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NUMERICAL INVESTIGATION OF REINFORCED CONCRETE COLUMNS WITH TRANSVERSE HOLES

By

FRAOL NEGASSA

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Abstract

It is not uncommon to provide traverse openings in reinforced concrete (RC) columns for various reasons. The presence of a hole in a reinforced concrete column will disrupt the stress distribution leading it to splitting and failure at an early life. The aim of this study is to numerically investigate the behavior of reinforced concrete columns with transverse holes and also evaluate means of strengthening to restore or increase performance losses due to presence of holes.

A nonlinear finite element analysis (NLFEA) using ANSYS software program was used for validation analysis of full-scale experimental result reported in literature and further perform parametric study on opening size, shape, single vs multiple, horizontal and vertical positions. Also, strengthening options namely CFRP Jacketing, Steel Casing and their combination are investigated to restore or enhance capacity of RC column with opening cutouts.

The results of the finite element analysis were compared with analytical methods. The impact of a hole with a diameter less than or equal to a third of the width of the column was linearly estimated. It was further observed that a square shaped hole results in 5.69% additional capacity reduction as compared to circular shaped opening whereas horizontal opening position has more influence in load carrying capacity than vertical. CFRP jacketing with a steel casing inside the hole was found to be the most significant strengthening method.

Keywords: Nonlinear Finite Element Analysis (NLFEA), transverse holes, columns with holes, CFRP jacketing.

CHAPTER 1

1. Introduction

Columns are one of the main structural members in buildings. They carry vertical loads and bending moments from corresponding floors and beams. Transverse holes in columns may be present due to reasons related drilling for test, utility lines & also architectural and esthetic needs. Core Drilling for a test is a partially destructive method that is still widely used for monitoring structural health, compressive strength tests, split cylinder tests and so on. These drilling positions will be on beams, columns and slabs. Utility service lines also need holes required for installation of cables, network lined, ducts, pipes and other building service lines. And it is usually recommended to provide the holes in beams and slabs, but there are times in which the presences of the openings (on columns) are an avoidable [15]. In those cases, a better understanding of the behavior of the columns with the openings Is needed. During construction contractors are strictly recommended not to create any holes and utility lines other than the ones on the approved plans that the designers are aware of. But due to workmanship errors and lack of knowledge holes will be provided for utility lines without regard to the approved design.

The presence of the holes and openings will affect the behavior of the column. If a thorough investigation on the effects of transverse holes on columns is not performed, uncontrolled problems like crushing, large deflection and splitting might occur. Previous studies have studied and recommended design and construction provisions of beams and slabs with holes. However relatively few studies exist on column with holes. There is a lack of recommendations and codes on this topic [28]. The existence of a hole in a column will disrupt the stress equilibrium and that disruption will depend on the geometry of the introduced hole. The geometry includes size, shape and depth of the hole. Preliminary work on the size of a hole was undertaken by [7]., as they investigated the effects of circular openings on the compressive behavior of Reinforced concrete columns. Their work focused on studying the compressive behavior of drilled columns and repairing of the column with slight-expansive cement-based mortar. The experimental design consisted twenty-four, 150mm by 300mm by 750mm (length-width-height) concrete columns reinforced with four 12mm longitudinal bars and 8mm stirrups, with a varying diameter of hole-column width ratio (d/b ratio) of 0.2(d=60mm), 0.3(d=90mm) and 0.4(d=120mm). Additional two columns with 120mm diameter of hole were prepared for the repairing material test. Two series of the above columns were prepared with two different concrete compressive strengths for series A with 20MPa and series B with 10 MPa compressive strengths to represent a good and poor concrete quality. The specimens were only investigated under compression load. Results were mainly interpreted by keeping the ultimate load as a dependent variable and plotted against strain induced. The presence of the holes produced an alteration of the stress strain state with a related load carrying reduction. However, the significant load carrying capacity reduction is not linearly dependent with the increment of the geometrical section of the holes. And the presence of a transverse reinforcement showed a good ductility condition. Those columns tested for the slight-expansive mortar gained their total load bearing capacities

Furthermore, [8] tried to study load carrying capacity of axially loaded RC members with circular openings using a different approach to the problem. The author tried to study the ultimate capacity of the columns using an experimental analysis and a theoretical strut and tie model (STM) to explain. the presence of a hole in axially loaded member alters the existing stress state a geometrical and stress trajectory discontinuity dispersion will occur because of the opening and that disturbed region (D-region) was analyzed theoretically using the Struct and Tie Method (STM). The approach was used to calculate the bursting tensile force that occurs because of the opening in the isostatic lines of stress trajectories (Figure 1-1). But the position of the busting tensile force was located near the hole unlike bottle shaped struts in which the tensile fore is located in the middle of the disturbed D- region. In the results, the most damaging effects had occurred when the center of the holes were placed along the column axis. A great amount of loss in load carrying capacity was noticed even for a small hole diameter if a low amount of transverse reinforcement was provided.

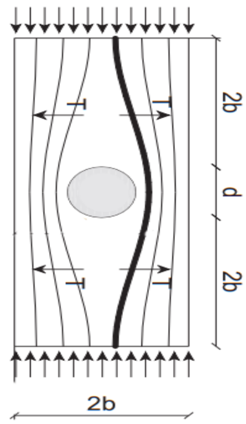

Figure 1-1, A bursting tensile force T occurring in the Middle of the disturbed region (D-region) [8].

The need for strengthening columns comes from wanting to upgrade the current behavior and strength of concrete. Building and structural members are strengthened for plenty of reasons. The common causes for the retrofitting are fire resistance, seismic resistance, weak test results, damage due to impact load, change in building function, corrosion, construction and design errors and etc.

The present study aims to investigate parameters that may affect the behavior in compressive strength of full-scale square columns when a hole is present. And also seeks to examine ways to strengthen the lost strength of the column with a transverse hole.

1.1. Statement of the problem:

Since columns are one of the critical elements of a structure, a deep knowledge of their behavior is always needed to be able to manipulate their geometry. And adding a hole to a column is most definitely one of those things that must be done only when its effects on the element is well understood and known. The effects of parameters of a hole in a column like size, position, number and shape must be well understood.

This research Investigates the behavior of full-scale RC columns with transverse holes and looks for ways to optimize strength reduction in reinforced column due to opening cut outs.

1.2. General Objectives.

The main objective of this research is to investigate the behavior of full-scale reinforced concrete columns with transverse holes.

1.3. Specific Objectives

- Perform parametric study on number of openings, opening geometry and location for least reduction in load carrying capacity of RC column.
- Investigate use of CFRP composites to restore lost strength in RC column.

1.4. Significance of the research

There is a practice to cut out transverse holes in new and existing reinforced columns due to utility needs and core drilling for assessment. This research gives insight to practicing and design engineers for designing reinforced concrete columns with holes and presents methods of retrofitting techniques and available choice of materials to restore lost strength of reinforced column.

1.4. Scope of the Study

Due to absence in full-scale testing facility here in Ethiopia, this research uses experimental result published in literature and further numerically studies variables mentioned in specific objective in parametric study.

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2. Methodology

2.1 Finite Element Modeling

Finite element modelling is a method of modelling a structure by dividing the original specimen in to finite small elements in order to analyze the structure and get a very accurate result. Among few commercially available software that are capable of solving FEM problems; to address and answer the objectives of this study ANSYS software is chosen. The Reinforced concrete columns are modeled and analyzed using this tool.

2.1.1 Geometry

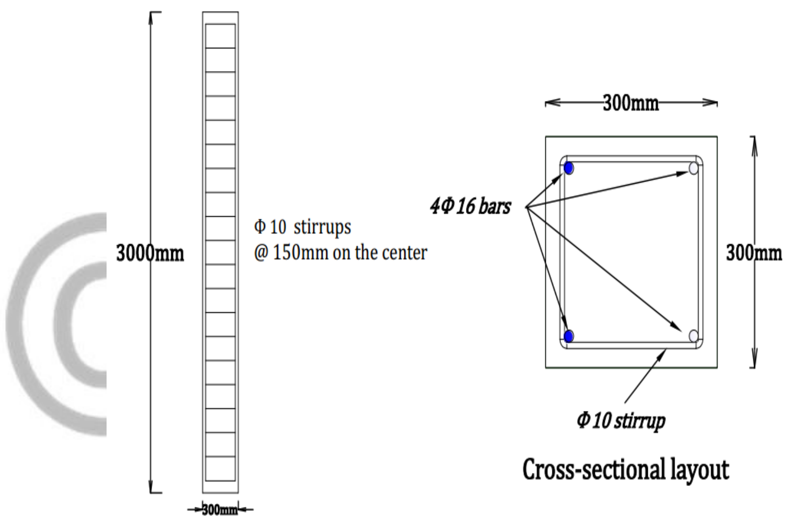

Figure 2-1 A geometrical properties of the selected full-scale column. and reinforcement detailing.

The RC columns are full-scale and have a similar cross-section of 300mm by 300mm square cross-section with 3000mm height. The size of the model is to represent a common column usually found in buildings. The boundary conditions are modeled to replicate the compression strength testing

2.1.2 Materials.

Concrete: -

The material property chosen determines the behavior of the model under the investigation. The material nonlinearity always occurs when the stress in the material surpasses the linearly elastic stage and when yielding occurs. The plastic deformation and behavior of a model can be seen if the material property used has nonlinear behavior. The concrete material used for modelling is an isotropic material with both linear and nonlinear properties considered.

The material model adopted for this research is Coupled Damage – Plasticity Microplane (CDP) model. CDP microplane model is a material idealization model for concrete in which the cracking (tension) and crushing (compression) in the material are represented by increasing values of hardening (softening) variables. These variables are the variables that control the formulation of yield surfaces. These hardening variables are called equivalent plastic strains in tension and compression. [28,29]. To cover a full range of possible stresses the plasticity in CDP model is defined via three surface microplane Drucker-Prager model [27]. The main properties of the concrete used are summarized in *Table.2-1*.

Table.2-1. Material property parameter for concrete model.

Material Parameters for concrete			
Young's Modulus	E	MPa	28723
Poisson's ratio	v	-	28722
Uniaxial compression strength	f_{uc}	MPa	33
Biaxial compressive strength	f_{bc}	MPa	37.95
uniaxial tensile strength	f_{ut}	MPa	3.103
Tension cap hardening factor	R_t	-	1
Hardening parameter	D	MPa	4.E+04
Compression cap location	σ_v^c	MPa	-37.95
Compression cap shape	R	-	2

Threshold for tension damage	Y_{t0}	-	0
Threshold for compression damage	Y_{c0}	-	2.E+05
Tension damage parameter	β_t	-	3000
Compression damage parameter	β_c	-	2000
Nonlocal interaction range parameter	c	mm^2	1600
Over nonlocal parameter	m	-	2.5

Reinforcement

In this study to the RC columns are modeled using the discrete reinforcing modelling option because the longitudinal rebars and the transverse rebars have different orientation and cross-sectional area. The mechanical properties of the rebar material used is summarized in the *Table 2-2* below.

Table 2-2, Reinforcement steel material property.

Material parameters for Reinforcing steel			
Young's Modulus	E	MPa	200000
Poisson's ratio	v	-	0.3
Yield Stress	f_y	MPa	460
Tangent Modulus	E_t	MPa	1000

CFRP

In this research, the design properties of the CFRP material considered are given *Table 2-3*. The tensile strength and stress strain behavior of the CFRP profiles is assumed to be linear. (Figure 2-2.). The tensile strength of the CFRP will increase linearly until the ultimate tensile strain happens. After the ultimate tensile strain happens the CFRP is considered to have failed (ruptured).

Table 2-3, CFRP material property parameters.

Material property for CFRP			
Modulus of Elasticity	E_{frp}	Mpa	230000

Ultimate tensile strength	f_{fu}	Mpa	3500
Ultimate rupture strain	ε_{fu}	-	0.015
Density	ρ	g/cm^3	1.79

Steel Casing

Steel Casing, L-80 steel casing tube is used for strengthening. It has a 11.9888mm thickness, 0.3 Poisson ratio, 200GPa Modulus of Elasticity, 522MPa minimum and 655Mpa minimum yield and tensile strength. This steel casing is a high-performance casing usually used for deep oil and gas wells due to its mechanical properties [11].

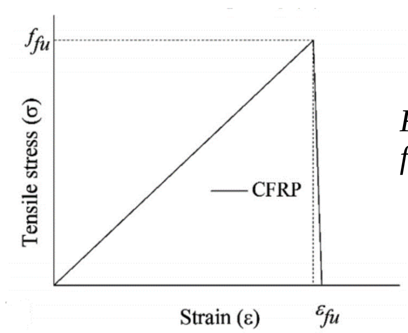

Figure 2-2. the stress vs strain model for CFRP[29].

2.1.3 Element

Material Elements

There are common elements (from many other options) that are used for concrete modelling SOLID (186, 185 & 65), and CPT (215, 216 & 217). In this study we have used the CPT element because of the less mesh sensitivity to the other elements. CPT215 and CPT217 elements are adopted for meshing the concrete. CPT215 is a 3D eight node coupled physics solid element with elasticity, stress stiffening, large deflection and large strain capabilities. However, CPT217 element is a higher order version of CPT215 element and is a 3D ten node element.

For Reinforcement steel the elements used for meshing depend on the geometry, orientation, modeling method and behavior of the rebar modeled. The method used is by modeling the concrete and the reinforcing steel as solid elements and merging the corresponding nodes using contact elements. Contact elements are element types used to simulate the connection between two bodies (i.e. concrete and reinforcing steel).

For CFRP and Steel casing, eight-node 3D solid elements were used to construct the models. The interface between the concrete with CFRP and Steel casing is modeled using bonded contact and target elements to merge the corresponding nodes. A perfectly bonded connection is assumed while preparing the models. No slipping and friction is considered. The use of contact elements is optimal approach to represent the concrete – steel bond behavior [34,35].

Contact Elements

The nodes between the different elements (concrete, CFRP and steel casing) were merged using contact and target elements CONTA174 and TARGE170. CONT174 is a 3D-8 node surface to surface contact element used to represent contact between contact and target elements. It is applicable to 3D structural and coupled-field contact analyses. TARGE170 is used to represent various 3-D “target surfaces for the associated contact elements [27].

2.1.4. Meshing

Elements in ANSYS have element shapes they support. However hexahedral dominant meshing is sensitive for geometry arrangements and element size. For example, the CPT215 concrete element does not support tetrahedral shaped elements [27] and if the meshing is created with tetrahedral elements there is a high order version of this element, CPT217 (**Error! Reference source not found.**b). Element size is also chosen carefully. When element size is increased the number of elements will decrease, resulting a lesser solution time. But with a less accuracy. to find out which mesh size gives an acceptable result mesh convergence test is done. Once the element size is selected then that size is further refined and modified using the Newton Raphson residuals. Newton Raphson residuals are force or displacement residuals of the nonlinear solution equilibrium iterations. If the residuals are more than the acceptable amount, the nonlinear solution will not converge. They are carefully observed to improve the solutions result. In the places where more residuals are present, finer meshes should be done to converge the solution. Places with high value of stresses and inappropriate contacts tend to have residuals, those places are refined with smaller mesh size in order for the solution to converge(*Figure 2-3*).

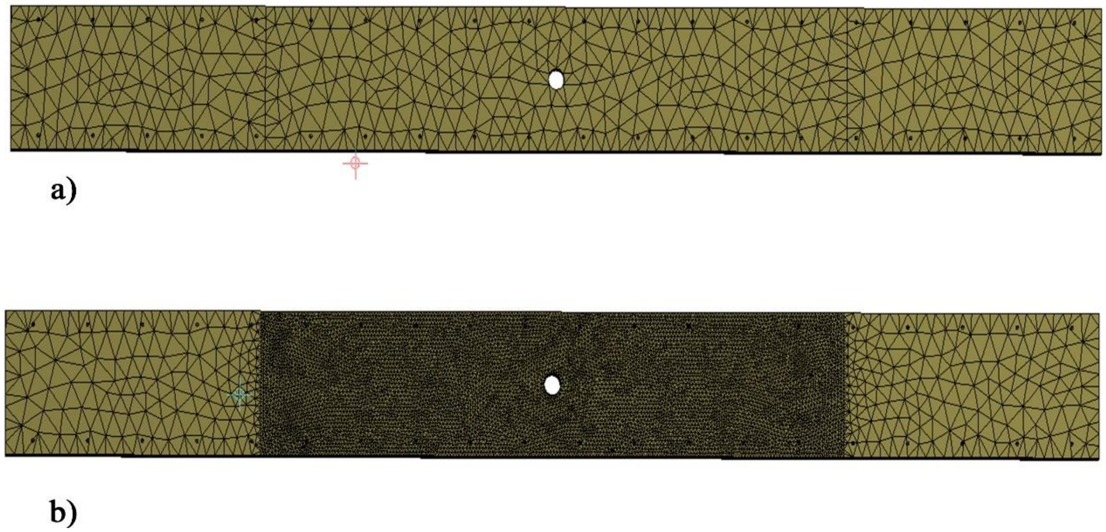

Figure 2-3. Mesh refinement, a) initial meshing & b) mesh refined using Newton Raphson residuals.

2.1.5. Loading

The concrete column models were tested for compressive strength and axial deformation. The load was induced as a constant displacement-controlled load of 6mm. The axal load was positioned on at the top face of the column. The load will be applied in a time-controlled manner using load steps. ANSYS will use an incremental load step value until the final load value is attained in the duration of a total 1 sec time (the time at the end of the load step).

2.1.6 Nonlinear Analysis

The nonlinear analysis is calculated using the Newton-Raphson procedure. This method is used to calculate the iterative solution in a good accuracy as long as the original estimation and boundary conditions are close to the true solution. The model's boundary conditions including loads are applied to the model gradually in substeps and the solutions is calculated after each substep.

2.2 Validation

Verification of the finite element analysis tool is necessary to make sure outputs of the analysis are able to estimate the actual results. Here in this section, two experimental data were chosen for the validation. The first one is full scale reinforced concrete column and the second one is large scale reinforced concrete columns.

2.2.1 Validation 1

The first experiment used for the validation study to verify the reliability of ANSYS is a reinforced concrete column tested by Antonio De Luca et al [3]. The experimental study was done on a full-scale concrete to evaluate FRP confined RC columns. In the

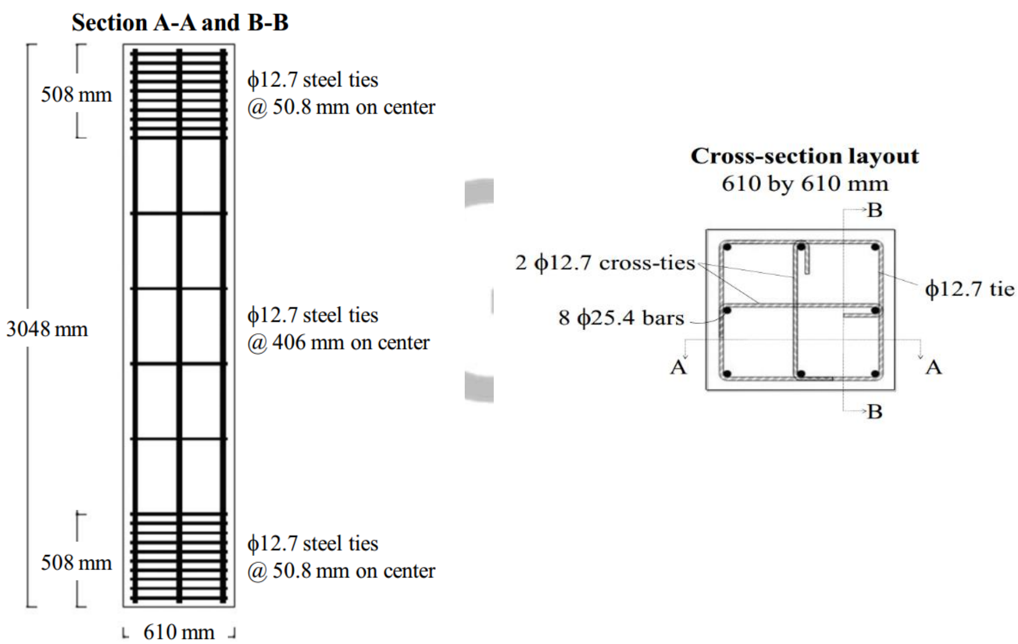

Figure .2-4, Geometry and Reinforcement detailing of the experimental column S1C [3]

experiment a total of 12 columns were tested by displacement controlled axial loading. LVDT sensors were used to monitor the results. The column chosen for the validation study named S1C is a control column for the experimental investigation conducted. The column's dimension and detailing are given in Figure .2-4.

The material used for the experiments are:

Concrete compressive strength $f'c = 37.3\ MPa$

Steel Reinforcement Bar (Gr 60) Yield Strength $fy = 420\ MPa$

The Finite Element Model of the column was done using ANSYS. A concentrated compressive load was applied in a displacement-controlled manner. The load was applied gradually using load substeps. The bottom column end was set with a fixed boundary condition. The Compressive axial stress vs axial deformation graph is plotted in *Figure 2-5*. The results are predicted with a good compliance, the maximum compressive axial stress is 29.50 MPa and 31.25MPa and the ultimate deformation was 9.84 mm and 8.638mm for the experimental and FEM respectively. The variation was 5.6% increment for the ultimate compressive stress and a 13.9 % increment in ultimate deformation.

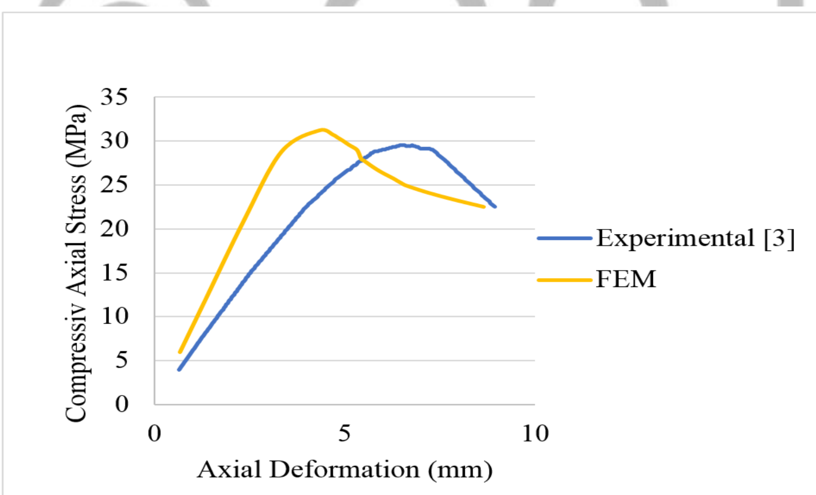

Figure 2-5 Axial stress vs axial deformation plot for column S1C (experimental and numerical).

2.2.2 Validation 2

The second experimental data chosen is an experiment conducted by G. Campione et al. [7], the experiment was done to study the effects of circular openings on the compressive behavior of RC columns. In the study the authors prepared two large scale series columns, A and B. Series A and B have different compressive strength classes 23MPa and 11.5MPa respectively. 497 MPa and 504MPa yield strength steel was used for the 8mm and 12 mm bars respectively. A total of twenty columns were tested experimentally under a compressive load. For the validation two columns were selected

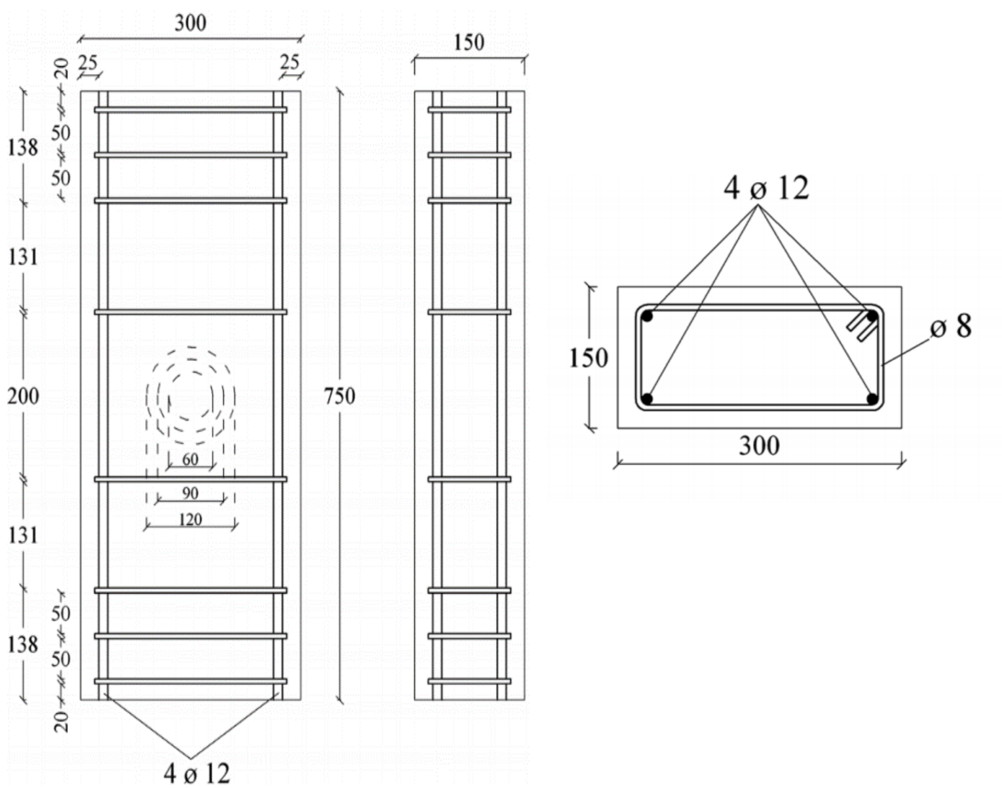

Figure 2-6, Geometry and reinforcement detail for Columns ARC01 and ARC1201. [7]

ARC01, & ARC1201. One solid and one with 120mm hole in the center. The dimension and reinforcement arrangement of the columns are given in Figure 2-6, Geometry and reinforcement detail for Columns ARC01 and ARC1201. [7]. The four selected column's nomenclature is. The columns were modeled and analyzed using the finite element method.

The columns were modeled with a fixed boundary condition at the bottom end and a displacement-controlled load applied with a load substep gradual application. The load carrying capacity values from the FEM method are given along with the experimental date in

Table 2-4, Results for column ARC01 and ARC120

Column	**Type**	**f'c (Mpa)**	**Ultimater Load Capcity (KN)**		**P_{fem}/P_{exp}**
			Experimental	FEM	
ARC01	solid	23	948.3	1111.06	1.17
ARC1201	120mm hole	23	663.5	742.8	1.12

The results for the ultimate load prediction comply for the experiment and numerical models. The maximum variation of the loads is 17% for the solid column, this may be because of the compressive strength data taken in the experiments may vary from specimen to specimen Since a number of tests are taken for the specimen and the average value is taken. Some degree of variation may come from the data taken.

2.3 Parametric Study

Parametric studies are often done by varying different input parameters of the model and studying the effects they have on the selected output parameters. Usually in a parametric study some variables are constraint and some variables are varying. Among the variables used for this research, there are some variables that were kept constant. The width, length and height of the column, the material properties and the boundary conditions were kept absolutely constant for all the varying parameters. The compressive strength of the models was investigated using the following parameters.

Key terms: Volume displaced (V_d)– is the volume voided by the hole/s. Vertical Position V_p – Center of holes measured from bottom end of column. Horizontal Position H_p – distance from the center of the hole/s measured from left edge of column.

1. Shape of the hole: models having different holes were considered, square and circular, position of the hole and volume displaced are kept constant.
2. Size of the hole: the size will be expressed using the diameter to width ratio (d/b) of 0.15b, 0.25b and 0.33b. where b is the width of the column (i.e. $b = 300\ mm$), volume displaced is kept constant.
3. Horizontal Position of holes: distance between center of the hole and the side edge of the column is varied as 0.33b and 0.5b. Vertical position, Volume displaced and diameter of hole are kept constant.
4. Vertical position of holes: distance between center of the hole and the upper edge of the column is varied as 0.25h and 0.75h, horizontal position, volume displaced and diameter of hole are kept constant
5. No of holes vertically positioned: two holes positioned with 0.33h c/c distance and three holes placed at the center of each third of the column (top, middle and bottom). Horizontal position, volume displaced are kept constant.
6. No of holes Horizontally positioned: a single hole with0.33b diameter and two holes with 0.167b diameter, Vertical position, and volume displaced are kept constant

A total of eleven models were prepared for the investigation. The nomenclature and specification of the models is given in *Table 2-5*. & Figure .3-14. The Control column CC1 is modeled with no opening. Most of the columns' hole diameter is related to column SC3's diameter $d = b/3 = 100mm$. Columns SC1 & SC2 have diameters of $d/3$, & $d/2$ respectively. In most of the columns except column SS1 since the volume displaced is kept constant the holes diameter has a relation with d. For example, for column NH1 the number of holes is 2, so the volume displaced will be equal to SC3 when the diameters of the two holes is $d/2$ each. (i.e. $2 * d/2 = d$). This also was applied to columns with 3 holes, column NV1 has three holes each with $d/3$ diameters. (where $d = 100mm$).

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Table 2-5. Parametric study models summary and specifications.

#	Name	Width (mm)	Lenth (mm)	Height (mm)	Diameter (mm)	Volume Displaced $[10^6](m^3)$	Vertical Position (mm)	Horizontal Position (mm)	Shape	Range (if vary)
1	CC1	300	300	3000	100	-	-	-	-	-
2	SS1	300	300	3000	-	0.48	1500	150	square	-
3	SC1	300	300	3000	45	0.85	1500	150	circular	-
4	SC2	300	300	3000	60	2.36	1500	150	circular	-
5	SC3	300	300	3000	100	2.36	1500	150	circular	-
6	HP1	300	300	3000	100	2.36	1500	200	circular	-
7	VP1	300	300	3000	100	2.36	500	150	circular	-
8	VP2	300	300	3000	100	2.36	2500	150	circular	-
9	NH1	300	300	3000	vary	2.36	1500	vary	circular	Hp = {100, 200} , d = 50, n = 2
10	NV1	300	300	3000	vary	2.36	vary	150	circular	Vp = {1000, 2000}, d = 50, n = 2
11	NV2	300	300							

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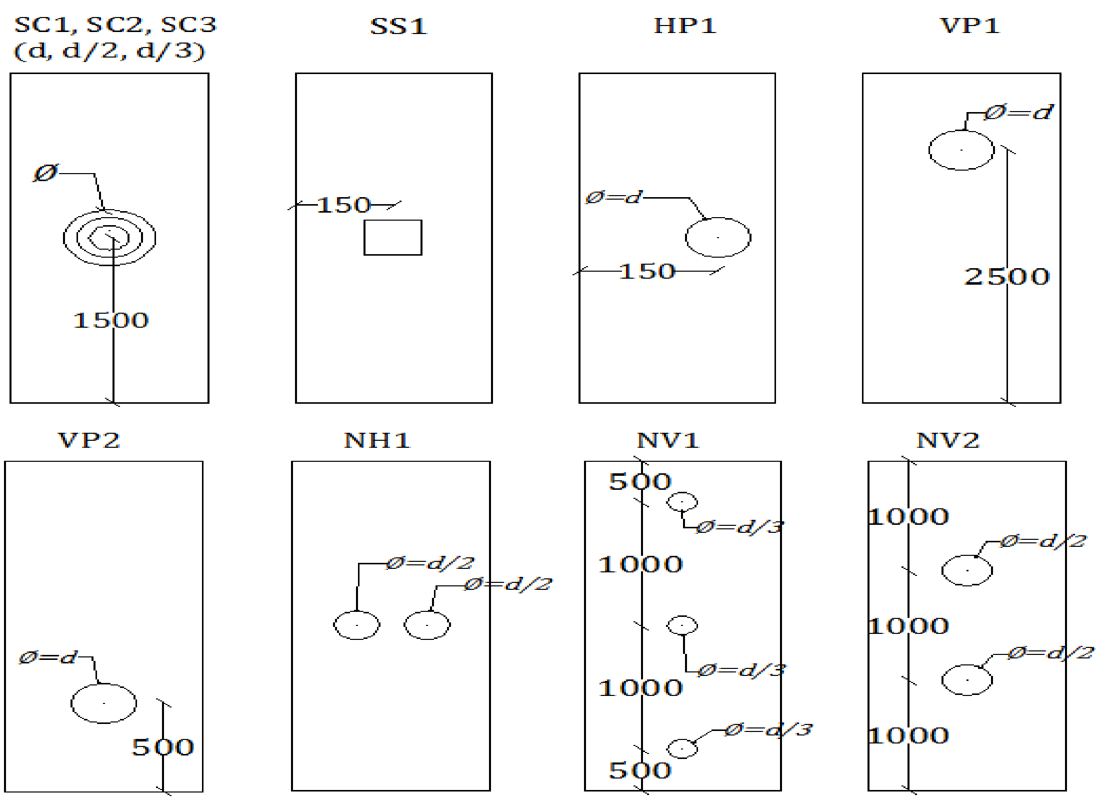

2.4 Strengthening Study

This section focuses on studying the possible options for strengthening the lost strength of a column by the transverse hole presence. This study conducts possible means for strengthening by not closing the hole. The extent of the region that was disturbed by the opening can be estimated by the St. Venant's Principle in which states the dispersion of the stress distribution will come to uniform distribution as the distance between the applied disturbance (hole) and cross-section examined is increased [9]. The main approach used in studying the strengthening of the columns is to gain the compressive strength capacity lost by the presence of the hole and to reduce the tensile force generated in the D region. Three options are investigated CFRP wrapping, Steel Casing and CFRP wrap plus steel casing.

Five models of reinforced concrete square columns with 300mm by 300mm by 3000mm with a circular hole in its center were prepared. Four columns were modeled with CFRP wrap b or 2b from the edge of the hole positioned both above or below of the hole. Two of them with 2 wraps and the other two with 3 wraps. The fifth and sixth model were modeled with a steel pipe inside the hole with and without CFRP wrapping respectively. The models are summarized in *Table 2-6*. The evaluation of the models will be done in comparison with C1 and SC3 models as a control from the parametric study.

All the columns were modeled in order to investigate the compressive strength behavior. A Constant displacement controlled gradual load provided from the top face and a fixed boundary condition modeled at the bottom end of the column. In the present study the contact between the CFRP and Concrete is assumed as bonded or no-separation. No slipand frictional behavior caused by the epoxy adhesive and both materials are not considered. Hence, the possible failure of the CFRP wrapped columns will be crushing of concrete, yielding of steel or rupture of the CFRP. Similarly, the contact between the steel casing and the concrete is also considered as bonded and no separation. The models all one hole with diameter d=100mm positioned vertically and horizontally in the center. And the CFRP wrap zone is considered in two conditions, b distance or $2b$ (where $b = 300mm$) distance from the outer edge of the hole. St. venant's principle suggests that the distribution dispersion will come to a uniform distribution after a member's depth [9]. The results will be used to check whether the principle holds.

Table 2-6, Strengthening study models summary and specifications.

	Name	Method	No of Wraps	Thickness of CFRP t_f (mm)	Wrap width
1	RCC1	CFRP	2	1.5	b (300mm)
2	RCC2	CFRP	3	1.5	b (300mm)
3	RCC3	CFRP	2	1.5	2b (600mm)
4	RCC4	CFRP	3	1.5	2b (600mm)
5	RSC1	Steel Casing	-	-	-
6	RSCC	CFRP + Steel Casing	3	1.5	b (300mm)

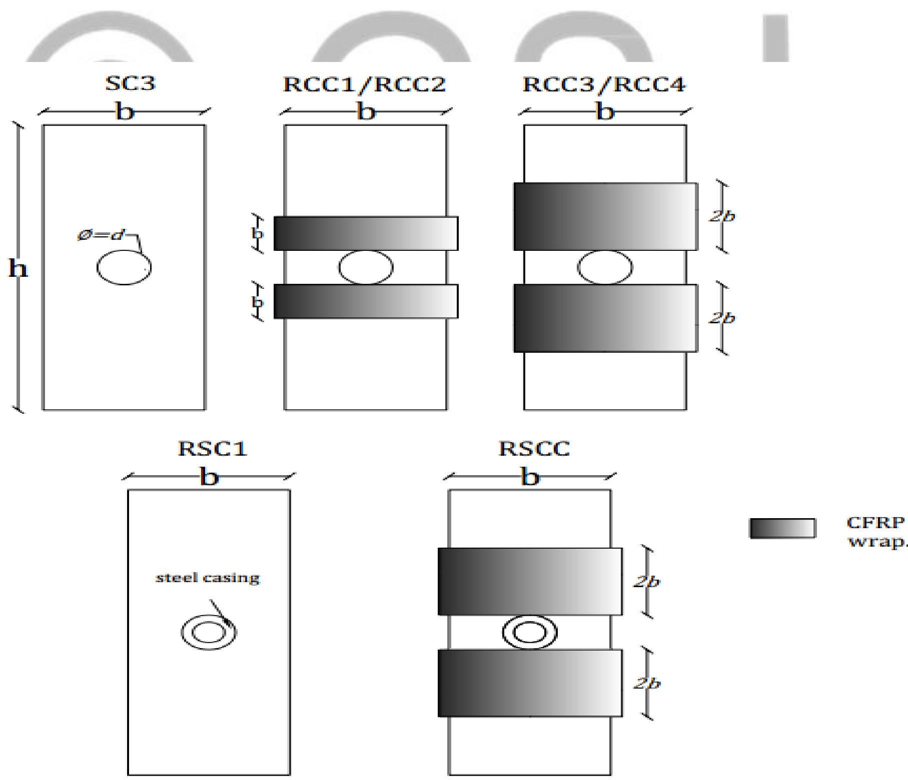

Figure 2-8. Model specification and detailing for the strengthening study.

CHAPTER 4

3. Analysis and Results

3.1 General

This chapter presents the results gotten from the parametric and strengthening studies done using finite element analysis. The parametric study was undertaken to investigate the arrangement of transverse holes and their effect on the load carrying capacity of the full-scale RC columns. The main parameters take in to consideration were shape, size, vertical & horizontal position, and number of holes. In relation to the parametric study, a strengthening study was undertaken to find out methods to get the lost strength back. The use of CFRP wraps and Steel casing is studied for strengthening.

Comparisons and discussions of results are made using axial stress vs axial deformation graphs and further explained using graphical out puts from the software.

3.2 Parametric study results.

The parameters studied in this section are explained in the previous chapter. Finite element analysis and simulation results of those parameters are discussed below.

3.2.1 Effect of shape of the hole.

In this part of the study the effect of change in shape of the hole is investigated. The parameter varied is shape. Three columns are compared, solid control column CC1, column with a central circular shaped hole SC3 and column with square shaped hole SS1. Both holes are placed in the vertical and horizontal center of the columns. Volume displaced (volume voided by the holes) is kept for both columns. Hence, the diameter of the circular hole on SC3 is 100mm and one side of the square shaped hole is 88.60 mm. The compressive axial stress versus axial deformation graph is given in Figure 4-1.

Table 3-1. Results for the parameter - shape of hole. SS1, SC3 and CC1.

Name	Shape	Maximum Axial Stress (Mpa) σ_{max}	Maximum Load (KN) P_{max}	$P_{max}/P_{max,cont}$	Deformation at Peak load (mm) Δ_p	Load Capacity Variation (%)
CC1	Control (Solid)	31.285	2815.65	1.00	4.3	-
SS1	Circular	22.441	2019.69	0.72	2.54	-28.27
SC3	Square	20.661	1859.49	0.66	2.41	-33.96

The presence of a hole in both models significantly decreased the load carrying capacity. For both models SC3 and SS1 the reduction in load carrying capacity is 28.27% and 33.96% respectively. The square shaped hole caused a 5.69% more capacity reduction than the circular shaped hole.

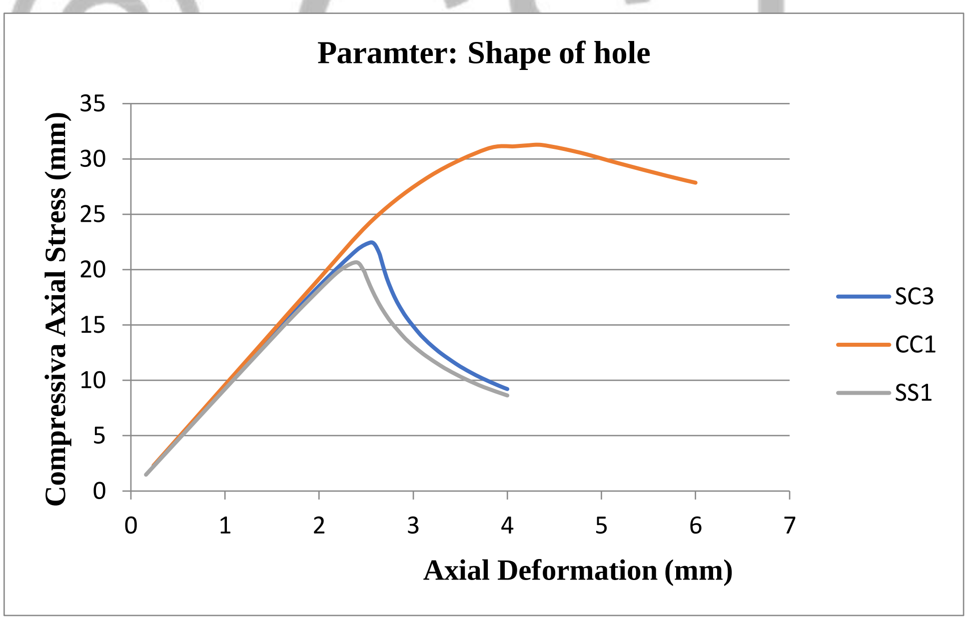

Figure 3-1. Compressive axial stress vs Axial deformation graph for SS1, SC3 and CC1.

3.2.2 Effect of change of size of hole.

Here the investigated parameter is the size of the hole. Three diameters were considered in relation to the width of the column. 33.33, 20 and 15 percent of the width of the column was taken as the diameter for three columns. Hence, three holes with 100mm, 60mm and 45 mm diameter were introduced in the columns SC3, SC2 and SC1 respectively. In this section, the change of volume displace can be investigated. The vertical and horizontal positions of the holes in all three columns is kept constant: at the center of the column. The compressive axial stress versus axial deformation graph is given in *Figure 3-2*.

Table 3-2, Results for the parameter - Size of hole. CC1, SC1, SC2 and SC3.

Name	Volume Displaced [10^6] (mm^3)	Maximum Axial Stress (Mpa) σ_{max}	Maximum Load (KN) P_{max}	$\frac{Pmax}{Pmax,cont}$	Δ_{peak} (mm)	Maximum Load Variation (%)
CC1	0	31.285	2815.65	1.00	4.3	-
SC1	0.47688	28.648	2578.32	0.92	3.35	-8.43
SC2	0.8478	25.998	2339.82	0.83	3.02	-16.90
SC3	2.355	22.441	2019.69	0.72	2.54	-28.27

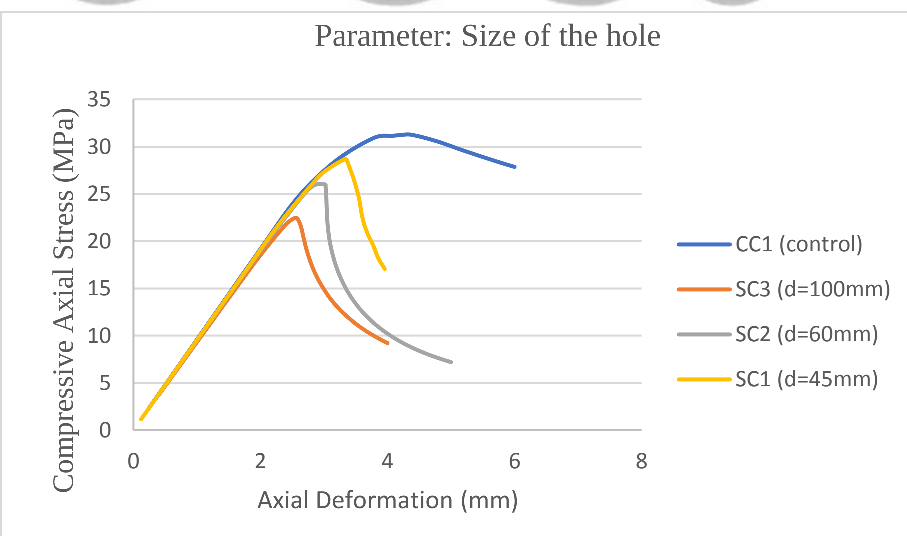

Figure 3-2. Compressive axial stress vs Axial deformation graph for SC1, SC2, SC3 and CC1

The three columns performed in load carrying capacity with a reduction directly related with the increasing diameter of the hole. Columns SC1, SC2 and SC3 showed a reduction in load carrying capacity of 8.43%, 16.9% and 28.27% respectively. The behavior of columns with holes related to the volume displaced is seen here. The linear representation of the relation of axial capacity reduction with the volume displaced is shown in Figure 3-3.

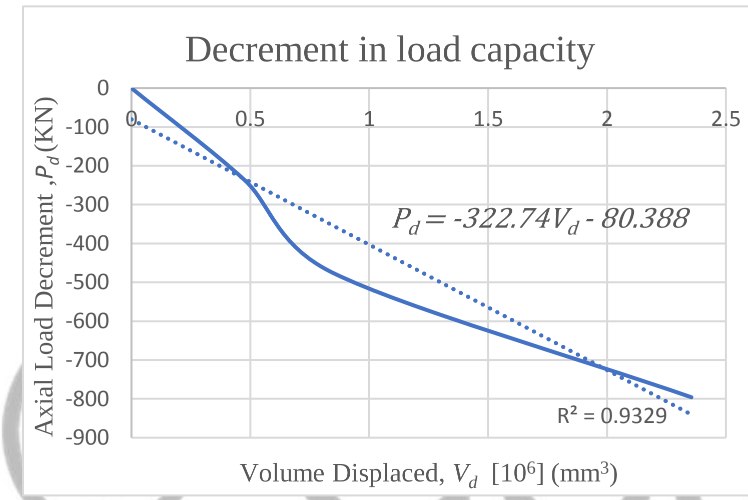

Figure 3-3. Volume displaced vs Axial Load Decrement

Comparisons of the results found in this study were validated using the normalized axial ultimate force and depth to weight ratio relationship given by [7]. *Figure 3-4* shows the plot of the results of this study with the values given by [7] and the alignment of the result of this study. Based on the validated results of this study, the load reduction capacity (P_d) of a column with a central hole of diameter d can be estimated using the following formula (1):

$$P_d = -322.74V_d - 80.388 \quad (1)$$

Where V_d *is the* volume displaced by the hole in 10^6mm^3, and $d/b < 1/3$

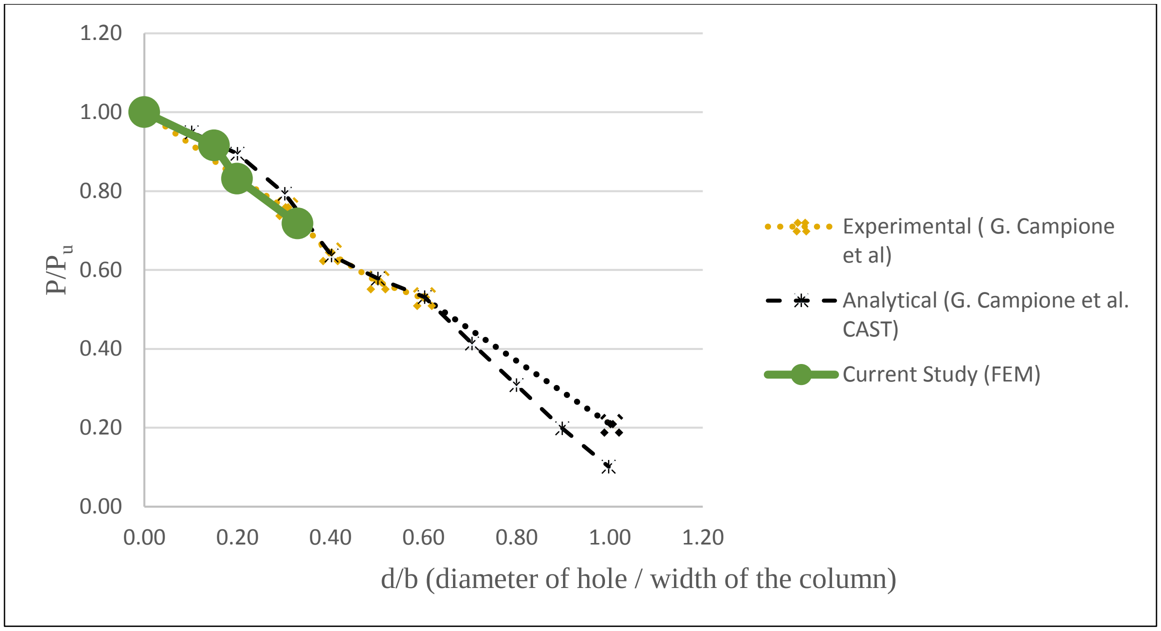

Figure 3-4, Variation off the normalized axial capacity with the hole diameter to width of column ratio, plotted with experimental and analytical data from [7].

3.2.3 Effect of change of Horizontal Position

In this section the effect of horizontal position Hp is investigated. Two conditions were considered when Hp (the distance from the left edge of the column to the center of the column) 0.5b and 0.67b (where b is the width of the column, 300mm). The Hp for column HP1 and SC3 is 150mm and 200mm respectively. The performance of the two columns against the compressive displacement-controlled load is observed and compared against the control column's (CC1) performance. The compressive axial stress versus axial deformation graph is given in *Figure 3-5*.

Table 3-3. Results for parameter - Horizontal position Hp

Name	**Hp**	**Maximum Axial Stress (Mpa) σ_{max}**	**Maximum Load (KN) P_{max}**	$\frac{Pmax}{Pmax, cont}$	**Δ_{peak} (mm)**	**Load Capacity Variation (%)**
CC1	-	31.285	2815.65	1.00	4.3	-
SS1	150	22.441	2019.69	0.72	2.54	-28.27
HP1	200	20.898	1880.82	0.67	2.41	-33.20

Column HP1 showed a 33.20% reduction in Axial load capacity. Which is 4.93% lower performance than the column with a center hole SC3. When the hole is placed 50mm away and near (to the left column edge) from the center the a 6.88% less performance is observed.

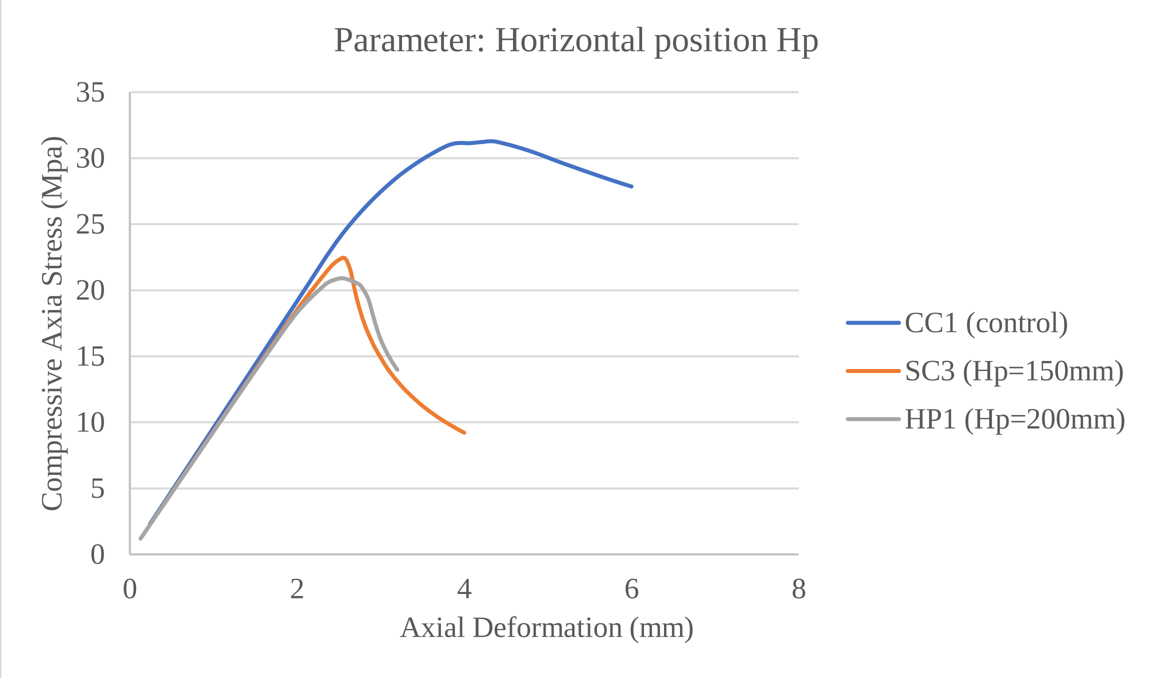

Figure 3-5. Compressive axial stress vs Axial deformation graph for HP1,SC3 and CC1

3.2.4 Effect of change of Vertical Position

In this case, the effect investigated is the vertical position of the hole keeping it horizontally in the center (Hp =150). Three models were prepared with different position of the hole vertically measured from the bottom end of the column (Vp). Three positions are investigated, 50mm, 1500mm and 2500mm. The positions are chosen in order to place the holes in the top, middle and bottom third of a column. The diameter of the hole, the volume displaced and horizontal position (Hp) are kept the same for all three models. VP1, VP2 and SC3's performance under a compressive load is compared with the solid control column using axial stress vs axial deformation plot.

Table 3-4, Results for parameter - Vertical position Vp

Name	Vertical Position Vp	Maximum Axial Stress (Mpa) σ_{max}	Maximum Load (KN) P_{max}	$\frac{Pmax}{Pmax,cont}$	Δ_{peak} (mm)	Load Capacity Variation (%)
CC1	-	31.285	2815.65	1.00	4.3	-
VP1	500	22.318	2008.62	0.71	2.58	-28.66
SC3	1500	22.441	2019.69	0.72	2.54	-28.27
VP2	2500	22.392	2015.28	0.72	2.53	-28.43

Varying the position of a hole vertically in the center of the top, middle and bottom third of a column produced an approximately the same performance of 25% capacity reduction (from the control). But the effect of the vertical position produced insignificant difference between the three columns. The deformation at which the peak load occurs (Δ_p) is also approximately the same (~2.55mm).

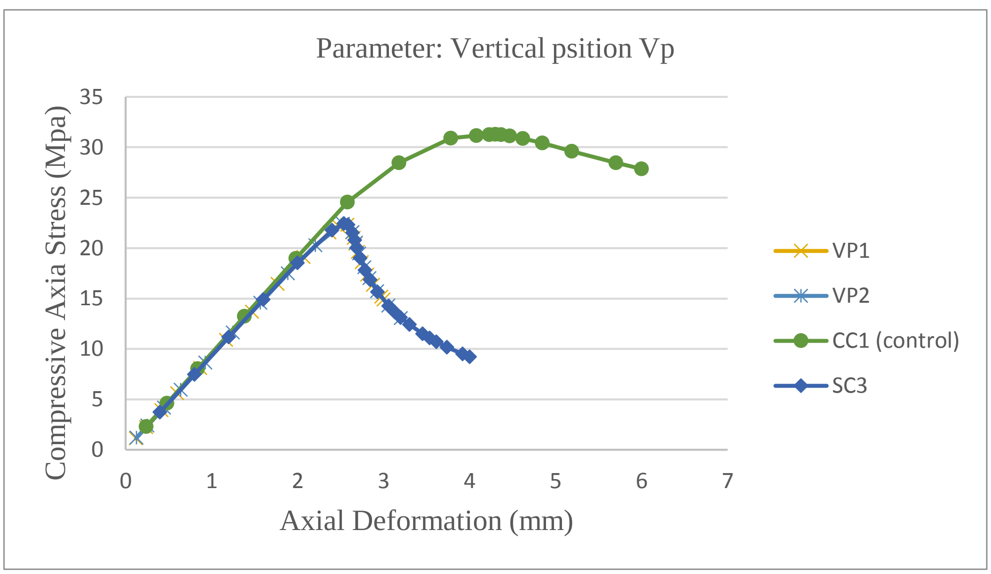

Figure 3-6. Compressive axial stress vs Axial deformation graph for VP1, VP2, SC3 and CC1

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3.2.5. Effect of Number of holes – Horizontal

In this part, to study the effect of number of holes on the columns two models were prepared. Column NH1 with two holes with 50mm diameter for each and column SC3 with a 100mm diameter were analyzed. In this analysis volume displaced, horizontal and vertical position are kept the same. The models' performance was investigated and compared with the control column CC1.

Table 3-5, Results for parameter - Horizontal number of holes. SC3, CC1 & NH1

Name	**Number of holes**	**Maximum Axial Stress (Mpa) σ_{max}**	**Maximum Load (KN) P_{max}**	$\frac{Pmax}{Pmax,cont}$	**Δ_{peak} (mm)**	**Maximum Load Variation (%)**
CC1	0	31.285	2815.65	1.00	4.3	-
SC3	1	22.441	2019.69	0.72	2.54	-28.27
NH1	2	25.632	2306.88	0.82	2.91	-18.07

Column NH1 has two holes placed in the center vertically and horizontally as shown in Figure 3.10. It performed significantly better than one holed column SC3; more than 10% increase in load carrying capacity.

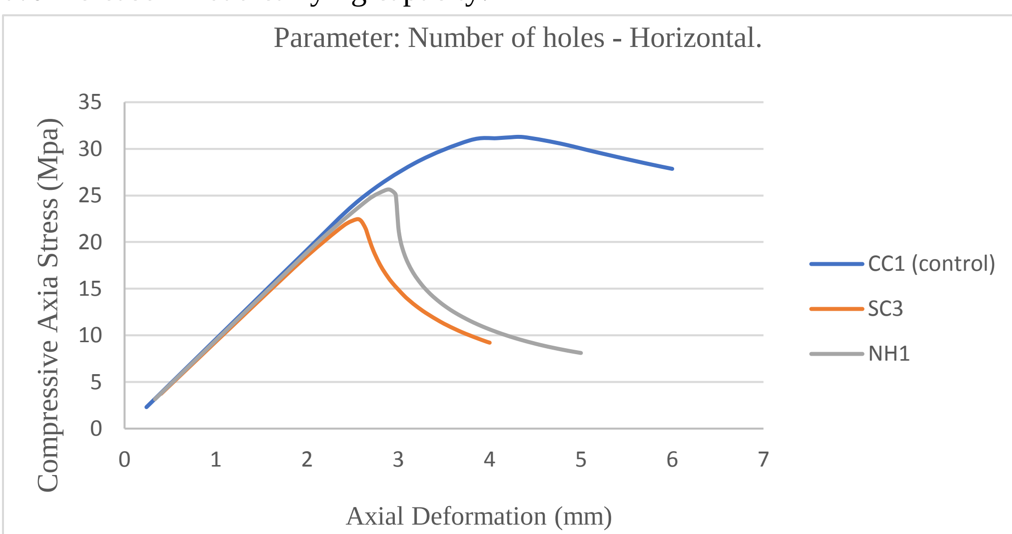

Figure 3-7. Compressive axial stress vs Axial deformation graph for CC1, NH1 and SC3.

3.2.6. Effect of Number of Holes – Vertical

In this investigation, three number of holes arrangement was studied. Columns SC3, VP1 and VP3 are modeled with 3 (d = 33.33mm each), 2 (d = 50mm each) and 1 (d = 100mm) holes respectively. The volume displaced are kept the same for all three columns. Horizontally the columns were put on the center line of the column. The response of the columns against compressive load is depicted in *Figure 3-7* .

Table 3-6, Results for parameter - Vertical number of holes. CC1, SC3, NV1 & NV2

Name	**Number of holes**	**Maximum Axial Stress (Mpa) σ_{max}**	**Maximum Load (KN) P_{max}**	$\frac{Pmax}{Pmax, cont}$	**Δ_{peak} (mm)**	**Maximum Load Variation (%)**
CC1	0	31.285	2815.65	1.00	4.3	-
SC3	1	22.441	2019.69	0.72	2.54	-28.27
NV1	2	28.235	2541.15	0.90	3.41	-9.75
NV2	3	29.785	2680.65	0.95	3.8	-4.79

The arrangements of holes in the above columns is shown in Figure .3-14 Model specification and details for parametric study. Note: d = diameter (varies) h = 3000mm and b=300mm. Columns NV1 and NV2 had a maximum load of 2541.15 KN and 2680.65 KN respectively. Both columns performed relatively well compare to the one holed column SC3. In relative to SC3 a 18.52% and 23.48% increment in load carrying capacity was seen for NV1 and NV2 respectively. Specially NV2 showed a very significant performance. Indicating that for equal amount of volume displaced, more number of holes should be provided vertically instead of one.

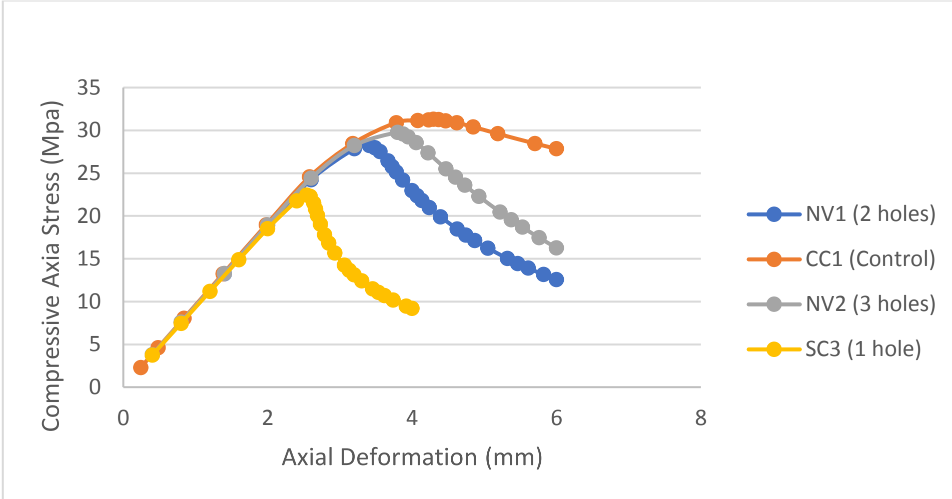

Figure 3-8 Compressive axial stress vs Axial deformation graph for SC3, NV1, NV2 and CC1.

3.2.6 Summary of the Parametric Study

Generalizing the parametric study, finite element analysis was conducted on the effects of shape, size, horizontal position, vertical position & number (vertical & horizontal) of transverse holes on RC columns.

In the whole study considering all the parameters, the column with the worst performance happened when placing the hole away from the center (HP1). Another consistent behavior seen is for columns with the same amount of volume displaced; providing more number of holes performed better than a single hole (NV1, NV2 and NH1). A direct relationship between peak deformation and load carrying capacity was also noticed.

Table 3-7, Parametric Study Result Summary.

#	Name	V_d , Hp, Vp, n	Maximum Axial Stress (Mpa) σ_{max}	Maximum Load (KN) P_{max}	$\frac{Pmax}{Pmax, cont}$	Δ_{peak} (mm)	Maximum Load Variation (%)
1	CC1	-	31.285	2815.65	1.00	4.30	-
2	SC1	0.47688 (V_d)	28.648	2578.32	0.92	3.35	-8.43
3	SC2	0.8478 (V_d)	25.998	2339.82	0.83	3.02	-16.90
4	SC3	2.355 (V_d)	22.441	2019.69	0.72	2.54	-28.27
5	SS1	2.355	20.661	1859.49	0.66	2.41	-33.96
6	HP1	200 (Hp)	20.898	1880.82	0.67	2.41	-33.20
7	VP1	500 (Vp)	22.318	2008.62	0.71	2.58	-28.66
8	VP2	2500 (Vp)	22.392	2015.28	0.72	2.53	-28.43
9	NH1	2 (n)	25.632	2306.88	0.82	2.91	-18.07
10	NV1	2 (n)	28.235	2541.15	0.90	3.41	-9.75
11	NV2	3 (n)	29.785	2680.65	0.95	3.8	-4.79

Note: V_d: volume displaced in (106 mm3), Vp: vertical position, Hp: Horizontal position and n: number of holes

3.3 Strengthening study

In this section, to meet the objective of this research a strengthening study was conducted. Means of restoring lost strength of a column with a circular hole (SC3, d=b/3) is investigated. The use of CFRP wrapping in the reduction effect of the tensile splitting force is mainly studied [8]. The other method investigated is the use of steel casing firmly placed inside the hole in the column. The use of combined CFRP wrap and steel casing is also one of the options considered. A total of 6 models were constructed to study the effects. The models were analyzed under a compressive displacement-controlled load and a fixed boundary condition at the bottom end of the column. Compressive strength capacity of the columns was carefully observed. The summary of results of the columns is given in *Table 3-8*.

Table 3-8, Results summary for the strengthening study.

	Model	Method	Maximum Axial Stress (Mpa) σ_{max}	Maximum Load (KN) P_{max}	$\frac{Pmax}{Pmax,cont}$	Δ_{peak} (mm)	Maximum Load Variation (%) [from control]	Load Increment % [from SC3]
1	CC1	control	31.285	2815.65	1.0000	4.30	-	
2	SC3	none	22.441	2019.69	0.7173	2.54	-28.27	0.00
3	RCC1	CFRP (b width, 2 wraps)	26.021	2341.89	0.8317	3.02	-16.83	15.95
4	RCC2	CFRP(b width, 3 wraps	26.796	2411.64	0.8565	3.13	-14.35	19.41
5	RCC3	CFRP (2b width, 2 wraps)	26.295	2366.55	0.8405	3.02	-15.95	17.17
6	RCC4	CFRP (2b width, 3 wraps)	27.308	2457.72	0.8729	3.02	-12.71	21.69
7	RSC1	Steel Casing	27.063	2435.67	0.8650	3.13	-13.50	20.60
8	RSCC	CFRP + Steel Casing	31.218	2809.62	0.9979	4.005	-0.21	39.11

Note: b = column width ($300mm$), diameter of the hole $d = b/3 = 100mm$.

The methods included in the investigation are designed in ways avoiding the closure of the hole, this is to allow for strengthening of columns when holes are introduced for utility lines and architectural needs.

RCC1 & RCC2

Figure 4.9. plots the concrete axial stress with respect to axial deformation of RCC1 and RCC2 strengthening study. Both columns performed with a load carrying capacity increase of 15.95% and 19.41% when compared to the drilled column SC3. The maximum load occurred at the same deformation for both models. Although the columns had a significant rise in load carrying capacity, the models still had 16.83% and 14.35% load carrying difference from the control solid column CC1.

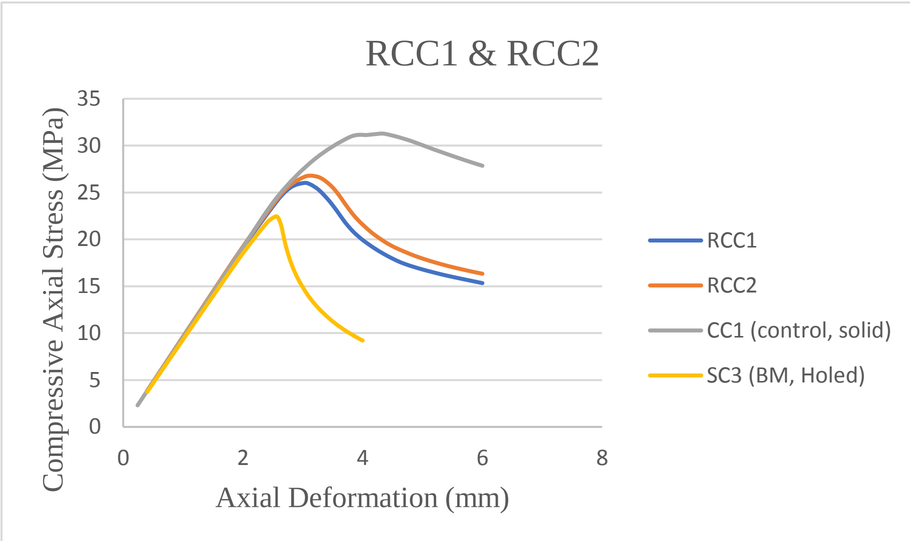

Figure 3-9.Compressive Axial stress vs Axial deformation plot for columns RCC1 and RCC2.

RCC3 & RCC4

The width of the wrap of the models RCC3 and RCC4 is twice of the wrap with in RCC1 and RCC2. The increment in wrap area gave an insignificant in the load capacity performance of the columns, only an average of 1.8% increase (for both columns). The

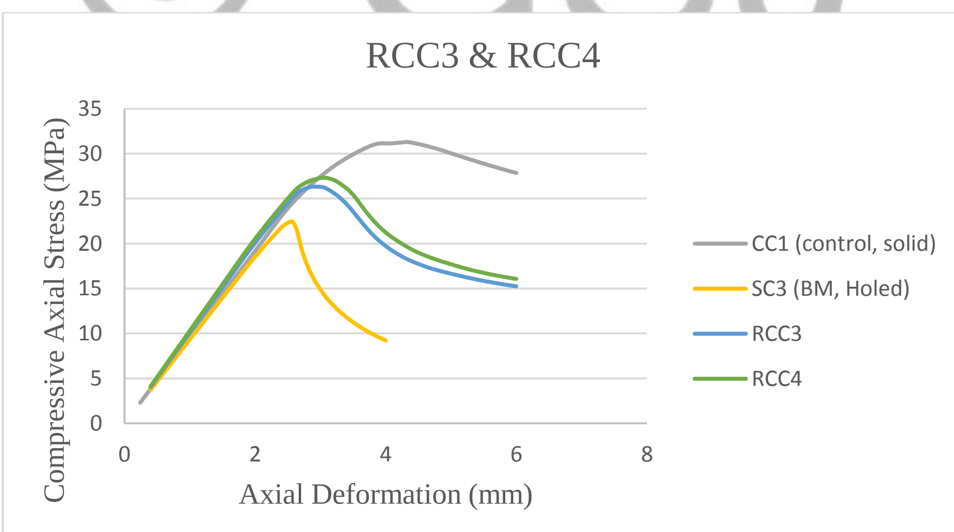

Figure 3-10, Compressive Axial stress vs Axial deformation plot for columns RCC3 and RCC4.

factors contributing to this maybe the applicability of St. Venant's principle. Since the width of the wrap is more than the width of the disturbed (D) region, its efficiency may have decreased simply because the tensile stress developed may have come to a uniform distribution. The stress vs deformation plot of the two columns is plotted in *Figure 3-10*.

RSC1 & RSCC

The behavior of the holed column with a steel casing (L-80) inside is shown in *Figure 3-11*. The results are as significant as the CFRP wrapped models. RSC1 had a 20.60% improved load carrying capacity compared to the bench mark SC3. The Compressive axial stress at the end of the load is though smaller than the CFRP wrapped columns. This is mainly because of the deformation enhancement of the CFRP on the columns. RSCC is the CFRP wrapped version of RSC1, wrapped with three wraps and b $(300mm)$ width from the edge of the hole (above and down). The most conspicuous result in the strengthening study is the performance of RSCC. A 39.11 % increment in maximum load carrying capacity compared to S13. Only 0.02% down from the control columns performance. However, only 26.55% of the compressive axial stress (control) at the end of the applied load is noticed. This indicates that past the elasticity and maximum load limit RSCC's behavior is very different from the control. As shown in *Figure 3-11* the slope of the plasticity zone is very steep.

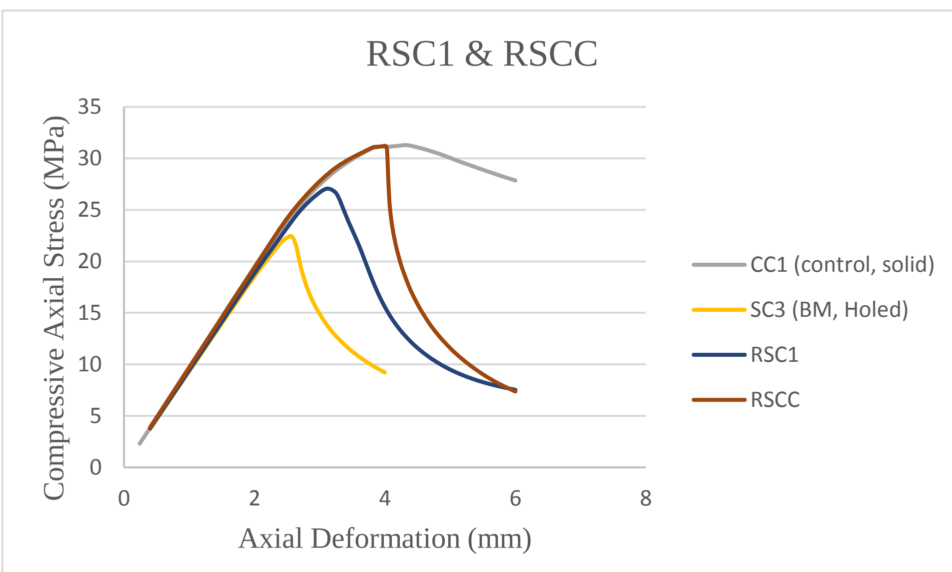

Figure 3-11, Compressive Axial stress vs Axial deformation plot for columns RSC1 and RSCC.

3.4. Stress Analysis of Models.

For SS1 the stress vectors are uniform except around the opening. On the other hand For SS1 the tensile stressed become propagated when it comes near to the opening; this is the result of the presence of the hole disturbing the uniform distribution of compression. The elements around the hole are experiencing tensile stresses. This state of stress decreases as it goes away from the hole (disturbance).

The stress tensors spread through the extent of the disturbed region. To find out the extent of the disturbed region, the isosurface of the stresses along the transverse direction are carefully studied (Figure 3-12b&c). At the time of maximum loading the stress distribution along the two transverse axes is shown in Figure 3-12d. Measurements made proofed that the extent of the tensile stresses is within 300mm (width of the column) from the center of the hole (disturbance). This has showed that St Venant's Principle "the disturbed stress distribution of a member will come to a uniform distribution after one-member depth from point of disturbance" holds.

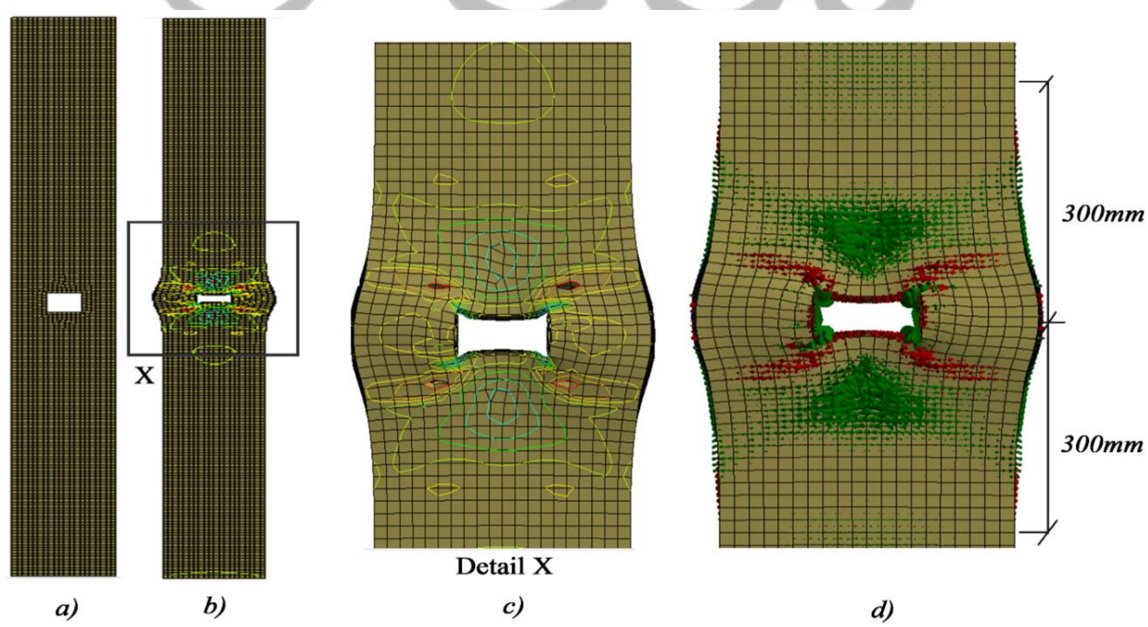

Figure 3-12, column SS1, a) undeformed b) deformed with isosurface plot c) isosurface contour plot around the hole and d) transverse stress tensors extent.

3.5 Plastic Strain Analysis

Plastic strains are strains that occur once the material goes past the elastically linear state. And areas where plastic strain occur, show permanent deformation or worse (damage). In concrete structures plastic strains happen in areas high stress accumulation. Permanent deformations in concrete may indicate cracking of the concrete happening. In Figure 3-13 the equivalent plastic strain versus deformation graphs for column SC3, CC1 & NV2 are plotted. The plot shows the deformation at which the plastic strain started rising and hence concrete cracking. For column with 100mm diameter in the center (SC3) a deformation of about 2.5mm had initiated the proliferation of the plastic strains leading up to a maximum of 0.069 mm/mm plastic strain. Compared to the control columns 0.0029 mm/mm maximum plastic strain its very pronounced. However, most of the strain is concentrated around the hole as seen in Figure 3-14.

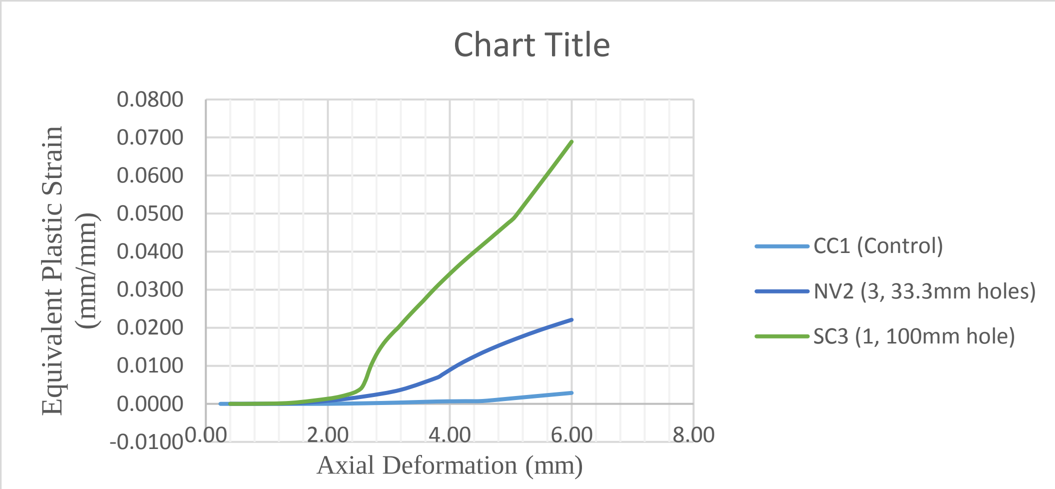

Figure 3-13, Equivalent Plastic Strain vs Axial Deformation for SC3, CC1 & NV2.

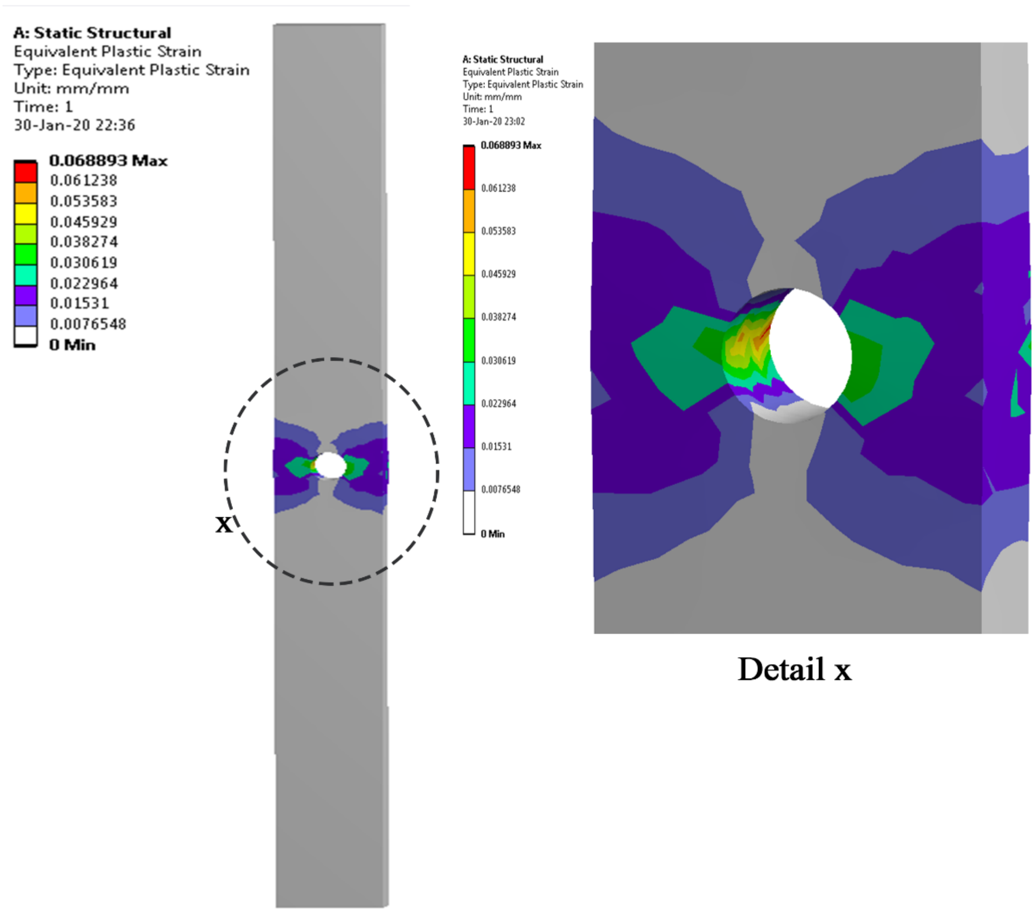

Figure 3-14, Equivalent plastic strain for SC3

The highest plastic strain values are concentrated around the hole, and specifically inside the hole left and right. This indicates that the maximum damage and cracking will start from the side walls of the hole. The maximum strain values will then spread more to the side ways. For a constant volume displaced, providing more number of holes was found to be good in load carrying performance (NV2). That has also been observed in plastic strain values, the maximum for NV2 is 32% less than for SC3.

3.6. Effect of CFRP on Plastic strain

The CFRP jacketing was done in two different width of wraps b and 2b from the edge of the hole. The effectiveness of the strengthening method can also be evaluated by how much damage and plastic deformations decreased. In figure** the plastic strain vs deformation plots of the columns SC3 (100mm hole), RCC1 (CFRP, 2 wraps) and RSC1 (CFRP + Steel Casing) are given.

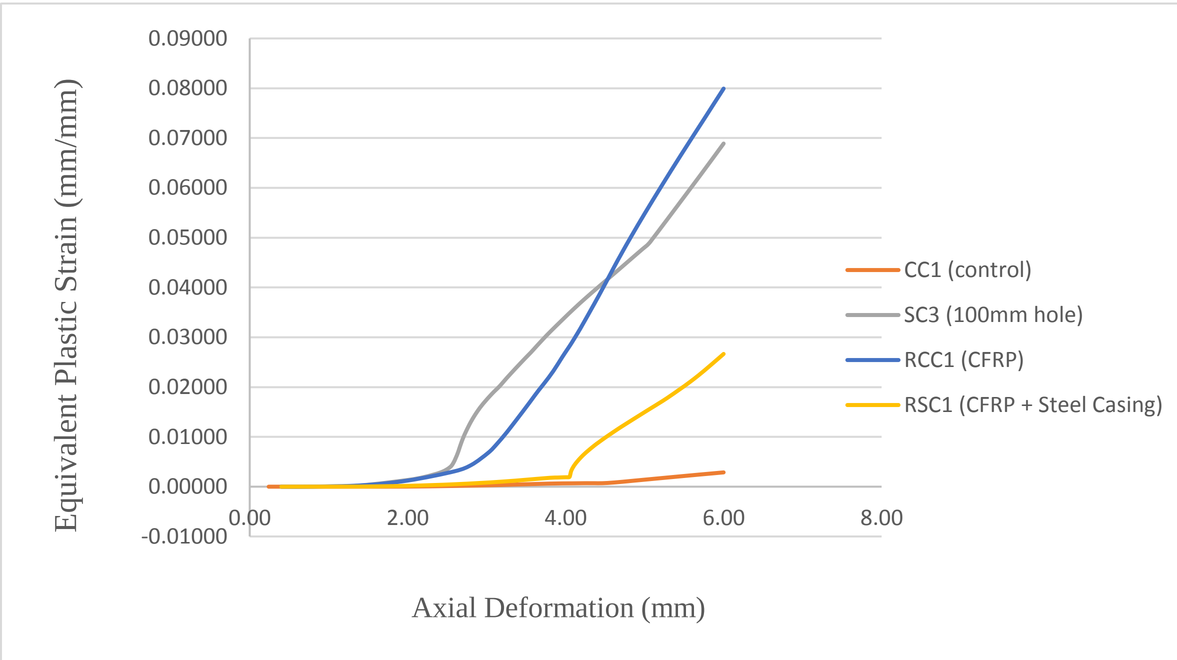

Figure 3-15, Equivalent plastic strain vs Axial Deformation plot for CC1, SC3, RCC1 & RSC1

When a method increases the load carrying capacity of the column; although expected, doesn't usually the reduce the highest strain values. RCC1 has increased the load carrying capacity of column SC3 by 15.97% but the maximum equivalent plastic strain value is higher than SC3. This may be because the confining effect of the CFRP has only concentrated the strains to smaller place. However, the CFRP wrapping in RCC1 has reduced the extent of the plastic strain in to a smaller area Figure 3-16. The most significant performance from the strengthening study (RSC1) was also evaluated for the plastic strain performance. As indicated in Figure 3-15, the maximum plastic strain value has been reduced by 39.02% when compared to SC3 (unstrengthened). But the most interesting result was the plastic strain concentration around the hole has almost been prevented in RSC1 completely, and the plastic strains measured are found near the bottom end of the column. In Figure 3-16 the progress of the unstrengthened column's plastic strain by the two methods in column (SC3, RCC1 and RSC1) is shown, the location of the plastic strain on column RSC1 is indicated.

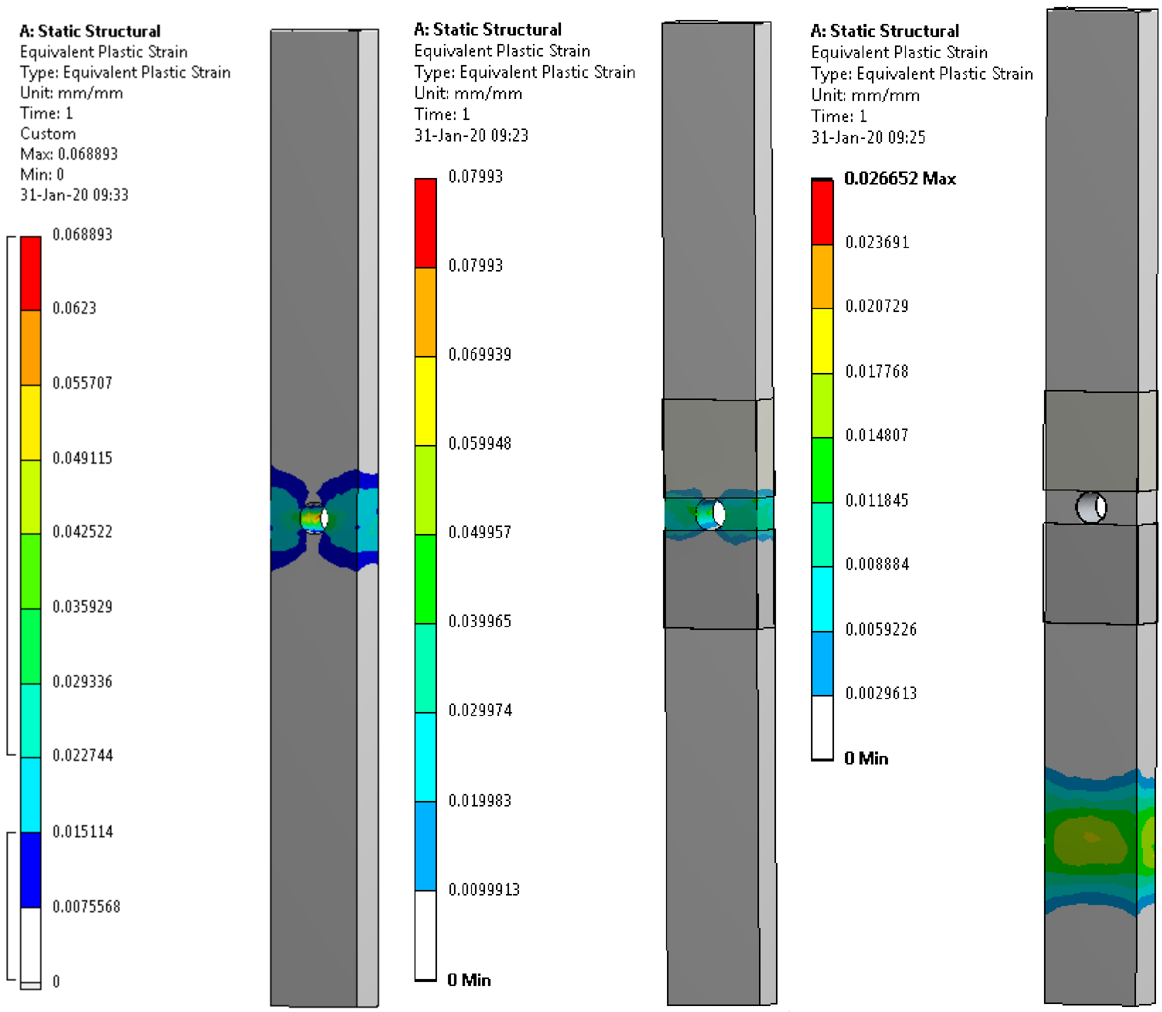

Figure 3-16, Equivalent Plastic Strain Plot of columns SC3, RCC1 & RSC1 (from left to right).

3.7. Comparison of FEM with Analytical

In this part of the study results gotten from the finite element method are estimated using empirical formulas and analytical methods. To analyze our concrete column as an axially loaded short column, the slenderness check given by ACI was done [1,9].

$$P_u = 0.85f'_c(A_g - A_{st}) + f_y A_{st} \tag{2}$$

Where P_u is the ultimate load, $0.85f'_c$ is 85% of the compressive strength of the concrete, A_g is the gross area of the section , f_y is yield strength of the steel and A_{st} is the area of the steel bars in the section.

However, this method is not applicable to the columns with holes. because of the stress disturbance because of the holes. A few studies are available that propose methods of estimation of ultimate load carrying capacity of columns with holes. In this analysis, the strut and tie model (STM) proposed by [8] was used in order to find analytical prediction of the finite element results Based on the models proposed by [8] a realistic prediction method was elaborated by [7]. The strut and tie model as seen in Figure 3-17 consists of four struts and one tie in the geometry. The two struts above are inclined in an angle α to the normal axis.

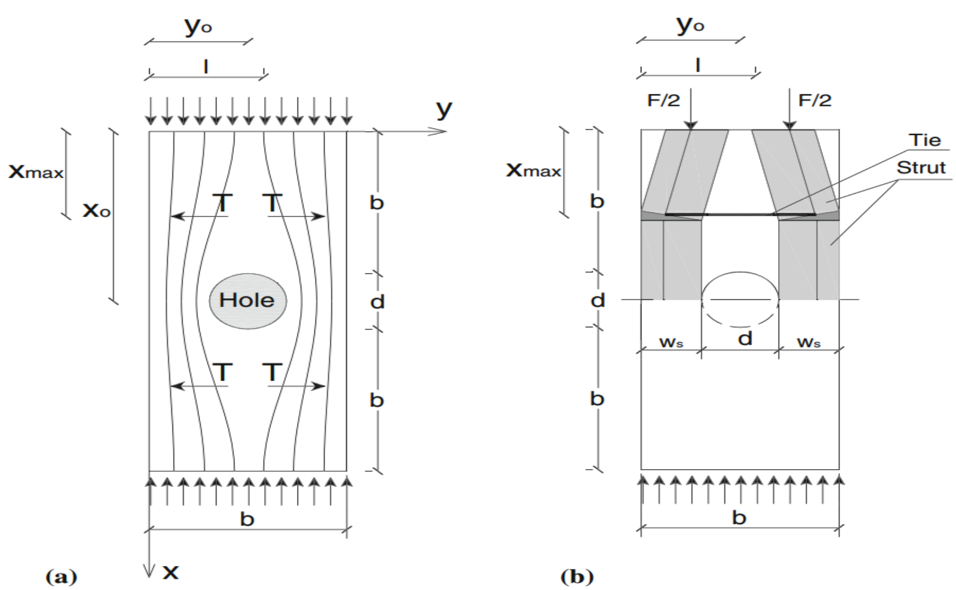

Figure 3-17, Strut and Tie Model idealization and geometry [7,8]

The control column in this study CC1 was analyzed using the ultimate load carrying capacity calculation given by ACI [1,9]. However, the columns with transverse holes are analyzed using Strut and tie method (STM). All the columns with holes are analyzed using the STM procedures explained in section **Error! Reference source not found.**. The ultimate load carrying capacity results are given in Table 3-9.

Table 3-9, Ultimate load capacity results FEM and Analytical

Column	Method	Ultimate Load Capacity (KN)		Variation %
		FEM	Analytical	
CC1	Empirical formula	2815.65	2870.06	1.9
SC1	Strut and Tie	2578.32	2593.95	0.6
SC2	Strut and Tie	2339.82	2375.986	1.5
SC3	Strut and Tie	2019.69	1980.07	-2.0
SS1	Strut and Tie	1859.49	2092.871	12.6
HP1	Strut and Tie	1880.82	1485	-21.0
VP1	Strut and Tie	2008.62	1980.07	-1.4
VP2	Strut and Tie	2015.28	1980.07	-1.7
NV1	Strut and Tie	2541.15	2475	-2.6
NV2	Strut and Tie	2680.65	2640.033	-1.5
NH1	Strut and Tie	2306.88	1980.99	-14.1

The analytical results are in good comply with the finite element results. The empirical formula predicted the ultimate capacity with a slight 1.9% increment. Among the columns analyzed using the STM, most of them are in good conformance. The maximum variation happened with HP1 and NH1 with 21 % and 14.1 % reduction, this variation may come from as the analytical strut and tie method is a lower bound plasticity theory and since it predicts the minimum load of the plastic deformation.

CHAPTER 5

4. Conclusion and Recommendation

4.1 Conclusions.

This investigation was done to study the behavior of full-scale reinforced concrete columns with transverse holes. Finite element method was used to analyze the reinforced concrete columns. The effects of different parameters of the transverse holes on the columns' load carrying capacity are mainly studied. This paper has also undertaken evaluation of means of restoring the lost strength of a column with transverse hole. In summary the following conclusions have been made:

- As the volume displaced by the hole increases the load carrying capacity also decreases significantly. For columns with circular holes in the center and diameter to column width ratio (d/b) less than 1/3, decrement of ultimate load capacity with the volume displaced can linearly be estimated by the proposed formula.
- Providing more number of holes instead of just one, has less impact in load carrying capacity for a constant volume displaced. Horizontally two holes created a 10% less load reduction. And vertically as the no of holes provided increased the load reduction seemed to decrease compared to a single holed column.
- A square shaped hole causes 5.69% more damage than a circular shaped hole.
- Vertical position of a hole has insignificant impact. On the contrary horizontally if a hole is off centered by a 50mm, a 6.88% more capacity reduction than a column with a central hole happens.
- CFRP wrapping of a column with 100mm diameter hole (1/3 of width of a column) improved the strength by 21.69% and restored 15.56% of the lost capacity of the control column.

- The use of steel casing firmly placed inside the hole restored 14.77% of the load carrying capacity lost by a center hole with 100mm diameter
- The use of CFRP wrapping and Steel casing together has demonstrated that 99.79% of the ultimate load capacity of a column with 100mm hole (1/3 of the width of a column) can be restored. However, after the crack and of the column happens past the elasticity the capacity of the restored column decreases very significantly.

4.2 Recommendations.

The following recommendations are made for further investigation and experimentation:

- The loading conditions considered in this paper is only an axial load, further research is needed to account for varying different loading conditions like uniaxial, biaxial and lateral loads.
- This research had thrown up many questions in need of further investigation of transverse holes in RC columns with different cross-sections and bracing arrangements.
- The hole depth considered in this study was, a hole cut all the way through. Different hole depths can be taken in to account for further works.

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