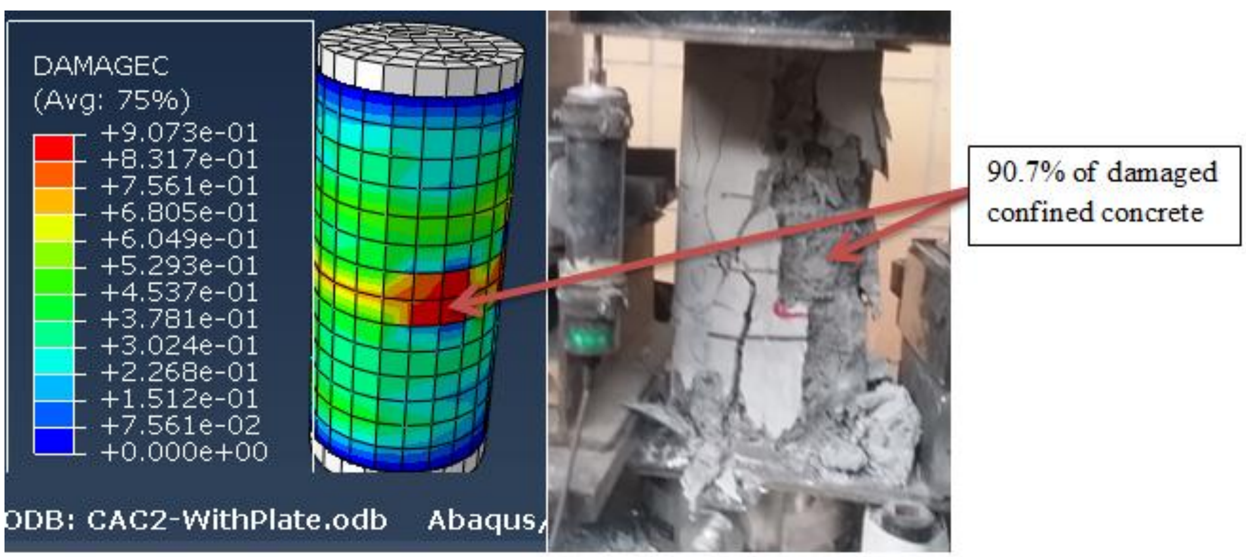
Undamaged spirally confined concrete specimen



Propagation of a network surface cracks



Concrete cover spalling stage



90.7% damaged concrete circular hoop confined concrete