

**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY**  
**SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING**



**FEM INVESTIGATION OF STEEL JACKETED RC COLUMN**  
**UNDER ECCENTRIC AND CYCLIC LOADING**

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**A Thesis in Structural Engineering**

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled ‘**FEM investigation of steel jacketed RC column under eccentric and cyclic loading**’ presented by **Yalem Mesfin**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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## UNDERTAKING

I certify that research work titled “**FEM investigation of steel jacketed RC column under eccentric and cyclic loading**” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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Yalem Mesfin

## ABSTRACT

Structural members encounter strength deficiency due to improper design, faulty construction and inspection. To overcome this problem, strengthening of structural members when found deficient is necessary and it can be applied prior to hazard or after hazard. Both strengthening ways are applied for different types of structural members (beams, columns, beam-column joints and other structural members). We can apply strengthening of structures members considering the present load carrying capacity and required demand. These strengthening methods result in structural capacity increment as it gives the reinforced concrete member a composite action. Columns are important structural members that transfer loads to foundation and they are sensitive as their failures may lead to complete collapse of buildings. The thesis investigates the structural performance of steel jacketed RC column (using steel cage made from vertical angle and horizontal connecting strip) for the specified parameters under different eccentricity levels and cyclic loading. The study parameters are effect of eccentricity, concrete grade, angle steel grade, horizontal strip grade and strip configuration.

**Key words:** steel jacket, steel cage, eccentricity, concrete grade, angle steel grade, horizontal strip grade, strip configuration, cyclic load.

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## LIST OF SYMBOLS

### Notations

$f$	Concrete compressive stress at $\varepsilon$
$f_c$	Concrete compressive stress
$E_c$	Modulus of elasticity
$\varepsilon_o$	Initial concrete strain
$\varepsilon$	Concrete strain
$\sigma_{cu}$	Ultimate compressive stress
$\varepsilon_{in}$	In elastic strain
$\varepsilon_{in}^{ck}$	In elastic cracking strain
$\varepsilon_t^{ck,h}$	Tensile cracking strain
$d_c$	Compression damage parameter
$d_t$	Tension damage parameter
$\varepsilon_t^{pl}$	Concrete plastic strain

### Abbreviations

ACI	American concrete institute
CFT	Concrete filled tube
CDP	Concrete damage plasticity
AASHTO	American association of state highway and transportation officials
GFRP	Glass fiber reinforced polymer

ANOVA      Analysis of variance

AISC-LRFD   American institute of steel and construction-load resistance factored design

SCM          Steel cage mortar

CS            Control specimen

WMM         Wire mesh mortar

## 1. INTRODUCTION

Civil engineering constructions are among the oldest human endeavors. On its long history, the construction sector is in a continuous improvement. As civil engineering constructions are directly related to human life, structural safety becomes a critical issue. In several places of the world, it is common to find structures constructed a long time ago that shows structural deficiency when compared to the present structural requirement. For example a previously unconsidered load like seismic load leads the structural member to be insufficient for the current code requirement. On the other hand, the structural usage of buildings sometimes changes, causing higher load beyond the designed capacity of structures which in turn results in structural deficient members. On such conditions, strengthening of civil engineering structures becomes very important to enhance the ultimate capacity. On the other hand after hazard occurred on structures, the defected member needs to be repaired so that it can sustain loads.

There are different types of strengthening and retrofiting methods used, which has effect on the global or local member performance of structural member under the given loading condition. For example, steel bracing, adding additional shear wall, column jacketing & beam jacketing are some types among different methods. Column jacketing enhances the axial, flexural and shear capacity of the column. We can have different types of column jacketing. For example, reinforced concrete (RC) jacketing, steel jacketing, fiber reinforced polymer (FRP) jacketing are commonly used that can be used prior to hazard or after has occurred.

Steel jacketing enhances the axial load capacity, flexural capacity, shear resistance and ductility of the original RC members. This is because it gives the RC column a composite property. The steel members added in either steel jacketing methods develop a confinement effect as it warps the original column by additional steel. The confinement property enhances the capacity of concrete by developing a lateral resistance under axial, eccentric and cyclic loading. Steel jacketing for

Reinforced concrete column is commonly applied by warping the column by steel sheets or by adding steel members (angles, channels, plates or a built in members formed by combining of different steel profiles) to the RC column. Steel cage made from vertical angle at corner of column and horizontal connecting strips in each sides of the RC column is one of the steel jacketing methods.

The thesis investigates the effectiveness of steel jacketing (i.e. steel cage jacket) for eccentric and cyclic loading. The key parameters covered in the research are the effect of eccentricity (uni directional and bi directional eccentricity), concrete grade, strengthening angle steel grade, strengthening strip steel grade and strengthening strip configuration. The study parameters are considered for both eccentric and cyclic loading.

For the investigation of the parameters, the non-linear finite element software ABAQUS CAE 2018 is used.

## **1.1. Statement of the problem**

Structural members encounter structural deficiency due to different conditions like improper design, faulty construction, and change in structural usage which leads to increased loading beyond the designed capacity of structural members. When this scenario encounters, the structural member needs to be strengthened so that it can be effective in resisting the extra loading.

## **1.2. General and specific objectives**

### **1.2.1. General objective**

The general objective of this thesis is to investigate the effectiveness of steel jacket (steel cage) for reinforced concrete column.

### **1.2.2. Specific objectives**

The specific objectives is to study

- The effect of eccentric loading on steel jacketed RC column.
- The effect of cyclic loading on steel jacketed RC column.

### **1.3. Significance of the study**

It is common for structural members like columns to experience large load beyond the designed ones. For example change in usage of buildings or previously unconsidered load scenarios like seismic load causes load increment on structural members. These increased loadings may come as pure axial, eccentric or cyclic load. Such conditions require strengthening of structural members.

### **1.4. Scope of the thesis**

The thesis investigates rectangular steel jacketed RC column for specified dimensions, height and reinforcement layouts under eccentric and cyclic load and therefore any other cross sections, different depth to height ratio, slenderness values and reinforcement variations are not considered.

### **1.5. Organization of the thesis**

As the thesis is a finite element investigation of Steel jacketed RC column for eccentric and cyclic load, the following procedures are used.

- Verification of the finite element program ABAQUS CAE 2018 using experimental result from published journal under eccentric load and cyclic loading.
- Considering the study parameters, detailed investigation of eccentric and cyclic load under the specified parameters.
- Discussion and findings for both the reference and strengthened column. For the specified parameters.

## 2. LITERATURE REVIEW

### 2.1. Experimental investigation

(Fabio D. T, Marco F. Giuseppe C.& Liborio C , 2019) assessed the effectiveness of steel jacketed RC columns for low and medium classes of concrete. Experimental investigation for two different class of concrete (i.e. low strength with  $f_{cu}=12.65\text{MPa}$  and medium strength with  $f_{cu} =24\text{MPa}$ ) was conducted and compared with a finite element modeling in Open Sees. In the experiment they perform two types of tests (i.e. axial and eccentric loading tests).

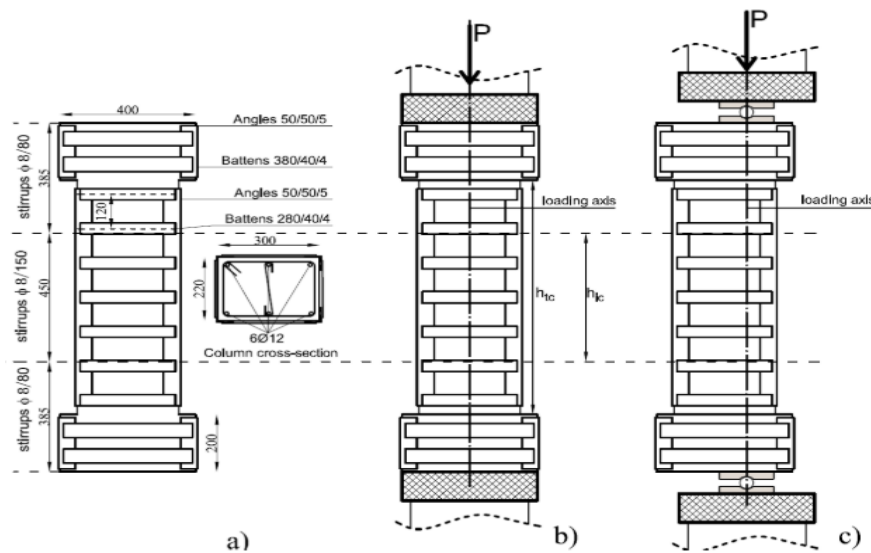


Figure 2-1 Experimental setup for Fabio Di Trapani & Marco Filippo

The non-linear modeling of Open Sees enables investigating RC jacketed column under different parameters. They define a fictitious stress-strain law to attribute the angle fibers to account for the frictional interaction between fibers. The governing parameters were the calibration of the values of the cohesion and the friction coefficient. The experimental result shows that the force transmission occurring in the interface layer is governed by frictional phenomena that can be described by a coulomb law and the cohesion of the results was obtained with a friction coefficient  $\mu =0.4$ .

( Elzbieta S., Wojciech Z. & Mirosław S, 2010 ) conducted an extensive experimental study and numerical investigation on built-up steel columns filled with concrete. The laboratory tests were

accompanied by numerical analysis carried out using general purpose, finite element program ABAQUS. Based on findings presented in the paper, the application of concrete filled columns with battened steel sections is economically very profitable. The numerical analysis confirmed increase of the load resisting capacity for the columns. For columns filled with concrete strength class C20/25 the increase of load bearing capacity was 42% and for elements filled with concrete strength class C50/60 above 100%. The application of the shorter distance between battens allowed additional increase of ultimate load (for concrete C20/25 – about 8%).

( Senthil K., Bishnu G. & Lakshmipathy M., 2014) conducts an experimental investigation to study the effectiveness of steel jacket mortar and wire mesh mortar (WMM) jacketed RC short square columns. They found that the wire mesh mortar jacket gave higher capacity and stiffness values for steel cage jacket. For analysis of test results, a plain reinforced column or control specimen (CS) was tested. A total of nine column specimens were tested after 28 days. Three of the specimens were control specimens, three with WMM and the remaining three were casted with steel cage mortar (SCM) jacketing. The design and the testing were done as per the Indian standard. On the other hand, theoretical capacities of columns were calculated and compared with the experimental one. Comparison was made with respect to load resistance capacity, stiffness and energy absorption. From the result analysis, it was observed that when compared to control specimen CS, WMM provides 1.75 times greater load resisting capacity than control specimen and SCM gives 2.28 times greater capacity increment than the CS. The stiffness of WMM was the highest value, initially 1.2 times higher than CS. The energy absorption was 5.01 times higher for WMM than CS. Finally, from the strength consideration SCM is preferred whereas from the stiffness and energy absorption consideration WMM is preferred.

( Eunsoo C., Young S. C, Joonam P.& Baik S. C., 2009) studied the effect of steel jacket thickness in the performance of the RC column. For this purpose, twelve concrete cylinders of 150 x 300 mm were fabricated with design strength of 24 MPa. A steel jacket and lateral strip bands were used to

confine a cylinder. The dimensions of each jacket were 290 mm in height and 480 mm in width. The thicknesses of the jackets were 1.0, 1.5, and 2.0 mm and the volumetric ratios of the steel jackets were 0.0133, 0.002, and 0.0267 respectively. The yield strength of the steel jackets was 400 MPa. The 2.0 mm Jacket consisted of two 1.0 mm Jackets, which is a double-layered jacket and a single, layered jackets were introduced. The newly jacketed cylinders show good results in terms of increasing the compressive strength and ductility compared to plain cylinders. The double-layered jackets show equal performance to that of a single steel jacket having the same thickness as the double-layered jacket. The proposed steel-jacketing method increases the ductility of lap-spliced RC columns. The double-layered jacketed column produces more ductile behavior than the single-layered jacketed column.

(Pasala N., Dipti R.& Durgesh C., 2018) uses steel caging technique for the seismic strengthening of reinforced concrete (RC) columns of rectangular cross-section. The steel cage consists of angle sections placed at corners and held together by battens at intervals along the height. In the study, a rational design method was developed to proportion the steel cage considering its confinement. An experimental study was also carried out to verify the effectiveness of the proposed design method and detailing of steel cage battens within potential plastic hinge regions. One ordinary RC column and two strengthened columns were investigated experimentally under constant axial compressive load and gradually increasing reversed cyclic lateral displacements. Both strengthened columns showed excellent behavior in terms of flexural strength, lateral stiffness, energy dissipation and ductility due to the external confinement of the column concrete. The proposed model for confinement effect due to steel cage reasonably predicted moment capacities of the strengthened sections, which matched with the observed experimental values.

(Cheng-xiang X., Sheng P., Jie Deng & Chong W., 2018) studied the seismic behavior of earthquake damaged composite steel concrete columns strengthened by enveloped steel designed and manufactured based on the current Chinese design code. Destructive tests on the models under low

cyclic loading were carried out to study the feasibility and effectiveness of earthquake damaged columns strengthened by enveloped steel. The experimental results show that enveloped steel strengthened earthquake damaged composite steel concrete columns meet the strong column-weak beam requirement of seismic design. The research shows that the failure mode of all the columns was in bending. The performance of the rehabilitated columns can reach or even exceed the level of their original seismic performance before seismic damage. Composite steel-concrete frame columns strengthened by enveloped steel were also simulated using the finite element analysis software ABAQUS. Comparison of analytical and experimental study found to be consistent with the experimental data.

(Hugo R., André F. & Ant´onio A, 2016) tested and analyzed six full scale RC rectangular columns to study the effects of variable axial load on the hysteretic behavior of RC building columns under biaxial horizontal loading. The column specimens has 1.70 m height and were cast in strong square concrete foundation blocks with dimensions  $1.30 \times 1.30 \text{ m}^2$  in plan and 0.50 m high. A vertical 700 kN capacity actuator was used to apply the axial load and two horizontal independent actuators to apply the lateral load paths on the columns (one with a capacity of 500 kN with  $\pm 150$  mm stroke and the other with a capacity of 200 kN with  $\pm 100$ -mm stroke). The experimental results show that the axial load variation combined with biaxial horizontal loading have significant effects on the nonlinear behavior and capacity of the column. It was shown that the initial stiffness is not significantly affected by the biaxial load path combined with axial load variation however; the stiffness degradation is significantly affected by axial loading variations for the different load paths. Under varying axial load, the stiffness degradation presents a smooth behavior when compared with constant axial load. It was also observed, as previously stated, that biaxial loading can introduce higher energy dissipation (circular, rhombus, and cruciform load paths) than uniaxial loading; however, this fact is not clearly observed in columns under varying axial load.

## 2.2. Analytical investigation

(Giuseppe C., 2013) provides simplified hand computation procedure for moment-axial forced interaction of RC columns externally strengthened with steel angles and strips. The Simplified procedure was developed by assuming equivalent stress-block parameters for internal force considering the confinement effect induced in concrete core by external cages. These simple analytical equations were proposed based on constitutive laws of confined concrete and steel angles. The proposed model gives results in a good agreement with experimental data and it allows one a hand control of the influence of main parameters governing the problems (angles, strips geometry, and mechanical properties of constituent material) on the behavior of RC columns externally strengthened with steel cages.

(Debasish S. & Mahbuba B, 2018) reviewed different experimental works and analytical models made with steel angle and strip strengthened RC columns. They conducted a comparative study considering available parameters, which includes grout materials, strip configuration, angle size, connection to specimen head, eccentricity, length of retrofitting & load state during strengthening. The parametric study indicates that strip configuration, loading approach on steel angle and length of retrofitting zone are the key parameters that have profound influences on the capacity of steel angles and strips strengthened RC column.

(Eduardo N., Santos J.& Fernando A, 2014) studied the performance RC column by circular steel jacket for cyclic load. For this purpose, seven column-footing models were built using concrete approximately 35 MPa (5076 Psi) nominal compressive strength and steel with 520 MPa (75,420 psi) nominal yielding stress. The dimensions adopted for the column cross section and height were 0.20 x 0.20 m<sup>2</sup> (0.656 x 0.656 ft<sup>2</sup>) and 1.35 m (4.43 ft), respectively. The researcher uses a symmetrically reinforced column with three bars of 10 mm (0.394 in.) diameters at each face. The transverse reinforcement of the column consisted of 6 mm (0.236 in.) diameter stirrups spaced 150

mm (5.905 in). Strain gauges connected to each central bar, close to the footing of the longitudinal reinforcement and on the second stirrup from the bottom in opposite branches, takes reading. Twenty-eight days after being strengthened the models were submitted to cyclic loading. The result provided that for undamaged columns with a bending moment/shear force ratio greater than 1.0 it is not necessary to consider any type of interface treatment before casting the RC jacket with a thickness less than 17.5% of the column width to obtain a monolithic behavior of the composite element.

(Bertha O, Manuel J, Gerardo G.& Guillermo M, 2019) studies the seismic vulnerability of retrofitted bridges piers with steel jackets. The steel jacket thickness was the main parameter studied on the seismic capacity and demand of the bridges. The bridges has two simple supported spans with 9 superstructure composed by AASHTO type girders and a substructure formed with one circular pier over a stiff foundation. The bridges seismic capacities were evaluated through nonlinear static analyses. The shear force and displacement demands were determined using capacity spectra with a group of 10 real accelerograms from a subduction source. The response spectra were scaled to several peak ground accelerations (PGA) with the aim to estimate four damage scenarios linked each one to a probability of exceedance in a specific period. Results show that the confining effect provided by the steel jackets substantially improves the seismic performance of the bridges piers. The increase of jacket thickness guides to important increments on columns base shear capacity, and the influence of the steel jacket thickness depend on the limit state and bridge slenderness ratio.

(Debashe S, 2018) studied the effect of steel angles and strips jacket on the eccentrically loaded RC column. A comparative study was conducted by considering available parameters like grout material, strip configuration, angle size, connection to specimen head, eccentricity and load state during strengthening which has influences in a large extent on the compressive strength of steel angles and strips strengthened RC columns. The results of the study indicate that steel angle and strip

jacketing scheme performs well under both concentric and eccentric loading. The capacity enhancement has been found to be about 240% under concentric loads compared to un-strengthened RC column, whereas the capacity enhancement was relatively more under eccentric loading compared to concentric loading. However, for this particular case eccentricity reduces the ultimate capacity of steel cage jacketed RC column of about 15% when eccentricity to column width ratio changes from 0 to 0.45. It also changes the ductile behavior of jacketed RC columns. From the finite element analysis, it has been found that the mean of experimental to numerical ultimate load capacity ratio was about 0.95, which indicates a fair agreement with slight overestimation. On the other hand, the available analytical model can predict load-moment interaction curve of steel jacketed RC columns with a high level of safety margin.

(Gattu A. Kumar & Harish N, 2016) presents a case study of G+5 storey building, where this G+5 storey residential building was converted to commercial building which results increase of live load in the building. Reinforced concrete jacketing and steel jacketing was employed and equivalent static analysis as per the Indian standard. The building was analyzed in ETABS v 9 for equivalent lateral force method before and after retrofitting. After application of RC jacket on column and beam column joint the shear and axial capacity significantly increases.

(Rodrigues H, Furtado H & Arêde A, 2016) conduct a study showing that during an earthquake, the reinforced concrete (RC) structures are subjected to deformations that may lead their structural elements to exceed the corresponding resistance limit state, forcing them to have nonlinear responses. The application of realistic numerical models that can represent the non-linearity of each structural element requires full examination and calibration. They evaluate the efficiency of a simplified numerical approach to represent strengthened RC columns with steel and carbon fiber reinforced polymer (CFRP) jacketing, subjected to biaxial horizontal loading. The shear-drift hysteretic behavior, initial stiffness and stiffness degradation, maximum strength and energy dissipation are compared between experimental and numerical model. The results provide a good

performance of the numerical models, mainly for the RC columns strengthened with CFRP jacketing technique.

### **2.3. Finite element investigation**

(Mahmoud F. B., Hatem M. M. & Sheriff A. M., 2014) investigates the performance of RC column jacketed by steel cage for axial load. A total of seven specimens were tested in a group of two un-strengthened specimen and five strengthened ones with different parameters. The parameters used in the experiment were shape of the steel jacket (angle, channel and plates), number and size of batten plates. A numerical investigation was also done using ANSYS v 12. The researcher found that, the size of the batten plates had significant effect on the failure load for specimens strengthened with angles, whereas the number of batten plates was more effective for specimens strengthened with C-channels.

(Ahmed M.S. & Hesham M.D, 2019) uses a non-linear finite element tool ANSYS v 15 to investigate and analyze the effectiveness of steel jacket (i.e. steel angle and horizontal strips) for the axial capacity of RC column. For this purpose, different parameters were studied like the column dimensions, the concrete strength, the cross section and yield stress of the steel, the stress yielded by the steel jacketing and the percentage of preloading. It was shown that axial load capacity of RC columns through the addition of the normal force from concrete and the normal force from steel reinforcement without strengthening could be confidentially determined. Meanwhile, the typical model from Euro code 4 was utilized for comparison and by making an addition of steel jacketing contributions right to the normal force of the RC column. The procedures ACI 318 and Euro code 4 come to an excellent match.

(Hamza M.S. & Mohammed H.Al-Sherrawi, 2018) uses a non-linear finite element study using ABAQUS v 6.13 to simulate and investigate the behavior of steel jacket to a preloaded and non-damaged RC column under axial loads for two cases. In the first case, the RC column was

preloaded with axial load less than the design capacity and in the second case the column was preloaded with axial load greater than the capacity. In ABAQUS the pre-loading was considered using the deactivated and reactivated techniques and in the strengthening process of an existing RC column stepped loading stages was used. For the first case, the strengthened RC column gives higher axial resistance than in case II, due to the pre-existing stress and strain in the concrete and the reinforcing bars produced by the unloading process. It was noted that the pre-existing stresses increase with increasing the percentage of loading the RC column before adding the steel jacket. The pre-existing stress and strain were considered as a loss in the original stress and strain of the component (concrete and reinforcing bars) and that causes a reduction in the resistance produced by the component itself, thus a reduction yields in the resistance of the strengthened RC column.

(John F.Rupp, 2012) in his thesis evaluated different models for evaluation of confinement property of steel-jacketed column and a load versus displacement behavior of columns under concentric axial load for concrete filled tube (CFT) columns and circular tube reinforced concrete (CTRC) columns. Firstly, steel cage and concrete under loading, secondly only concrete in axial load where there is no direct contact between steel cage and load and thirdly, the steel cage passive load resistance. The proposed model in the thesis uses equations of the reinforced concrete model with modifications made to the effective confining pressure coefficient as well as the constants based on the strength of the unconfined concrete and the steel tube, the length of the column, and the thickness of the steel tube. The proposed model predicts the ultimate axial strength with an acceptable degree of accuracy with improved corresponding peak strain predictions.

(Anan M, Tousif M. & Mahbuba B, 2016) conduct a nonlinear finite element analysis of graphite fiber reinforced polymer (GFRP) reinforced concrete columns using ABAQUS/standard finite element tool. The researchers verified the analytical model with experimental result to show the reliability of finite element tool. In the model, they used a damage plasticity model to simulate the behavior of reinforced concrete. The perfect bonding between GFRP rebar and concrete was

simulated using embedded element algorithm. A static risk formulation was implemented to trace the stable load-displacement history of GFRP reinforced concrete up to failure. The numerical model was compared with the behavior of three GFRP reinforced columns and two steel reinforced concrete columns under concentric loading. It was shown that the model reliably produced the peak axial stress, axial deformation at the peak stress, the post-peak behavior and the failure mode observed in the tests.

(Karthik A.R. and N.S.Kumar, 2017) studied the ultimate load capacity of circular concrete-filled steel tubular columns, with lightweight concrete as infill for two different grades M 20 and M 30 according to the Indian standard. The ultimate load capacity obtained by using the finite element software ABAQUS 6.10.1 was verified with Experimental result with Analysis of variance (ANOVA) approach. The parameters considered were different combination of length, thickness & diameter. The study presents a numerical investigation into the behavior of concrete filled tubular columns using three-dimensional nonlinear finite element software ABAQUS v 6.10.1. The analytical results obtained were compared with the numerical results obtained from ABAQUS 6.10.1. For this purpose, a comparison between designs codes Euro code -4 and American institute of steel and construction-load resistance factored design (AISC-LRFD) procedures, evaluating the axial compressive strength of concrete filled tubular columns. The obtained results were analyzed with the help of signal/noise (S/N) ratio, main effects plot & analysis of variance (ANOVA) using mini Tab v16. Regression equations were developed for all two grades of infill's separately. Ultimate load values obtain by Eurocode-4 and ACI methods varied between 0.83% and 18.46% when compared with ABAQUS values and result obtained from the experiment is approximately equal to ANOVA equation obtained by regression method.

(S.V.Chaudhari & M.A.Chakrabarti, 2012) studied the usage of different concrete plasticity models. This plasticity models were concrete smeared crack model and concrete damage plasticity approach found in ABAQUS. The researcher also validates the model to the desired behavior under

monotonic loading. The study considers different mesh size and plasticity models. The finding was that the smeared crack model is suitable in coarse mesh size than the concrete damage plasticity model.

(Abdurra'uf M.Gora, 2017) in his study presents the results of nonlinear finite element (FE) analysis of graphite fiber reinforced polymer (GFRP)-confined rectangular reinforced concrete (RC) columns under eccentric loads. The test variables were the number of GFRP layers and intensity of load eccentricity. It was found that the FE analysis results agreed favorably with the results of the experimental studies reported in the literature. The FE analysis results showed that GFRP wrapping of RC columns has significantly increased their load carrying capacity and ductility. The results also indicate that the presence of eccentricity of loading reduces the load carrying capacity and performance of the strengthened RC columns.

(Chunli Z, Xiaowei L, Dongbo W.& Shunxiang X, 2019) study the bearing capacity and seismic performance of steel jacketed circular RC columns. A formula for calculating the bearing capacity of circular RC columns strengthened with externally wrapped steel plates was derived, with reference to the code for design of strengthening concrete structure. Finite element analysis with ABAQUS software was conducted with the vertical monotonic static loading and the horizontal low-cyclic reversed loading before and after the strengthening of the full-size RC columns. The results showed that the bearing capacity of the normal section of the RC column after strengthening was about 80% higher than that before strengthening and the results of FEM software were in accord with the calculation results of theoretical formula to some degree. Under horizontal low-cyclic reversed loading, the columns after strengthening had plumper hysteresis curves, higher ductility factors and equivalent viscous damping coefficient than those before strengthening, indicating the energy dissipation capacity, plastic deformation capacity, and seismic performance of the RC columns after strengthening were all obviously improved.

(Jiepeng L, Dan G, Xuhong Z.& Biao Y, 2018) investigates the cyclic shear behavior and shear strength of tubed reinforced-concrete short columns with a large diameter-to-thickness/width-to-thickness ratio ( $d/t$ ), four specimens were designed and tested under a constant axial compression combined with quasi-static cyclic lateral loading. Three parameters were considered in the test (i.e. type of column cross section (circular and square), depth to thickness ratio and axial load ratio between 0.4 and 0.6). All the columns showed shear-failure mode during the tests, and the sheared plates of steel tubes yielded when the peak load had reached. The circular columns showed good ductility, while the square ones were just in opposite. Based on the analysis results, a simplified shear strength model for both circular and square columns was proposed, in which the relationship between cyclic shear strength and lateral drift ratio of the columns and the shear-resisting mechanisms for both shear and hoop stresses of the tube were considered.

(Hsuan T.H, Chiung S.H.& Z.Liang, 2005) study proper material constitutive models for concrete-filled tube (CFT) columns subjected to an axial compressive force and bending moment in combination. The results obtained were verified by using the nonlinear finite element program ABAQUS. In the numerical analysis, the cross sections of the CFT columns were categorized into three groups (i.e. ones with circular sections, ones with square sections, and ones with square sections stiffened with reinforcing ties). It was shown that the steel tubes can provide a good confining effect on the concrete core when the axial compressive force is large. The confining effect of a square CFT stiffened by reinforcing ties is stronger than that of the same square CFT without stiffening ties but weaker than that of a circular CFT. Nevertheless, when the spacing of reinforcing ties is small, a CFT with a square section might possibly achieve the same confining effect as one with a circular section.

### 3. FINITE ELEMENT MODELING

#### 3.1. Material properties used in the finite element model

##### 3.1.1. Concrete

The material properties in the finite element method for concrete are the compressive behavior and tensile behavior. The compressive stress strain relationship for concrete is based on numerical expressions proposed by (Prakash Desayi and S. Krishnan, 1964).

$$f = Ec * \varepsilon / [1 + (\varepsilon / \varepsilon_o)^2] \quad [3-1]$$

$$\varepsilon_o = 2 * fc / Ec \quad [3-2]$$

The modulus of elasticity of concrete for compression is calculated based on the ACI 318-14 equation.

$$Ec = 57000 \sqrt{f'c} \text{ Where } f'c \text{ in Psi} \quad [3-3]$$

In this research modulus of elasticity is defined in MPa. The equivalent expression of Psi to MPa (i.e. 1Psi = 0.00689MPa)

$$Ec = 4730 \sqrt{f'c} \text{ Where } f'c \text{ in MPa} \quad [3-4]$$

ABAQUS provides the concrete damage plasticity model which describes the compressive and tensile behavior of concrete and it is capable of representing the linear, plastic and damage portion of the stress strain curve for concrete.

##### 3.1.1.1. Concrete damage plasticity model

Concrete damage plasticity (CDP) model uses stress-strain relationship to define relative concrete damage. The model is a continuum, plasticity-based damage model for concrete that is capable of predicting both compressive and tensile behavior of the concrete material. Compression hardening and tension stiffening models are used to define the complete behavior of concrete under loads. Therefore, CDP model has been used to simulate the concrete material behavior in the steel angle

and strip jacketed RC columns. In ABAQUS, the input for this model is stress- inelastic curves, and converted to stress-plastic strain curve automatically using damage variable.

### 3.1.1.2. Compressive behavior

The uniaxial compression stress strain curve is defined in terms of the inelastic strain and the damage portion that is given by the parameter,  $d_c$  (damage parameter).  $d_c$  represents the degradation of the elastic stiffness of the material in compression.

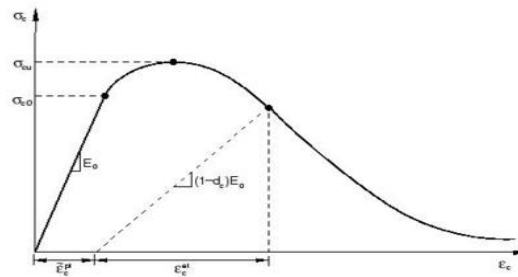


Figure 3-1 Compression stress strain curve for concrete

The following equation calculates the inelastic strain and damage parameters.

$$\epsilon_c^{in} = \epsilon_c - \frac{f_c}{E_c} \quad [3-5]$$

The compression damage parameter is calculate using the following formula

$$d_c = 1 - \frac{\sigma_c}{\sigma_{cu}} \quad [3-6]$$

The important parameters necessary for the concrete damage plasticity model are given below.

Table 3-1 CDP parameters used in the study

CDP Parameters	Values used in FEM
Dilatation angle	36°
Flow potential eccentricity	0.1
Ratio of initial equi biaxial compressive yield stress to initial uniaxial compressive yield stress	1.16
Ratio of the second stress invariant on the tensile meridian to that on the compressive meridian	0.667
Viscosity parameters	0.001

### 3.1.1.3. Tensile behavior

The uniaxial tensile strength of concrete,  $f_t'$  is calculated based on the ACI 318-14 equation for normal weight concrete.

$$f_t' = 6.7\sqrt{f_c'} \quad (\text{Where } f_c' \text{ in Psi}) \quad [3-7]$$

Converting Psi to its equivalent MPa expression we get

$$f_t' = 0.56\sqrt{f_c'} \quad (\text{Where } f_c' \text{ in MPa}) \quad [3-8]$$

Concrete tension properties for damage model are defined in two stages: the linear elastic portion up to the tensile strength and the nonlinear post peak portion, which is called the tension stiffening. The first part is defined using the modulus of elasticity of concrete ( $E_c$ ) and the yield stress of concrete in tension. After peak point, strain softening.

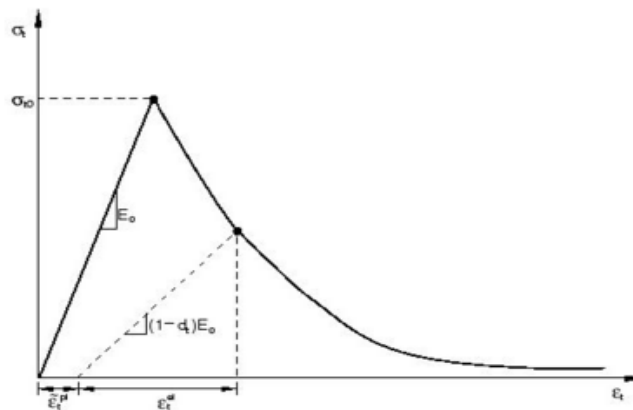


Figure 3-2 Tension stress strain curve for concrete

The tensile damage parameter is calculated using the following equation

$$d_t = 1 - \frac{\sigma_t}{\sigma_{t0}} \quad [3-9]$$

Once the damage parameter is calculated the cracking and yield strain automatically calculated using the following equation.

$$\varepsilon_t^{ck,h} = \varepsilon_t - \frac{\sigma_t}{E_0} \quad [3-10]$$

$$\begin{cases} \varepsilon_t^{ck,h} = \varepsilon_t - \frac{\sigma_t}{E_o} \\ \varepsilon_t^{pl} = \varepsilon_t - \frac{\sigma_t}{E_o} \left( \frac{1}{1-d_t} \right) \end{cases} \quad [3-11]$$

### 3.1.2. Steel

The steel property is approximated by elastic region and plastic region. The elastic region is presented by the young's modules and the plastic region is given by the yield stress and the plastic strain values in ABAQUS.

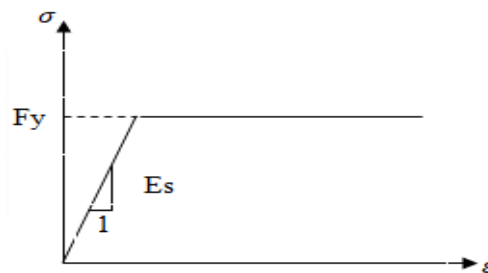


Figure 3-3 Elastic plastic stress strain response of steel

## 3.2. Validation of results

### 3.2.1. Experiment

An experiment carried out by (Ezz-Eldeen, H. A,2016) was used to compare with the FEM of RC column. The dimension of column was 120X160X1000 mm with a column head 260X300 mm at top and bottom.



Figure 3-4 Experimental setup for the test used for verification of eccentric load

In the experiment both pure axial load and eccentric load was considered with  $\varnothing 8$  main reinforcement and  $\varnothing 6$  stirrup at 120 mm. The yield strength of all reinforcements was of 240 MPa.

### 3.2.2. Modeling

For concrete, steel angles and strips the C3D8R elements is used in the model. The C3D8R element is an eight-node reduced integration brick element with three translational degrees of freedom at each node. Two-noded truss elements designated as T3D2 has been used to model the longitudinal and tie reinforcements.

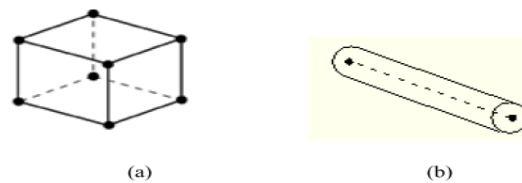


Figure 3-5 Solid and line elements used in the FEM

The mesh size was set at 20 mm after performing a mesh sensitivity analysis, considering the computational time and accuracy. The figure below shows the RC column after meshing for both reference and strengthened column.

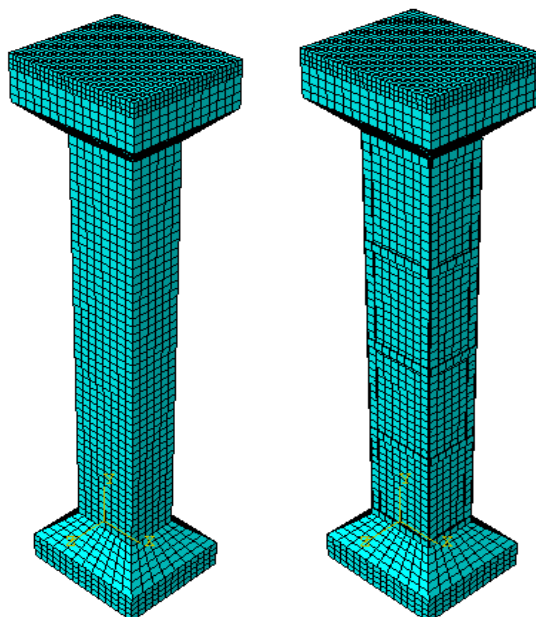


Figure 3-6 Meshing of reference and strengthened column

Load displacement curve for different mesh sizes are shown below.

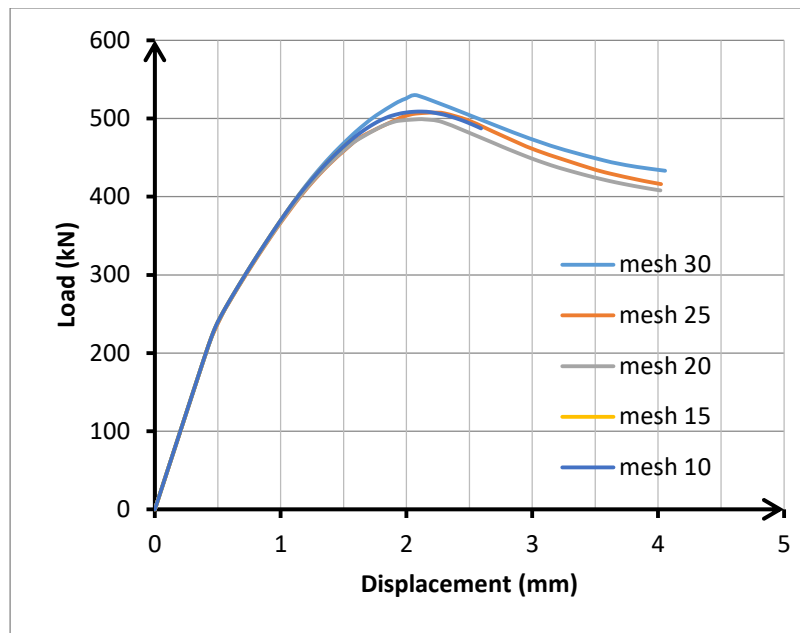


Figure 3-7 Mesh sensitivity analysis for FEM study

The experimental result for un-strengthened specimen for 10 mm eccentricity is 490 kN. The table below uses this value for comparison.

Table 3-2 Ultimate capacity of RC column for different mesh size

	Mesh size 30mm	Mesh size 25mm	Mesh size 20mm	Mesh size 15mm	Mesh size 10mm
Ultimate capacity (kN)	529.42	507.5	498.8	506.9	508.8
Difference from experimental result (%)	8.04%	3.58%	1.81%	3.46%	3.85%

### 3.3. Interaction of different components

To get the actual behavior of steel jacketed RC column in the FEM model, it is necessary to define proper interaction among these contact surfaces. In finite element study, “tie” and “embedded” constraints are used for combining different parts. In “tie” constraint there is no relative movement

between two surfaces and hence each node of the two surfaces moves together showing perfect bond between them. It is necessary to define the master and slave surface for ‘tie’ constraint. The embedded constraint used for concrete reinforcement interaction allows bonding the nodes of reinforcing bars to the compatible degrees of freedom (DOF) of the host region elements (concrete).

### **3.3.1. Steel angle to concrete interaction**

The ‘Tie’ constraint is used. Steel angle is defined as master and concrete is defined as slave in each angle to steel interaction. In ‘Tie’ constraint, a perfect bond between master and slave surfaces is assumed and hence each node of the bodies in this constraint moves together and no slip between nodes of master and slaves is assumed.

### **3.3.2. Steel strip to steel angle interaction**

A strong bond between vertical angle and horizontal strip is achieved by welding the two parts this is simulated in ‘Tie’ constraint. As each node shows the same movement with the combined node, perfect bond between nodes is assumed. Here contact surface of angle and strip are assumed as master and slave surface respectively.

### **3.3.3. Concrete to steel load plate interaction**

Lower part of load plate is assumed as master surface and the upper part of concrete as slave surface. Each nodes of the two surfaces show similar motion and perfect bond is assumed.

### **3.3.4. Reinforcement to concrete interaction**

To ensure bonding between the concrete and the reinforcing bars, the longitudinal bar and stirrup reinforcements were defined as ‘embedded’ in the concrete, which effectively couple the behavior of the rebar with the adjacent concrete medium.

### **3.3.5. End boundary conditions**

The thesis considers eccentric as well as cyclic load on the top part of the RC column and therefore

the lower part is made fixed by restraining translational and rotational degree of freedom.

### 3.4. Loading mechanism

Finite element method application of load on structural members can be force controlled or displacement controlled. In this thesis the second method is selected because displacement controlled method can trace the behaviors of the RC column after reaching maximum loading capacity and hence failure types and mechanism can be obtained.

### 3.5. Experimental and FEM comparison

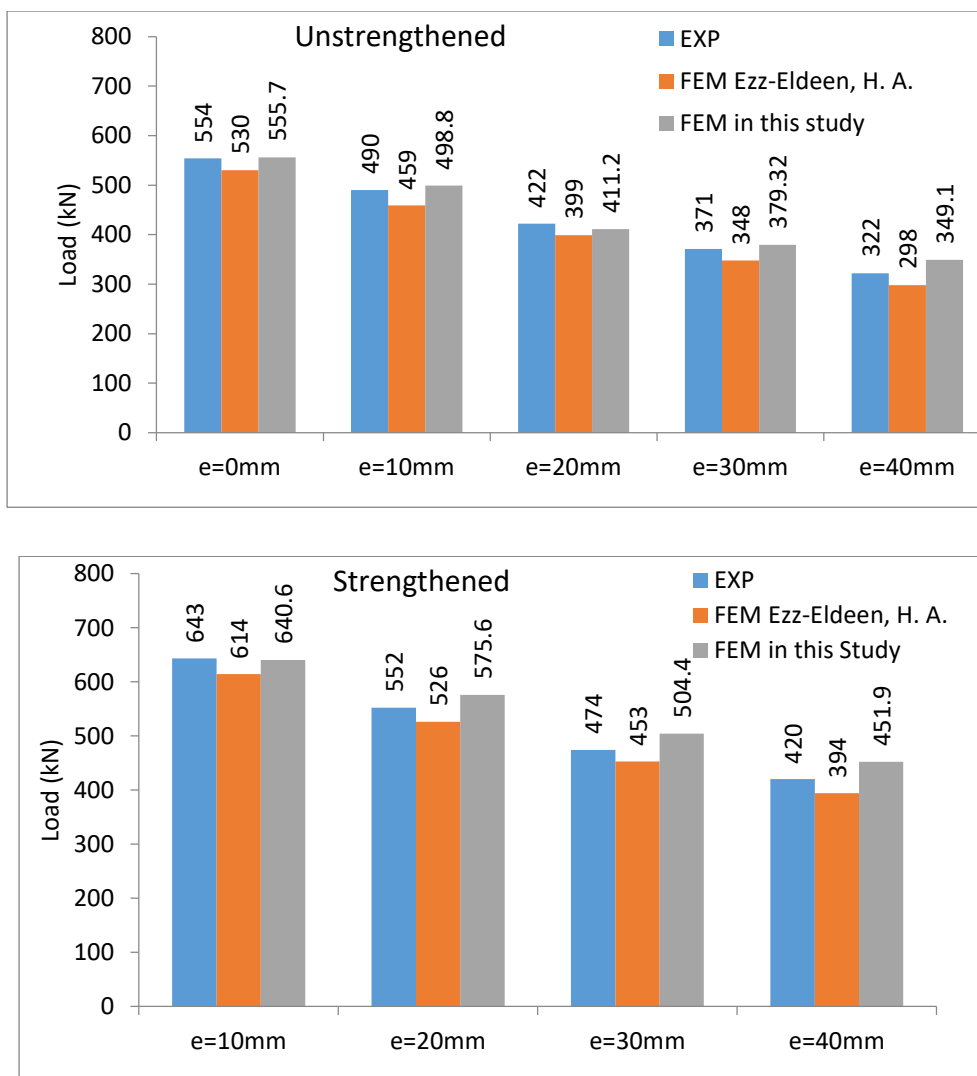


Figure 3-8 Experimental and FEM results for Ezz-Eldeen, H. A

A correlation between experimental and FEM values is shown below

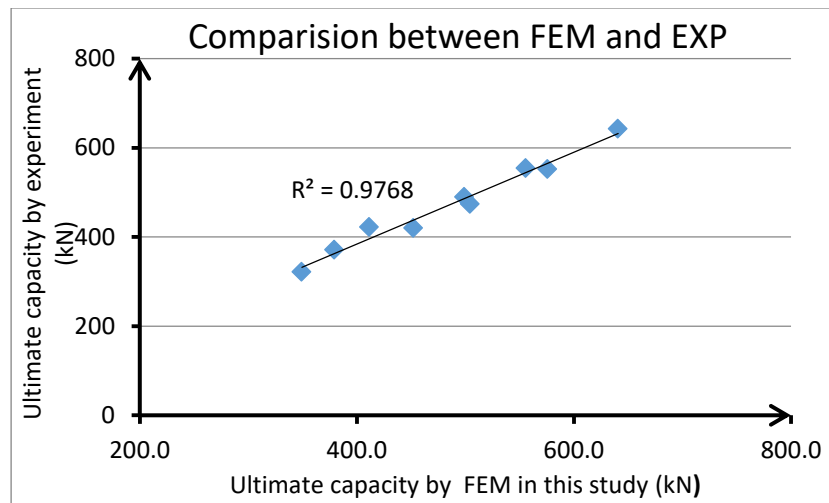


Figure 3-9 Comparison between FEM in this study and Experiment

From the results, we can see that the FEM and experimental results agree

Table 3-3 Results for the reference and strengthened column

		Ultimate capacity (kN)				
		Experiment	FEM in this study	Diff. from experimental result (%)	FEM Ezz-Eldeen, H. A.	Diff from experimental result (%)
Un strengthened column (kN)	e = 0 mm	554	555.7	0.31%	530	4.53%
	e = 10 mm	490	498.8	1.80%	459	6.75%
	e = 20 mm	422	411.2	2.56%	399	5.76%
	e = 30 mm	371	379.3	2.24%	348	6.61%
	e = 40 mm	322	349.1	8.42%	298	8.05%
Strengthened column (kN)	e = 10 mm	643	640.6	0.37%	614	4.72%
	e = 20 mm	552	575.6	4.27%	526	4.94%
	e = 30 mm	474	504.4	6.41%	453	4.64%
	e = 40 mm	420	451.9	7.60%	394	6.60%
Average				3.77%		5.85%
Standard deviation				2.88%		1.16%

## 4. FINITE ELEMENT METHOD STUDY OF RC COLUMN

Finite element study of structural members is capable of predicted the required structural response under a given input values and hence the effectiveness of the entire investigation depends on the reliability of input variables. For this purpose, certain fixed variables are set in order to consider the study parameters.

Table 4-1 Material properties used in the FEM study for eccentric loading

Elements	Values
Concrete compressive strength	30 MPa
Column dimension	200x200x2500mm
Main bar	4 $\Phi$ 12
Stirrup	$\Phi$ 8 c/c 200mm
Main bar yield strength	360 MPa
Stirrup yield Strength	240 MPa
Angle	4L50x50x5
Batten	150x100x5
Angle and strip yield strength	360 MPa
Loading plate	200x200x50 mm

### 4.1. Study parameters

The following are the study parameters for the above material properties.

- Effect of eccentricity (Uni-directional and Bi-directional)
- Effect of concrete grade for different eccentricity
- Effect of angle steel strength for different eccentricity
- Effect of strip steel strength for different eccentricity
- Effect of connecting strip configuration for different eccentricity
- Effect of concrete grade for cyclic loading

- Effect of angle steel strength for cyclic loading
- Effect of strip steel strength for cyclic loading
- Effect of connecting strip configuration for cyclic loading

## 4.2. Effect of eccentricity

To study the performance of strengthened RC column under different level of eccentricity both Uni-directional and Bi-directional eccentricities are considered.

### 4.2.1. Uni-directional eccentricity

Keeping the above parameters (i.e. concrete grade, reinforcement, angle and plate properties) constant, the capacity for different values of eccentricity was obtained from FEM analysis. Displacement eccentric loading were applied on a loading plate 50mm thick with a 25mm eccentricity interval and the load displacement response is drawn for each eccentric loading. The ultimate loading capacity was obtained from the outputs of the FEM analysis.

The load application direction can be X or Y axis and the X axis is selected as the studied column is square type and have similar results.

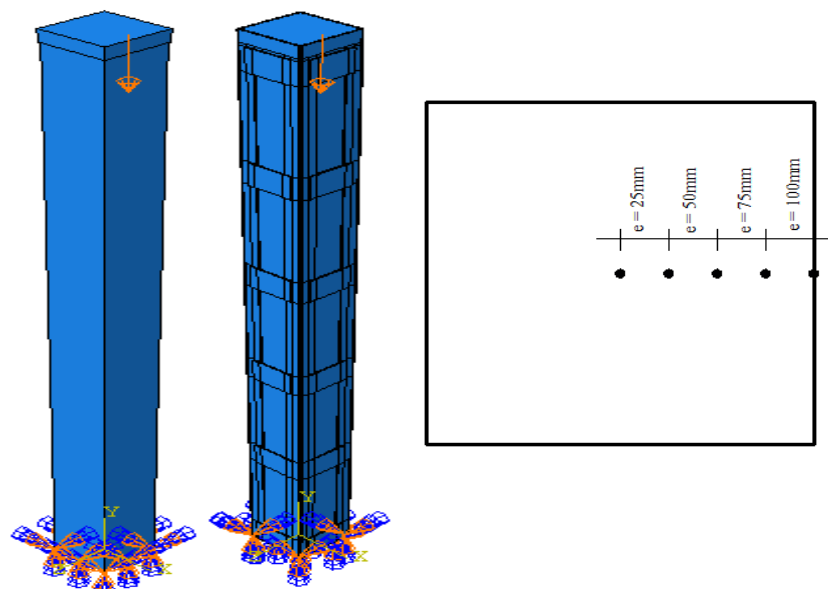


Figure 4-1 Eccentric loading on reference & strengthened column

#### 4.2.1.1. Pure axial load (0 mm eccentricity)

The structural load resistance of RC column significantly increases when we use this strengthening method.

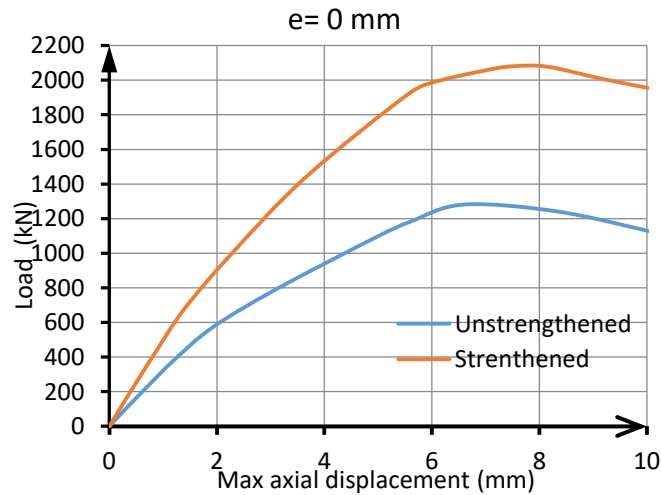


Figure 4-2 P-U relation of reference and strengthened column for pure axial load

As we can clearly see from the results the axial load, resisting capacity increases significantly when compared to un strengthened column.

For Comparison purpose, the analytical ultimate capacity of column is calculated using the ACI procedure.

$$\begin{aligned}
 P_{u,f} &= f'_c(A_c - A_{st}) + (f_y A_{st}) & [4-1] \\
 &= 30 \cdot (200 \cdot 200 - 4 \cdot 113) + (360 \cdot 4 \cdot 113) \\
 &= 1349.2 \text{ (kN)}
 \end{aligned}$$

The table below shows values of analytical and FEM capacity of column for pure axial load

Table 4-2 Results of reference and strengthened column for pure axial load

	Ultimate capacity (kN)	Ultimate capacity (kN)	Difference b/n FEM and analytical ultimate capacity (kN)
	FEM	Analytical	
Un-strengthened column (pure axial)	1281.32	1349.2	5.32%

#### 4.2.1.2. Capacities increments under different eccentricity

The ultimate capacity of reference and strengthened column under different eccentric values are shown for different eccentricity values ( $e = 25\text{mm}$ ,  $50\text{mm}$ ,  $75\text{mm}$  and  $100\text{mm}$ ) or  $e/L$  ratio of (12.5%, 25%, 75% and 50%).

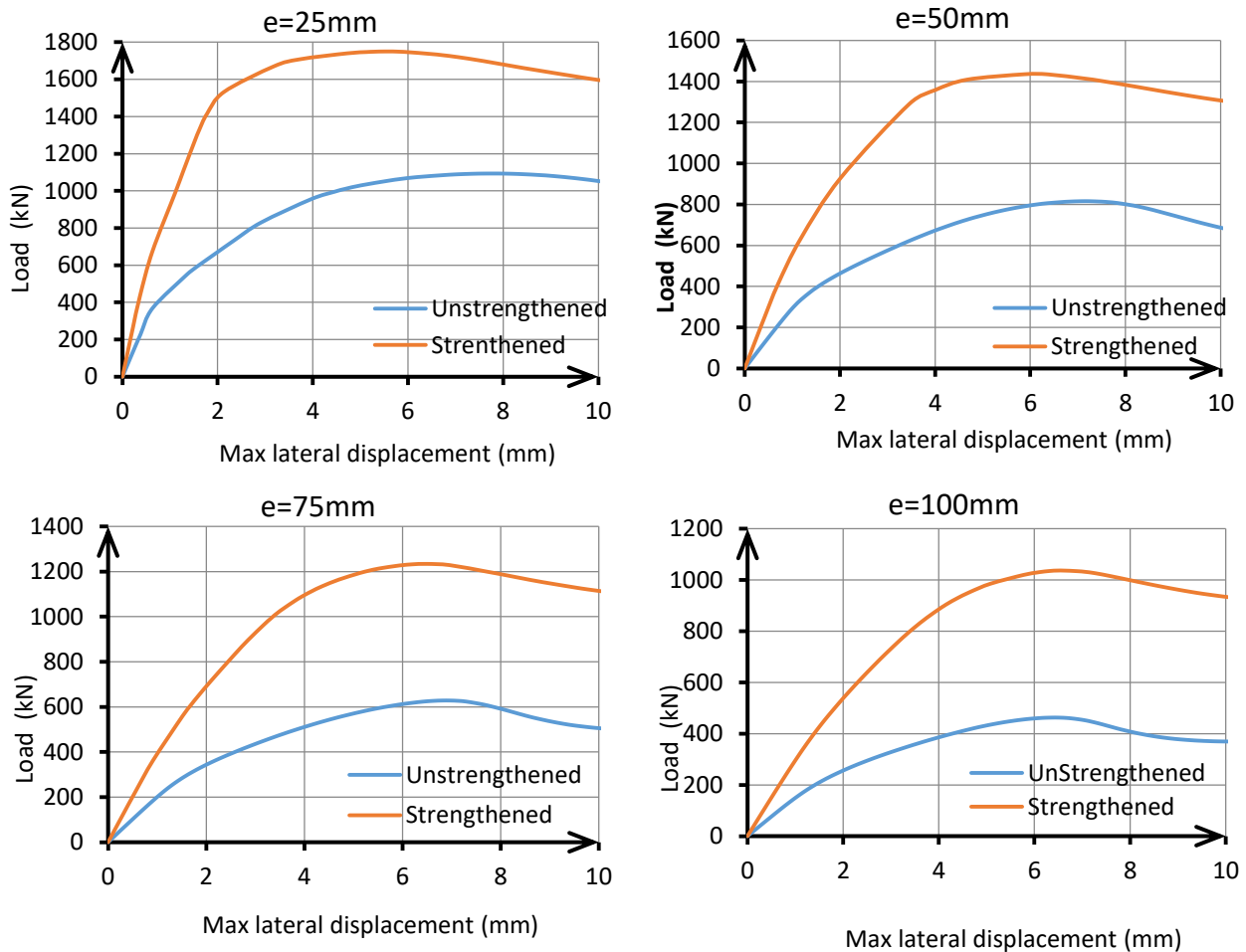


Figure 4-3 P-U responses under different eccentricity

Table 4-3 Results of reference and strengthened column for different load eccentricity

	$e = 25\text{mm}$	$e = 50\text{mm}$	$e = 75\text{mm}$	$e = 100\text{mm}$
	Ultimate capacity (kN)	Ultimate capacity (kN)	Ultimate capacity (kN)	Ultimate capacity (kN)
Un-strengthened column	1093.24	815.79	628.01	462.94
Strengthened column	1749.87	1435.3	1233.77	1037.3
% Increase with respect to un-strengthened column	60.06%	75.94%	96.46%	124.07%

### 4.2.2. Bi-directional eccentricity

In structural members, it is common to find a bi directional eccentricity ( $e_x$  &  $e_z$ ). The FEM analysis gives the maximum load carrying capacity for different values of combined eccentricity.

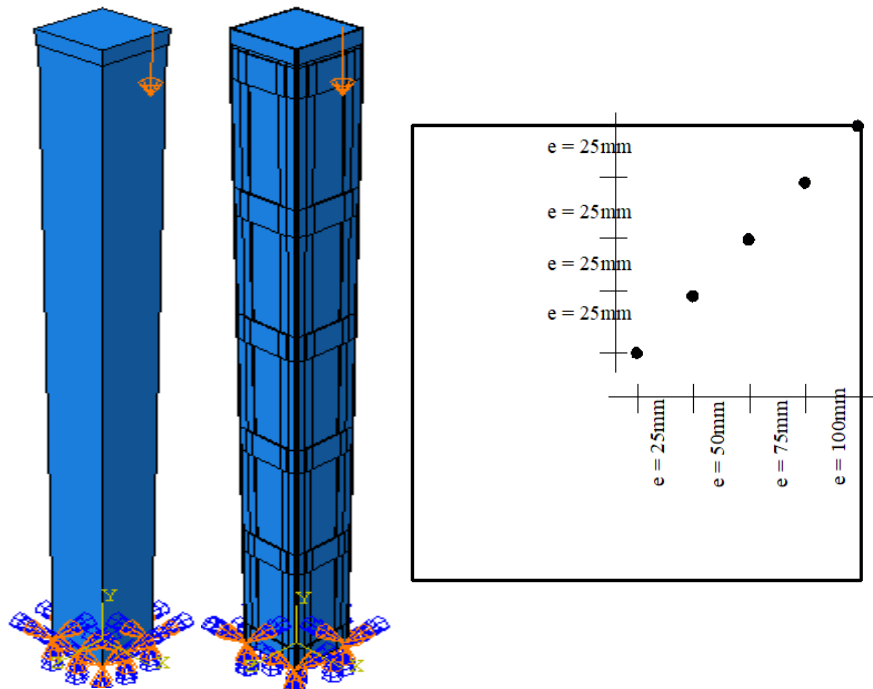


Figure 4-4 Bi axial eccentric loading on strengthened column

#### 4.2.2.1. Capacity of the column under bi directional eccentricities

The Bi directional ultimate capacity of reference and strengthened column under different eccentricity values ( $e_x, e_z = 25\text{mm}, 50\text{mm}, 75\text{mm}$  and  $100\text{mm}$ ) is shown.

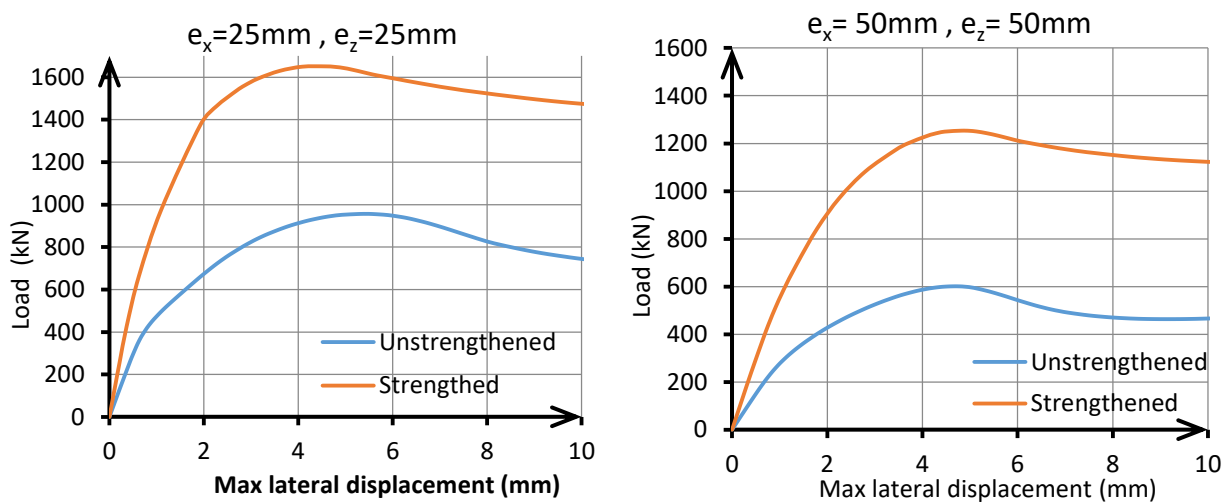


Figure 4-5 Bi axial eccentric P-U relations for 25 and 50 mm eccentricity

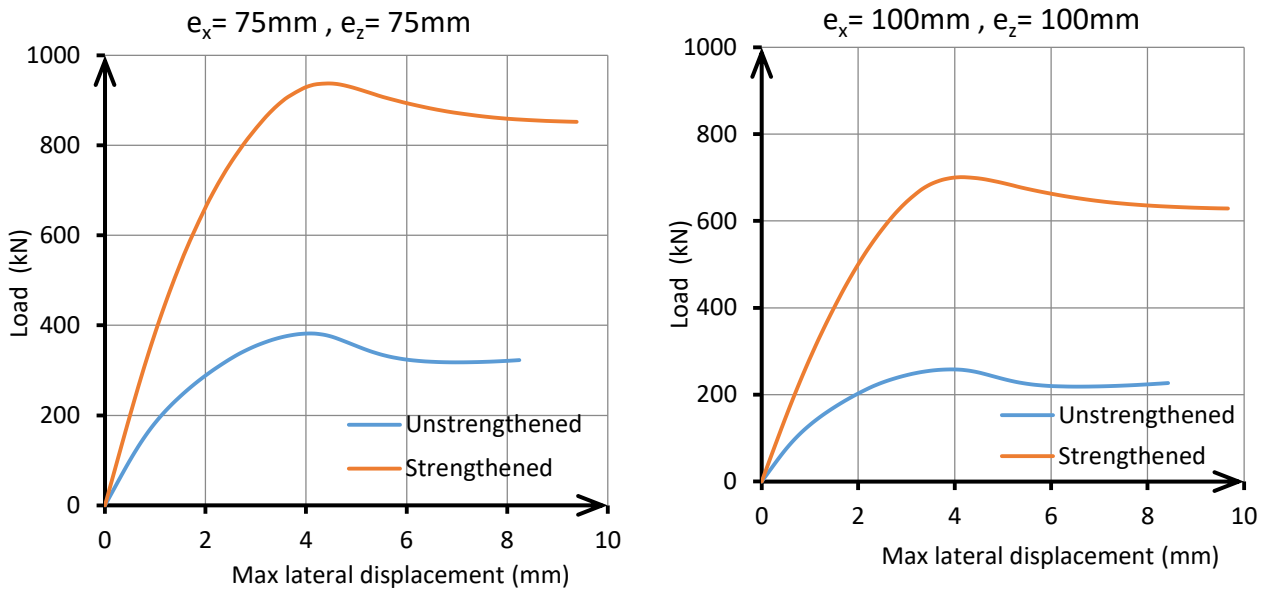


Figure 4-6 P-U for 75 and 100 mm Bi directional eccentricity

Values for reference and strengthened column under Bi directional eccentricities are given below.

Table 4-4 Results of reference and strengthened column for different Bi directional eccentricity

	$e_x = 25\text{mm} \ \& \ e_z = 25\text{mm}$	$e_x = 50\text{mm} \ \& \ e_z = 50\text{mm}$	$e_x = 75\text{mm} \ \& \ e_z = 75\text{mm}$	$e_x = 100\text{mm} \ \& \ e_z = 100\text{mm}$
	Ultimate capacity (kN)	Ultimate capacity (kN)	Ultimate capacity (kN)	Ultimate capacity (kN)
Un strengthened	956.45	601.08	381.98	258.26
Strengthened	1651.32	1253.5	937.58	700.83
% increase with respect to un-strengthened column	72.65%	108.54%	145.45%	171.36%

### 4.2.3. Effect of concrete grade

Generally, the structural load capacity is directly proportional with concrete grade. With increasing concrete grade, strength increases. The strengthening method (steel cage with angle and strip) is effectiveness in increasing column capacity both for axial as well as in eccentric loading.

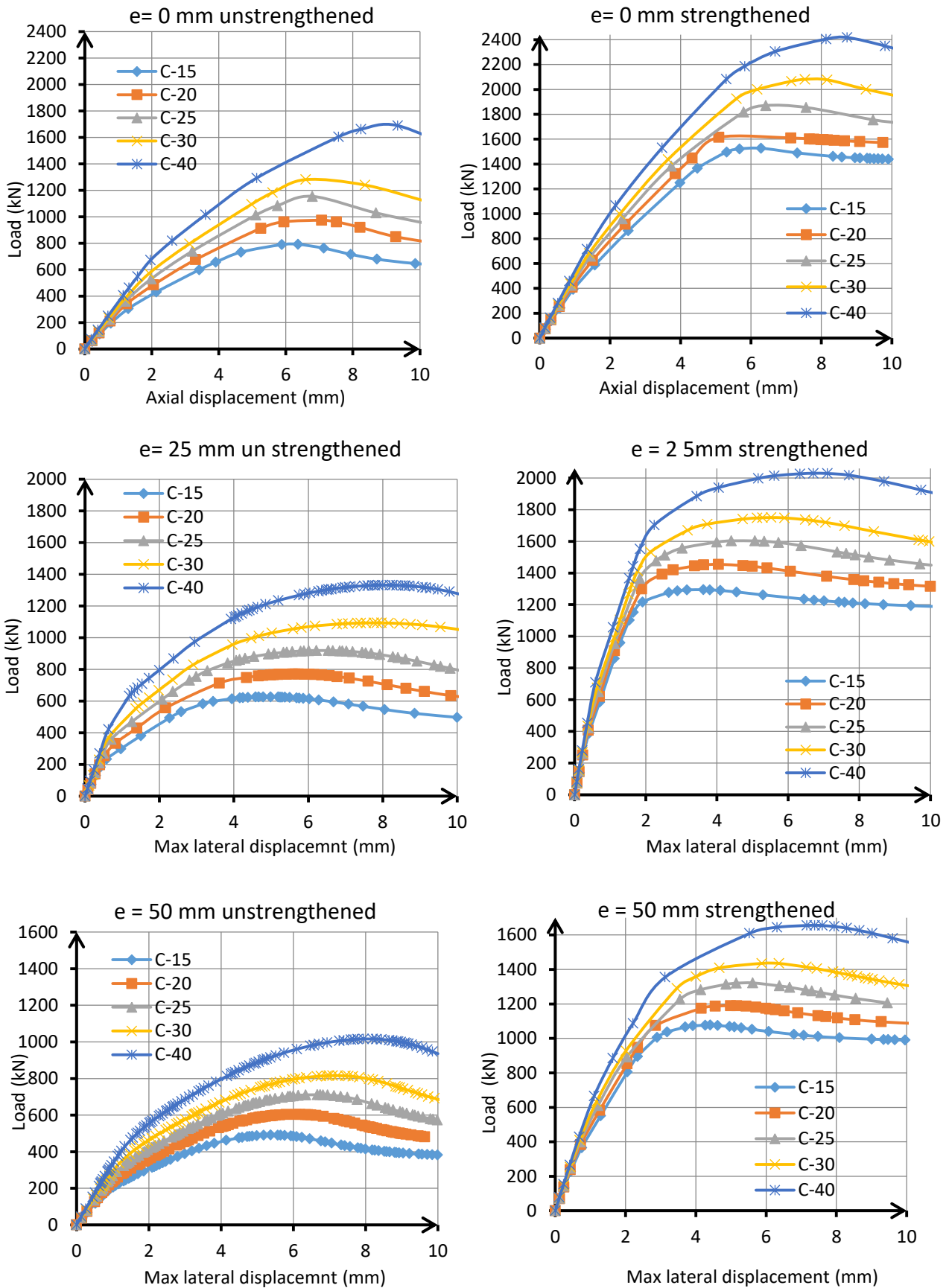


Figure 4-7 P-U responses of different concrete grades for 0 mm, 25 mm & 50 mm

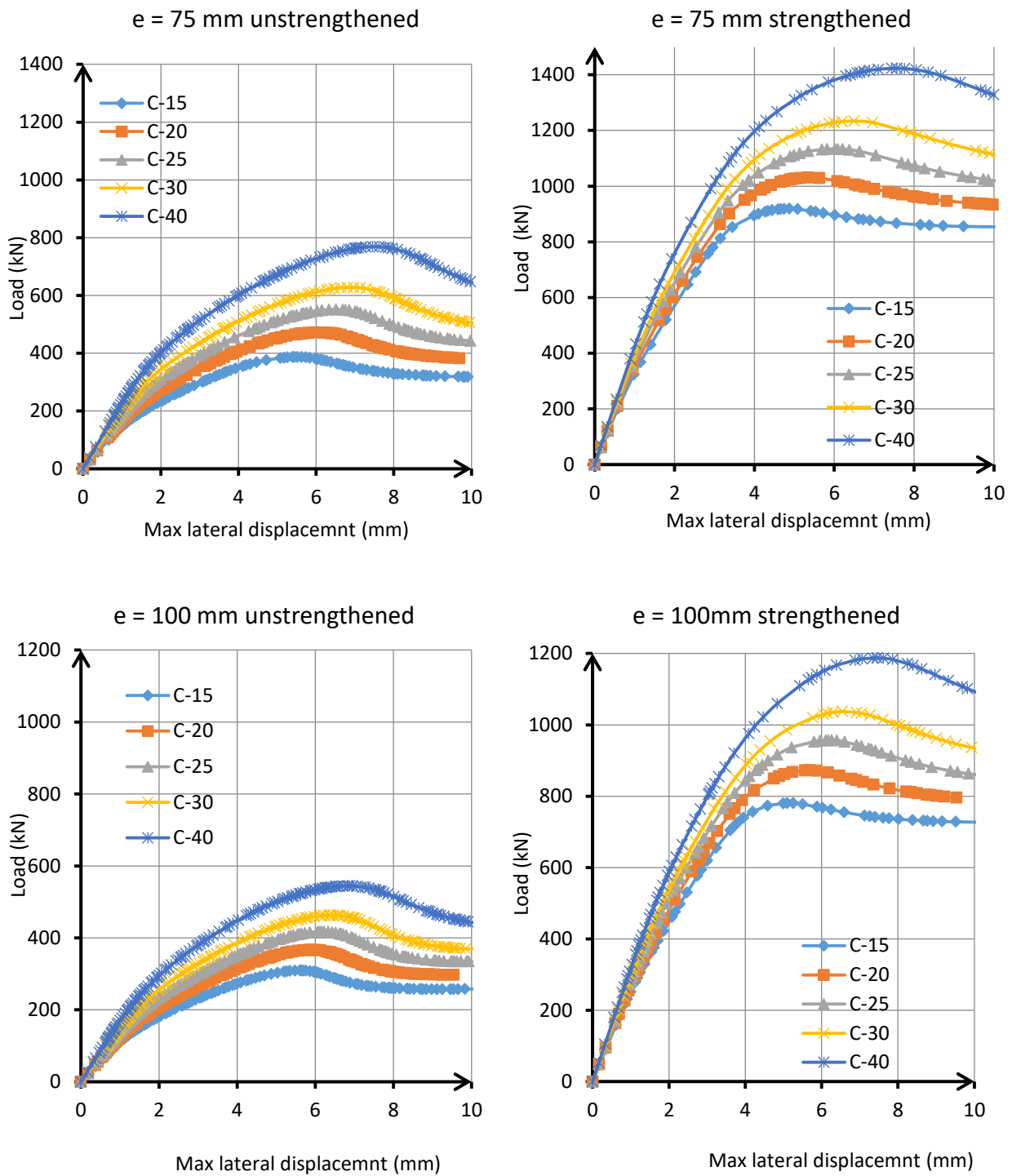


Figure 4-8 P-U responses of different concrete grades for 75 mm & 100 mm eccentricity

The result shows the efficiency of the strengthened method decreases as the concrete grade increases and hence for column designed with low concrete grade the method is very effective as compared with medium strength concrete.

Table 4-5 Ultimate capacity values for concrete grade for all eccentricity levels

		Ultimate capacity (kN)		
		Un strengthened column	Strengthened column	% increase with respect to un-strengthened column
e = 0 mm	C-15	792.01	1526.84	92.78%
	C-20	973.38	1615	65.92%
	C-25	1154.69	1870.65	62.00%
	C-30	1281.32	2080.95	62.41%
	C-40	1689.34	2417.61	43.11%
e = 25 mm	C-15	626.41	1294.29	106.62%
	C-20	769.94	1454.82	88.95%
	C-25	918.77	1602.91	74.46%
	C-30	1093.24	1749.87	60.06%
	C-40	1331.36	2029.11	52.41%
e = 50 mm	C-15	490.85	1076.65	119.34%
	C-20	603.73	1189.67	97.05%
	C-25	711.17	1321.92	85.88%
	C-30	815.79	1435.3	75.94%
	C-40	1016.23	1655.87	62.94%
e = 75 mm	C-15	387.03	918.92	137.43%
	C-20	471.66	1030.65	118.51%
	C-25	551.76	1133.72	105.47%
	C-30	628.01	1233.77	96.46%
	C-40	768.88	1423.19	85.10%
e = 100 mm	C-15	309.32	780.14	152.21%
	C-20	366.61	872.27	137.93%
	C-25	417.39	956.69	129.21%
	C-30	462.94	1037.3	124.07%
	C-40	544.32	1187.36	118.13%

From the above table we can see that for all eccentricity level the ultimate capacity of steel jacketed RC column decreases as concrete grade increases, and for a given concrete grades, as eccentricity increases the structural capacity decreases. For pure axial load a larger ultimate capacity is obtained for all concrete grades.

#### 4.2.4. Effect of angle grade

The composite action of RC structures is a function of the structural steel grade and the research considers four steel grades S-230, S-300, S-360 and S-460.

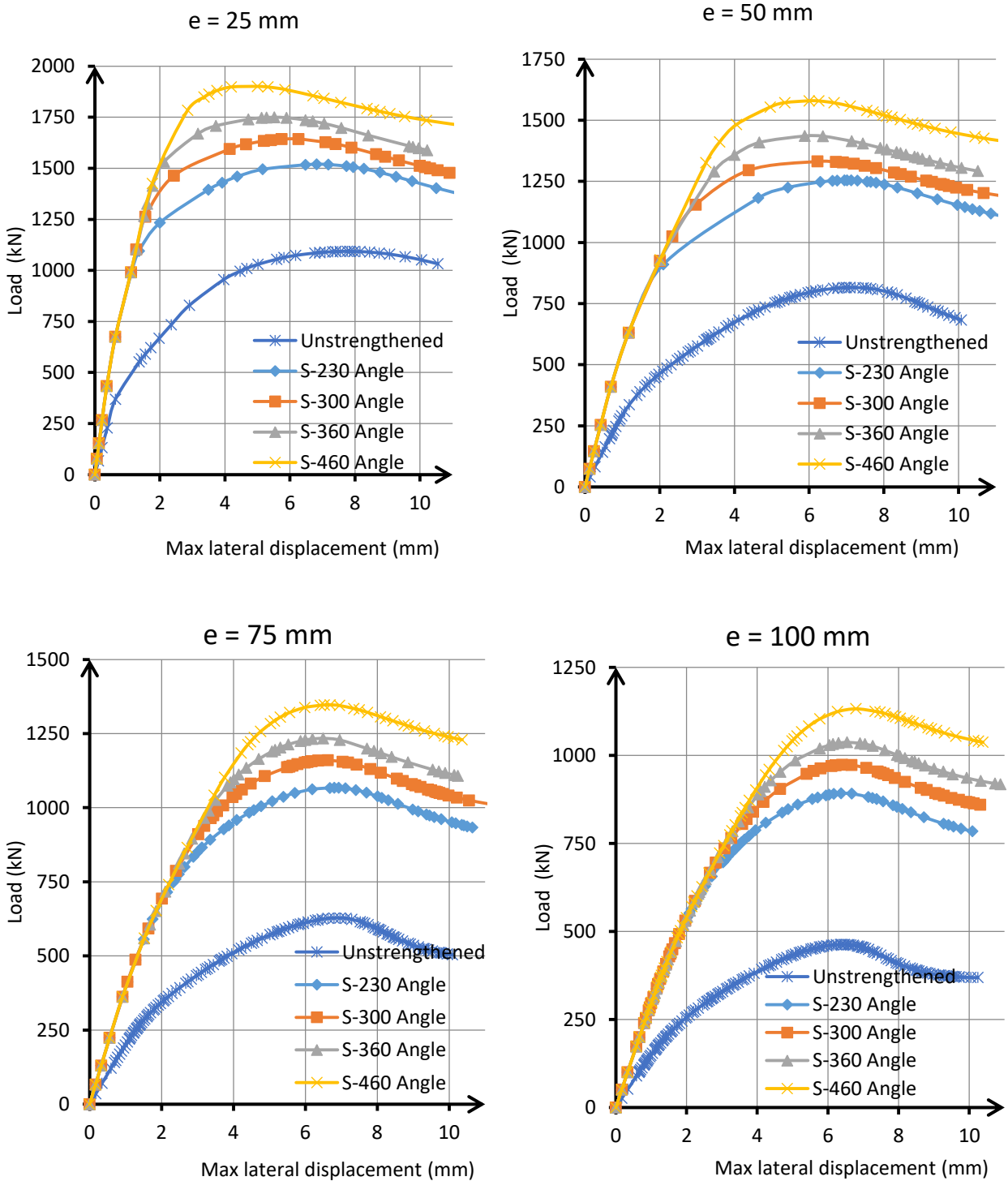


Figure 4-9 P-U responses of angle steel grades for different eccentricity

Table 4-6 Ultimate capacity values of different angle steel grades for different eccentricity

			Ultimate capacity (kN)	% increase with respect to Un-strengthened column
e = 0 mm	Un strengthened		1281.32	-
	Strengthened	S - 230	1837.57	43.41%
		S - 300	1979.69	54.50%
		S - 360	2080.95	62.41%
		S- 460	2204.45	72.05%
e = 25 mm	Un strengthened		1093.24	-
	Strengthened	S - 230	1519.65	39.00%
		S - 300	1643.62	50.34%
		S - 360	1749.87	60.06%
		S- 460	1901.21	73.91%
e = 50 mm	Un strengthened		815.79	-
	Strengthened	S - 230	1254.23	53.74%
		S - 300	1331.45	63.21%
		S - 360	1435.3	75.94%
		S- 460	1579.51	93.62%
e = 75 mm	Un strengthened		628.01	-
	Strengthened	S - 230	1067.28	69.95%
		S - 300	1160.16	84.74%
		S - 360	1233.77	96.46%
		S- 460	1347.04	114.49%
e = 100 mm	Un strengthened		462.93	-
	Strengthened	S - 230	892.16	92.72%
		S - 300	973.41	110.27%
		S - 360	1037.3	124.07%
		S- 460	1132.38	144.61%

As we can see the structural capacity increases as angle steel grade increases however, for pure axial load we get the smallest capacity increment for the steel jacketed RC column.

#### 4.2.5. Effect of horizontal strip grade

The study investigates the effect of different steel grades for connecting strip (i.e. S-230, S-300, and S-360 and S-460 MPa).

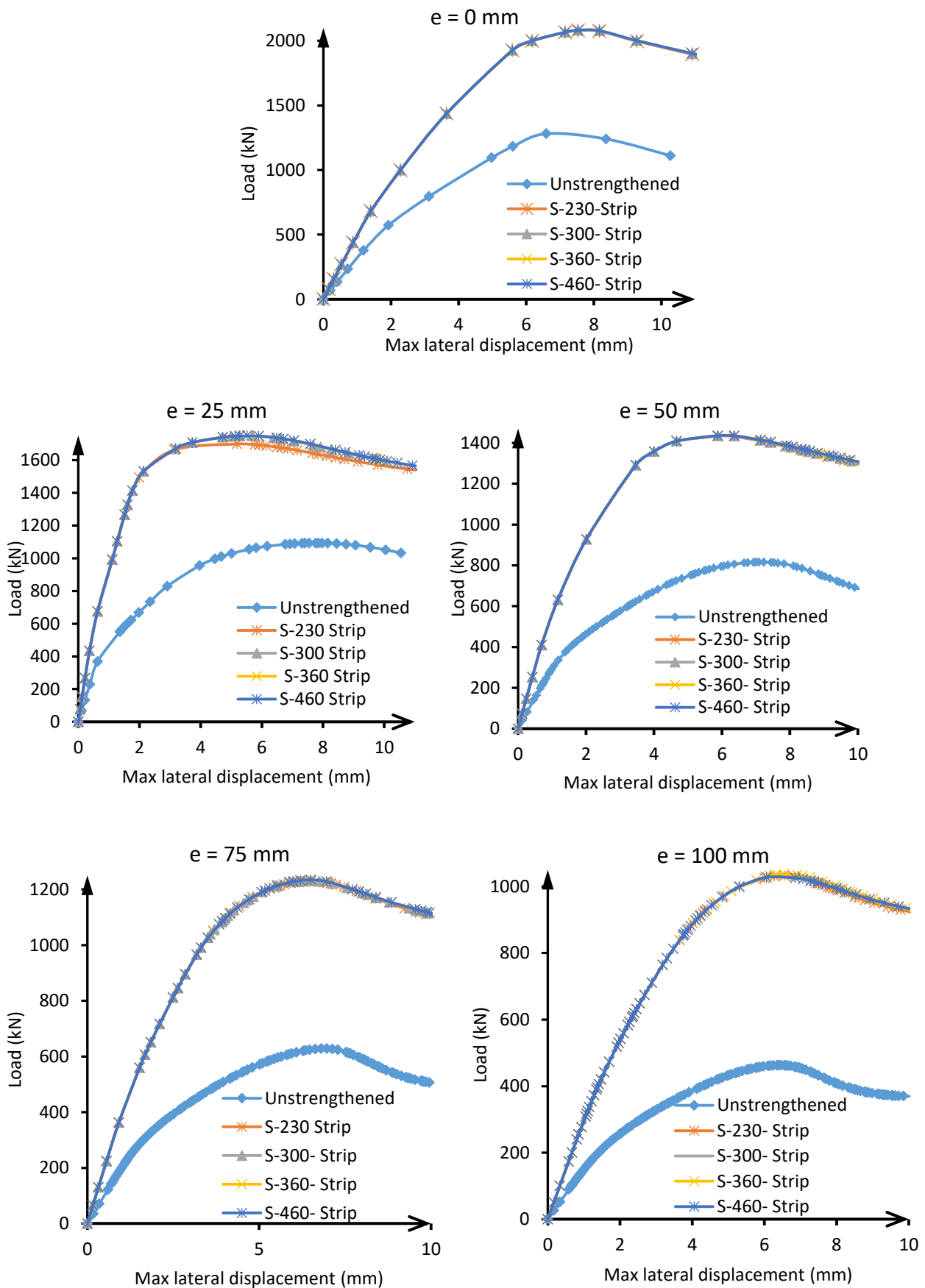


Figure 4-10 P-U responses of horizontal strip steel grades for different eccentricity

Table 4-7 Ultimate capacity values of different angle strip grades for different eccentricity

			Ultimate capacity (kN)	% increase with respect to un-strengthened column
e = 0 mm	Un strengthened		1281.32	-
	Strengthened	S - 230	2080.1	62.34%
		S - 300	2095.95	62.41%
		S - 360	2095.95	62.41%
		S- 460	2095.95	62.41%
e = 25 mm	Un strengthened		1093.24	-
	Strengthened	S - 230	1698.71	55.38%
		S - 300	1748.75	59.96%
		S - 360	1749.87	60.06%
		S- 460	1749.94	60.06%
e = 50 mm	Un strengthened		815.79	-
	Strengthened	S - 230	1433.33	75.69%
		S - 300	1434.96	75.89%
		S - 360	1435.3	75.93%
		S- 460	1435.31	75.94%
e = 75 mm	Un strengthened		628.01	-
	Strengthened	S - 230	1230.32	95.91%
		S - 300	1229.94	95.84%
		S - 360	1233.77	96.45%
		S- 460	1234.05	96.51%
e = 100 mm	Un strengthened		462.93	-
	Strengthened	S - 230	1032.18	122.96%
		S - 300	1033.87	123.32%
		S - 360	1037.3	124.07%
		S- 460	1027.68	121.92%

The structural capacity increases as strip steel grade increases however, for the specified level of eccentricity varying strip grade does not contribute much for capacity increment.

#### 4.2.6. Effect of plate configuration

The thesis investigates different plate configuration (11P 100X150X2.5mm, 6P100X150X5mm and 11P 50X150X5mm). The plate configurations were selected to have similar steel concrete ratio. The first configuration consists of 11 horizontal plates in each side with a plate thickness of 2.5mm and 100mm plate depth. The second configuration consists of 6 horizontal plates in each side with a thickness of 5mm and 100mm plate depth. The third has 11 plates in each side with thickness of 5mm and plate depth of 50mm.

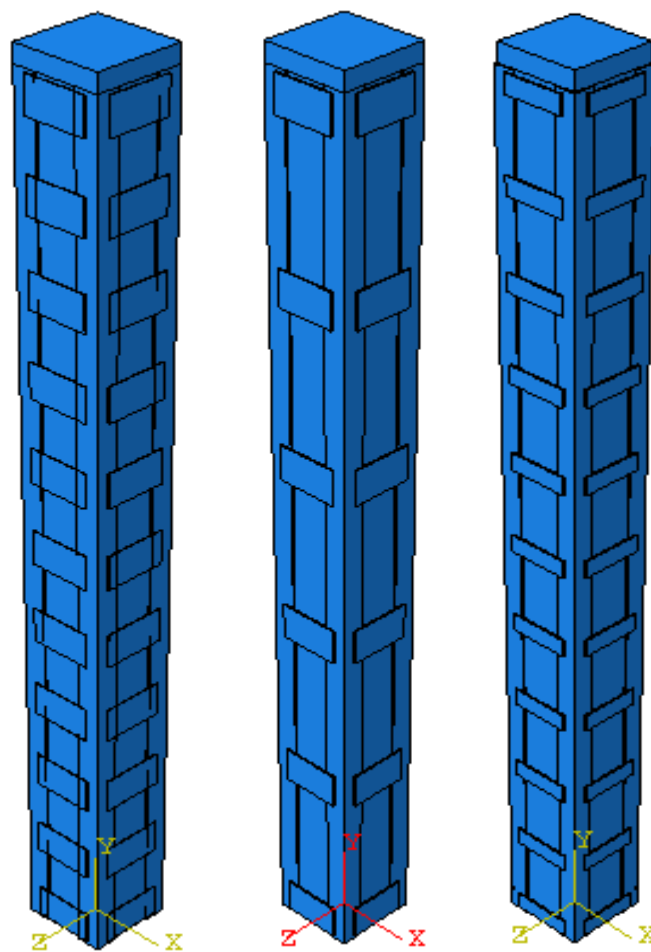


Figure 4-11 Strip configurations

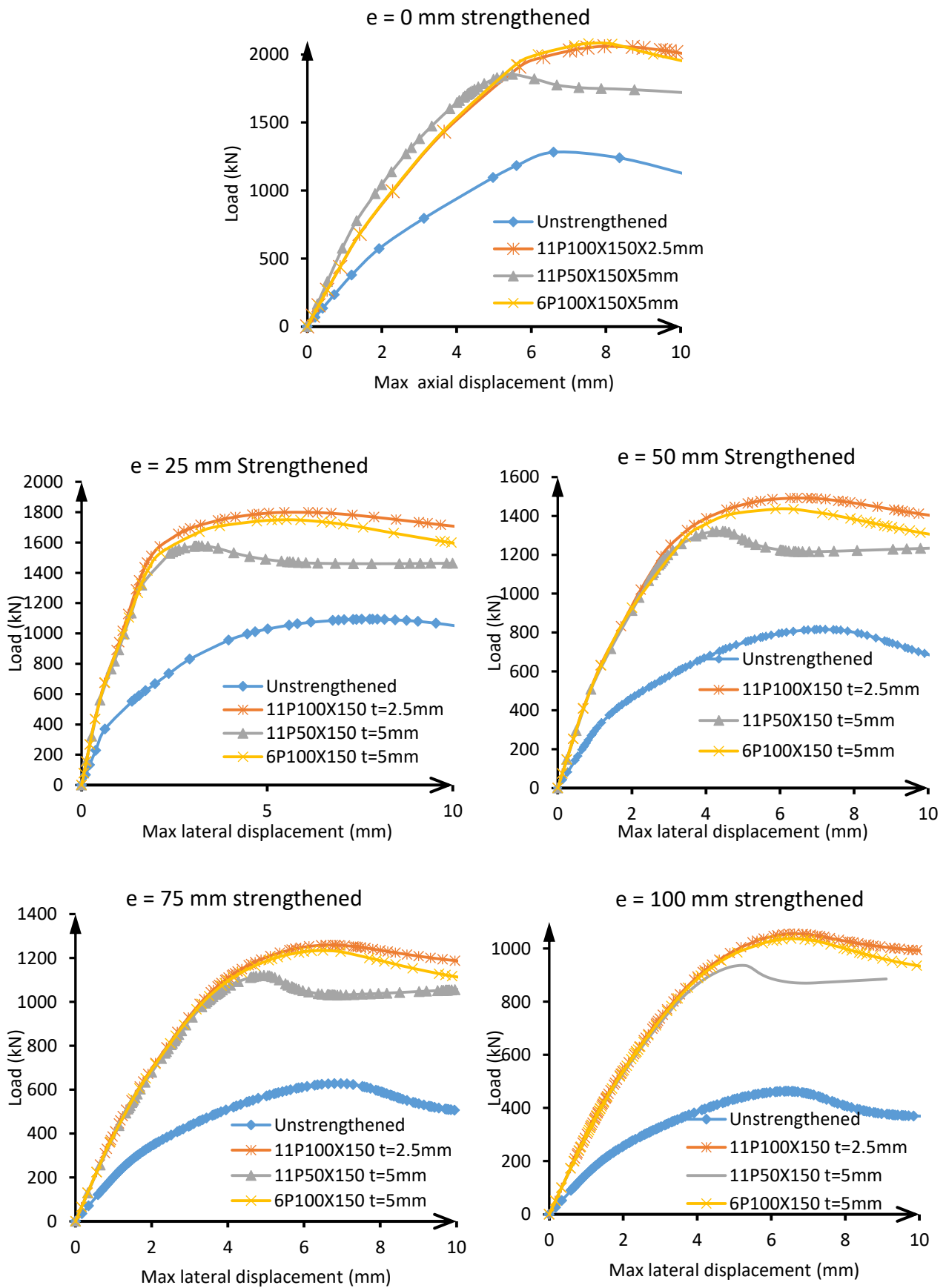


Figure 4-12 Capacity of column for different strip configuration and different eccentricity

Table 4-8 Ultimate capacity values for different strip configuration under different eccentricities

			Ultimate capacity (kN)	% increase with respect to un- strengthened column
e = 0 mm	Un-strengthened column		1281.32	-
	Strengthened	11P100X150-t=2.5mm	2059.57	60.73%
		11P50X150-t=5mm	1854.41	44.72%
		6P100X150-t=5mm	2080.95	62.41%
e = 25 mm	Un-strengthened column		1093.24	-
	Strengthened	11P100X150-t=2.5mm	1799.04	64.56%
		11P50X150-t=5mm	1576.6	44.21%
		6P100X150-t=5mm	1749.87	60.06%
e = 50 mm	Un-strengthened column		815.79	-
	Strengthened	11P100X150-t=2.5mm	1492.32	82.93%
		11P50X150-t=5mm	1321.34	61.96%
		6P100X150-t=5mm	1435.3	75.93%
e = 75 mm	Un-strengthened column		628.01	-
	Strengthened	11P100X150-t=2.5mm	1258.72	100.43%
		11P50X150-t=5mm	1120.3	78.38%
		6P100X150-t=5mm	1233.77	96.45%
e = 100 mm	Un-strengthened column		462.93	-
	Strengthened	11P100X150-t=2.5mm	1055.9	128.08%
		11P50X150-t=5mm	936.38	102.33%
		6P100X150-t=5mm	1037.3	124.06%

### 4.3. Critical parameter for eccentric load

From the parametric study of steel jacketed RC column a comparisons on ultimate capacity of angle grade, strip grade and strip configuration is made for different eccentricities. The critical parameter is obtained by comparing the ultimate capacity of strengthened column and reference column in terms of percentage increment with respect to un strengthened column.

Table 4-9 Ultimate capacity of angle grade, strip grade & strip configuration for eccentric load

		Ultimate capacity (kN)				
		e= 0mm	e= 25mm	e= 50mm	e= 75mm	e= 100mm
	Un strengthened	1281.32	1093.24	815.79	628.01	462.93
Angle grade	S-230	1837.57	1519.65	1254.23	1067.28	892.16
	% increase with respect to un-strengthened	43.41%	39%	53.74%	69.95%	92.72%
	S-300	1979.69	1643.62	1331.45	1160.16	973.41
	% increase with respect to un-strengthened	54.50%	50.34%	63.21%	84.74%	110.27%
	S-360	2028.95	1749.87	1435.3	1233.77	1037.3
	% increase with respect to un-strengthened	62.41%	60.06%	75.94%	96.46%	124.07%
	S-460	2204.45	1901.21	1579.51	1347.04	1132.38
	% increase with respect to un-strengthened	72.05%	73.91%	93.62%	114.49%	144.61%
Strip grade	S-230	2080.1	1698.71	1433.33	1230.32	1032.18
	% increase with respect to un-strengthened	62.34%	55.38%	75.69%	95.91%	122.96%
	S-300	2095.95	1748.75	1434.96	1229.94	1033.87
	% increase with respect to un-strengthened	62.41%	59.96%	75.89%	95.84%	123.32%
	S-360	2095.95	1749.87	1435.3	1233.77	1037.3
	% increase with respect to un-strengthened	62.41%	60.06%	75.93%	96.45%	124.07%
	S-460	2095.95	1749.94	1435.31	1234.05	1027.68
	% increase with respect to un-strengthened	62.41%	60.06%	75.94%	96.51%	121.92%
Strip configuration	11P100X150t=2.5mm	2059.57	1799.04	1492.32	1258.72	1055.9
	% increase with respect to un-strengthened	60.73%	64.56%	82.93%	100.43%	128.08%
	11P50X150t=5mm	1854.41	1576.6	1321.34	1120.3	936.38
	% increase with respect to un-strengthened	44.72%	44.21%	61.96%	78.38%	102.33%
	6P100X150- t=5mm	2080.95	1749.87	1435.3	1233.77	1037.3
	% increase with respect to un-strengthened	62.41%	60.06%	75.93%	96.45%	124.06%

From the above table we can see that the capacity increments for angle grade is between 43.41% - 72.01%, while strip grade gives a capacity increments between 62.34% - 62.41% and the strip

configuration provides 44.2% - 62.41%. From this result we can see that the angle grade steel property is the most critical parameter for strengthening under eccentric load.

#### 4.4. Combined effect of angle and strip grade for pure axial load

Table 4-10 Combined effect of angle and strip grade

			Ultimate capacity (kN)	% increase with respect to un-strengthened column
C-15	Un strengthened		792.01	-
	Strengthened	Angle S – 230 & Strip S-230	1289.5	62.81%
		Angle S – 300 & Strip S-300	1402.68	77.1%
		Angle S – 360 & Strip S-360	1526.84	92.78%
		Angle S – 460 & Strip S-460	1700	114.6%
C-20	Un strengthened		973.38	-
	Strengthened	Angle S – 230 & Strip S-230	1486	52.66%
		Angle S – 300 & Strip S-300	1621.5	66.58%
		Angle S – 360 & Strip S-360	1724.3	77.14%
		Angle S – 460 & Strip S-460	1879	93.03%
C-25	Un strengthened		1154.69	-
	Strengthened	Angle S – 230 & Strip S-230	1670	44.62%
		Angle S – 300 & Strip S-300	1816	52.27%
		Angle S – 360 & Strip S-360	1925.8	66.78%
		Angle S – 460 & Strip S-460	2109	82.64%
C-30	Un strengthened		1281.3	-
	Strengthened	Angle S – 230 & Strip S-230	1863	45.39%
		Angle S – 300 & Strip S-300	1983	54.76%
		Angle S – 360 & Strip S-360	2098	62.4%
		Angle S – 460 & Strip S-460	2286	78.41%
C-40	Un strengthened		1689.34	-
	Strengthened	Angle S – 230 & Strip S-230	2213	30.99%
		Angle S – 300 & Strip S-300	2362	39.81%
		Angle S – 360 & Strip S-360	2457	45.44%
		Angle S – 460 & Strip S-460	2638	56.15%

When we compare with strengthened column made with constant strip grade-different angle grade (i.e. effect of angle grade) and different angle grade-different strip grade (i.e. the above table), we can see that there is no significant variation in ultimate load thus, we can say that a combined effect of using higher concrete grade and higher angle grade is critical for pure axial load.

#### 4.5. Finite element modeling of cyclic load

##### 4.5.1. Verification for cyclic load

The reliability of the finite element tool for cyclic loading is verified by using experimental test performed by (Pasala N., Dipti R. & Durgesh C, 2018)

The test setup and loading protocol is shown below.

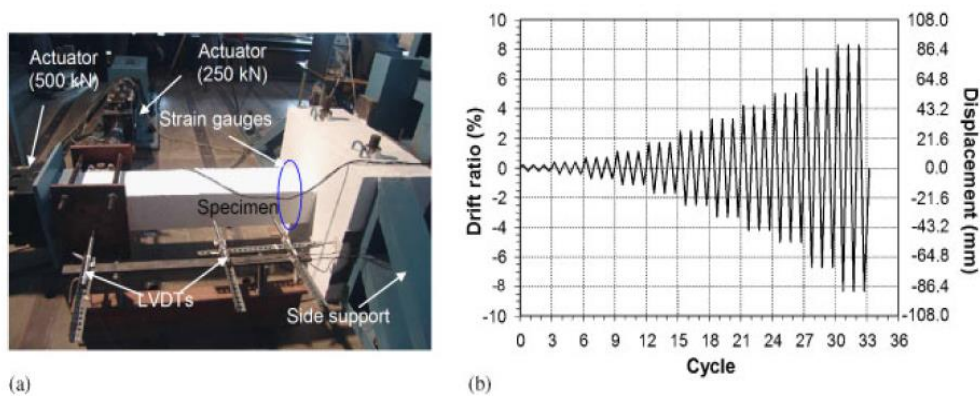


Figure 4-13 Experimental setup and loading for verification experiment

Finite element modeling of reference and strengthened column is shown below.

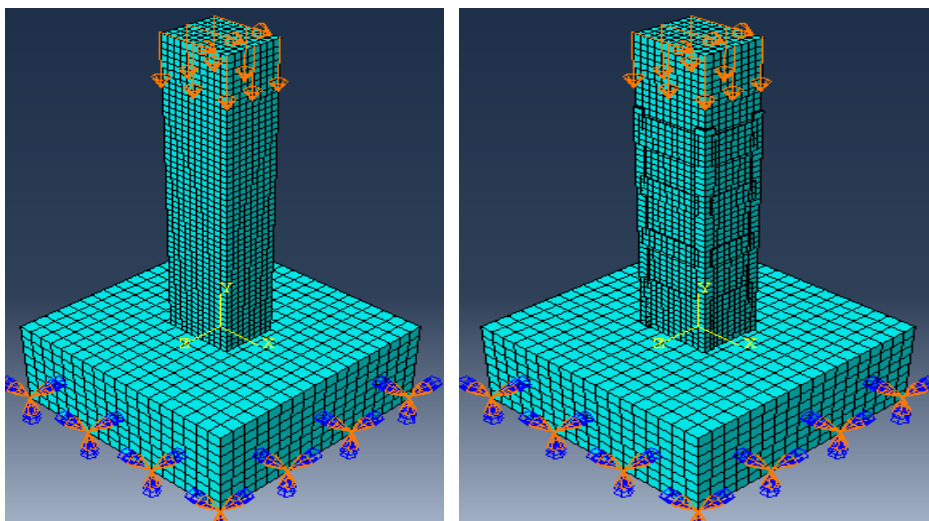


Figure 4-14 FEM modeling for reference and strengthened column for Nagaprasad

A comparison between experimental and FEM load displacement curve (hysteresis curve) for both reference and strengthened column is shown below.

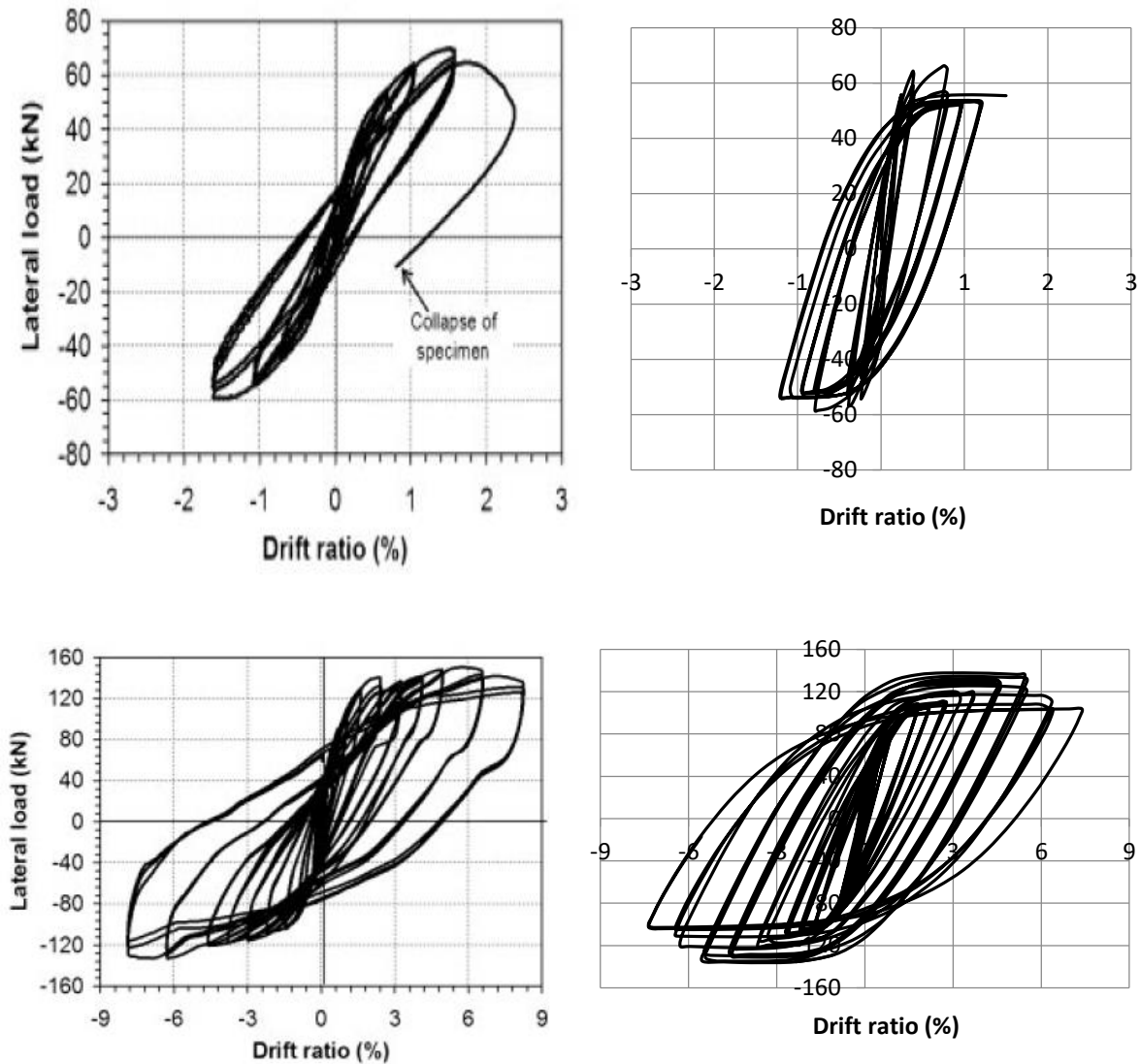


Figure 4-15 Verification P-U curve of EXP and FEM for reference & strengthened column

The numerical values for the reference and strengthened column under experimental and FEM are shown below

Table 4-11 Experimental and FEM results for Nagaprasad

	Maximum lateral strength (kN)	
	Experiment	FEM
Reference column	64.4	68.45
Strengthened column	141.5	137.6

From the experimental and finite element method results we can see that the FEM tool is capable of predicting the maximum lateral strength of the steel jacketed RC column. However, the FEM hysteresis curve tool does not fully reflect the stiffness degradation or pinching. Therefore it is clear that the FEM tool effectiveness is better for monotonic loading.

#### 4.5.2. Applied cyclic loading in the FEM

The Cyclic loading considered on the study is a reverse cyclic loading and is shown on the figure.

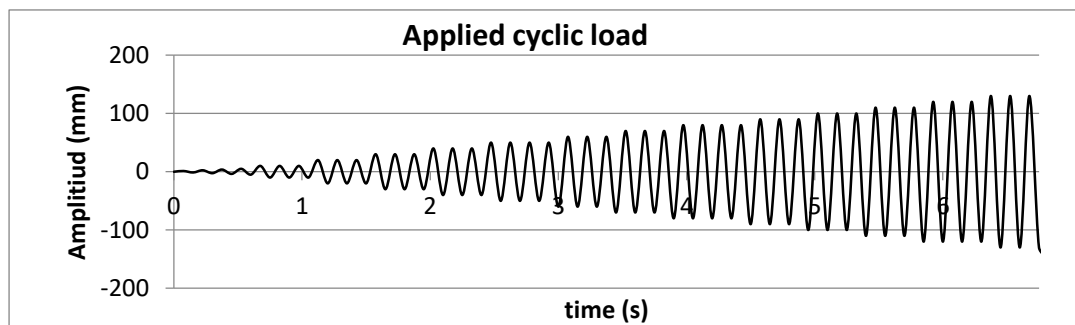


Figure 4-16 Cyclic load application for the FEM study

The loading is applied horizontally on the top of the column in X direction and axial load applied at the top of column in Y direction to simulate the structural loads from beam and slab. The base shear-displacement curve (hysteresis curve) for both reference and strengthened column is compared.

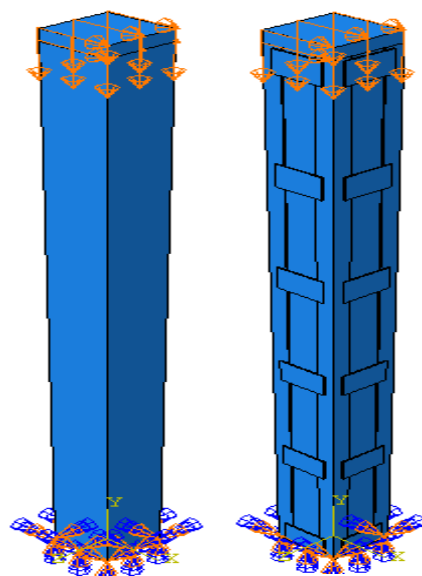


Figure 4-17 Cyclic load on reference and strengthened column

### 4.5.3. Effect of concrete grade

The studied concrete grades for cyclic response are C-15, C-20, C-25, C-30 and C-40. This concrete grades represent most of the current constructions.

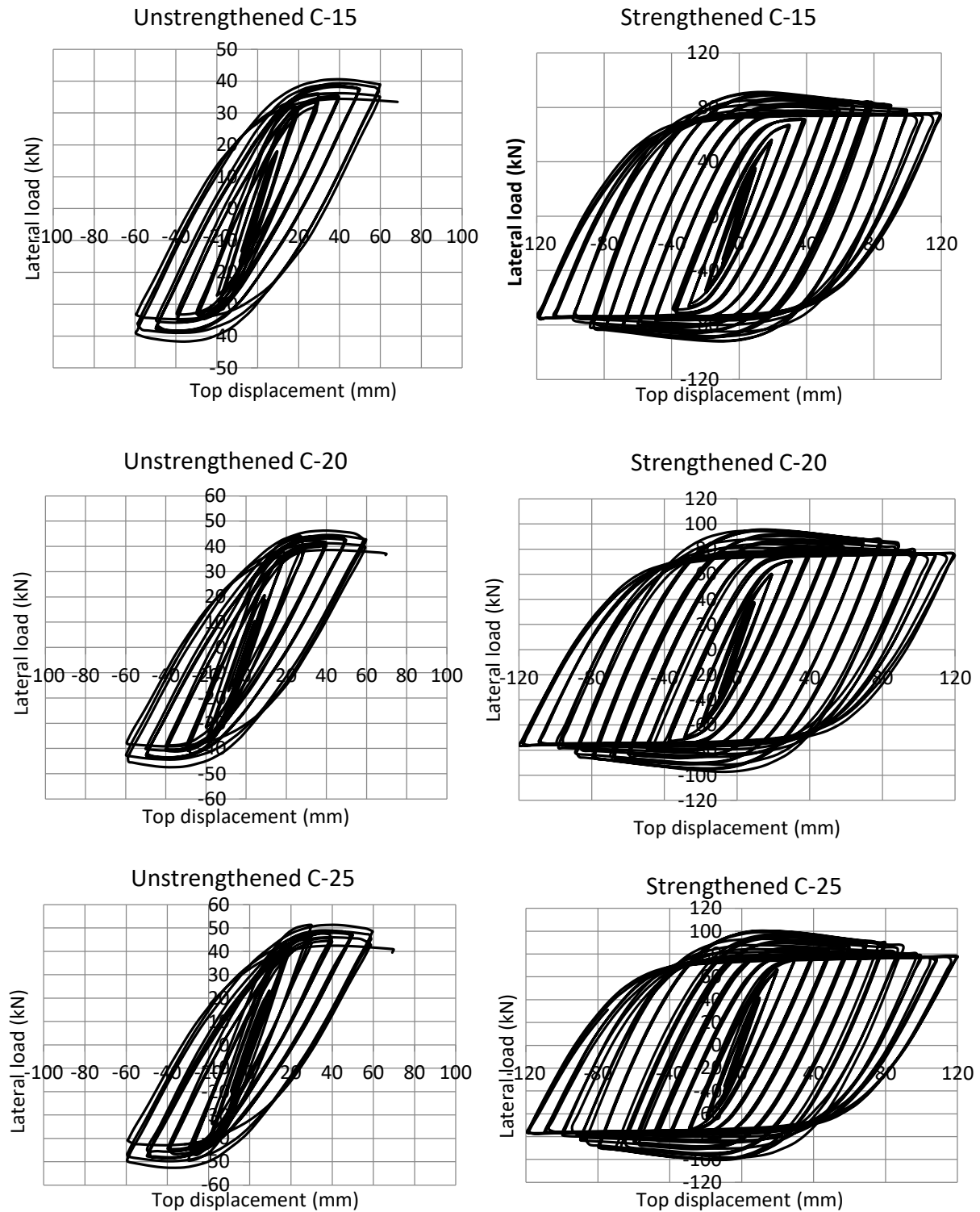


Figure 4-18 Hysteresis response for C-15, C-20 & C-25 concrete grade

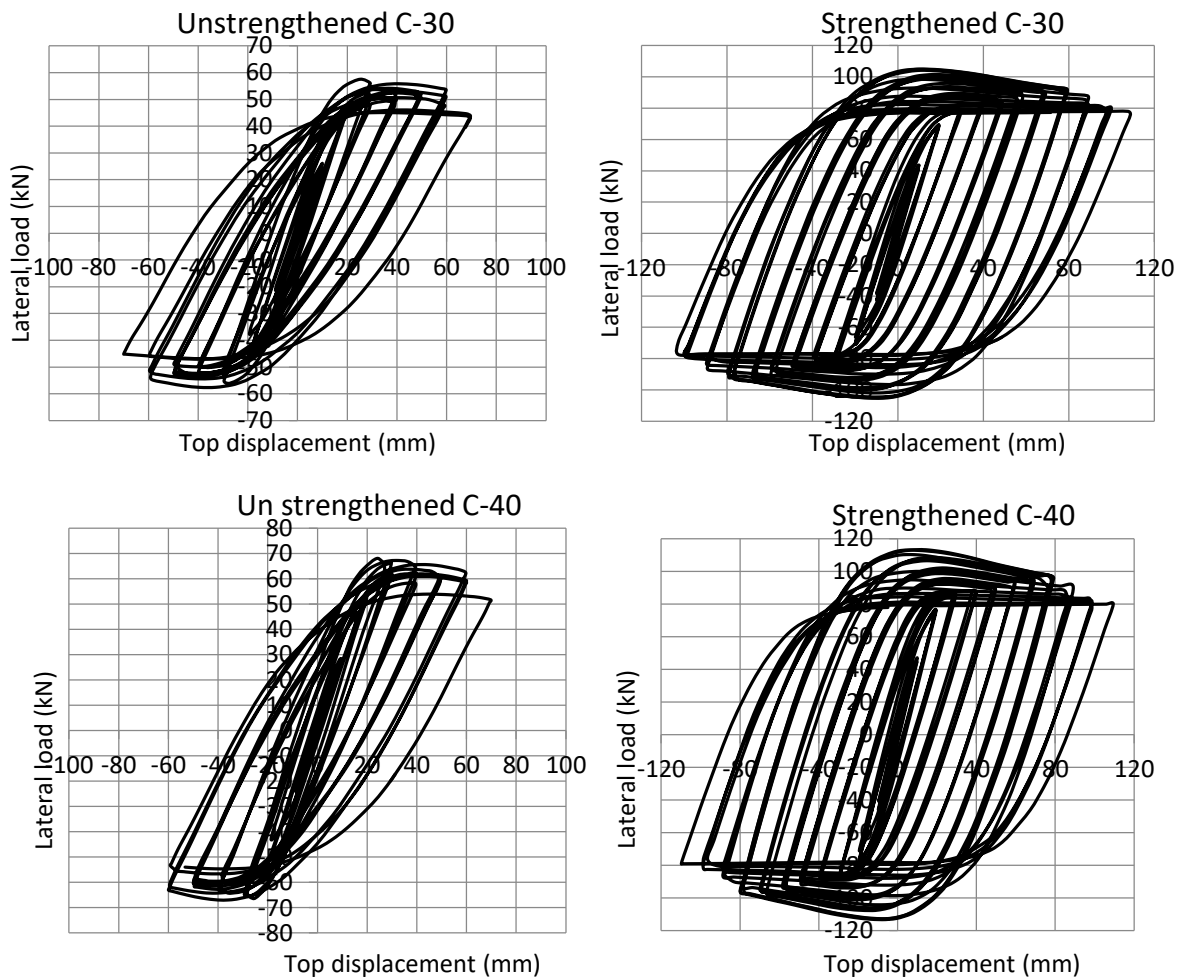


Figure 4-19 Hysteresis response for C-30 and C-40 concrete grade

Table 4-12 Ultimate capacity under cyclic load for different concrete grades

		Ultimate capacity (kN)	% increase with respect to un- strengthened
C-15	Un-strengthened	40.58	124.71%
	Strengthened column	91.21	
C-20	Un-strengthened	46.25	106.73%
	Strengthened column	95.61	
C-25	Un-strengthened	51.34	95.55%
	Strengthened column	100.39	
C-30	Un-strengthened	57.53	82.43%
	Strengthened column	104.96	
C-40	Un-strengthened	68.04	66.60%
	Strengthened column	113.37	

A significant strength increment is obtained for the given level of cyclic loading and uniform axial loading applied on top of column.

#### 4.5.4. Effect of angle grade

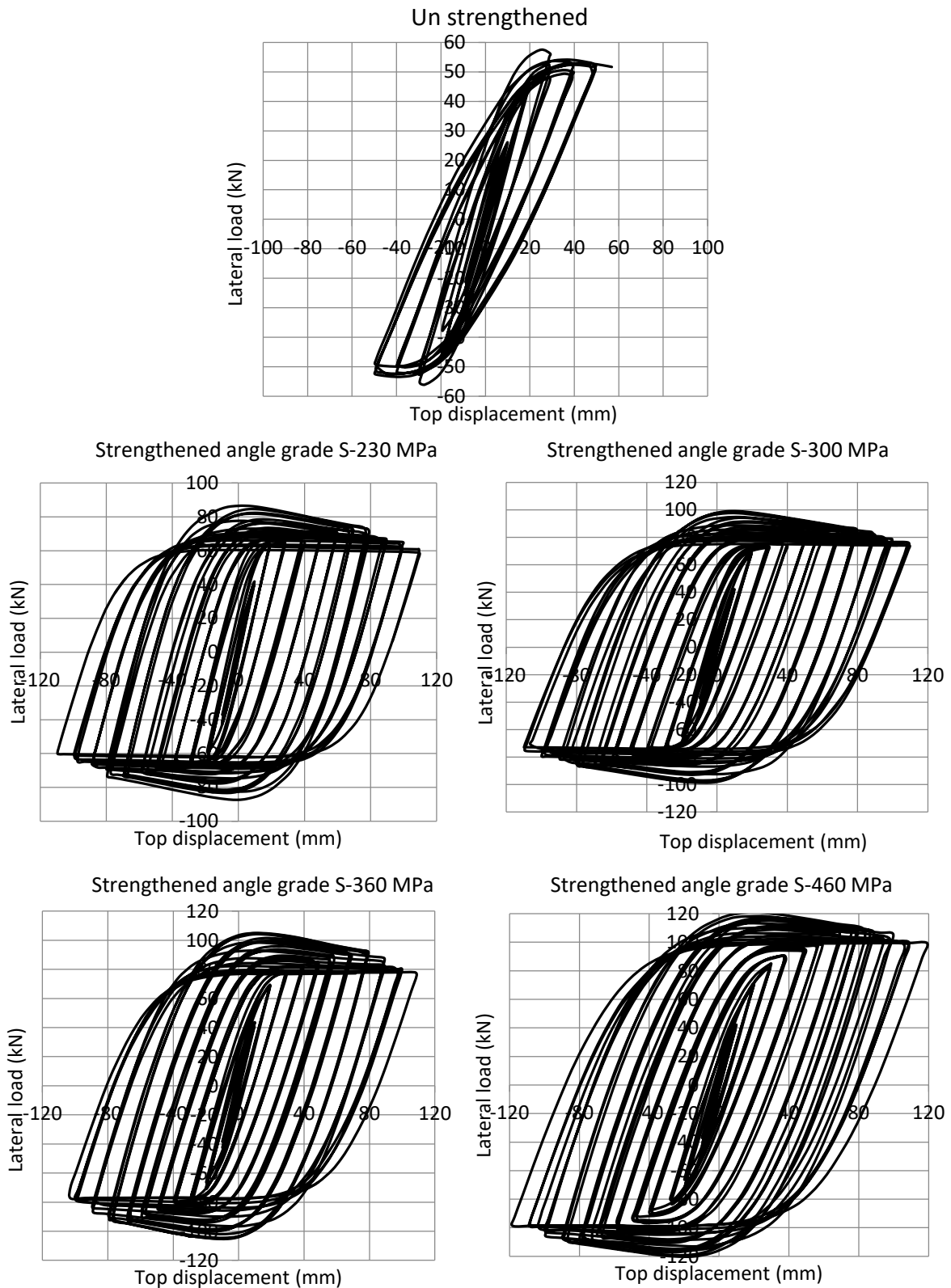


Figure 4-20 Hysteresis responses for different angle grade values

Table 4-13 Ultimate capacity for different angle grades

	Ultimate capacity (kN)			
	Strengthened S-230 MPa	Strengthened S-300 MPa	Strengthened S-360 MPa	Strengthened S-460 MPa
Un-strengthened column	57.53			
Strengthened column	86.61	99.09	104.95	121.01
% increase with respect to un-strengthened	50.55%	72.24%	82.43%	110.38%

#### 4.5.5. Effect of horizontal strip grade

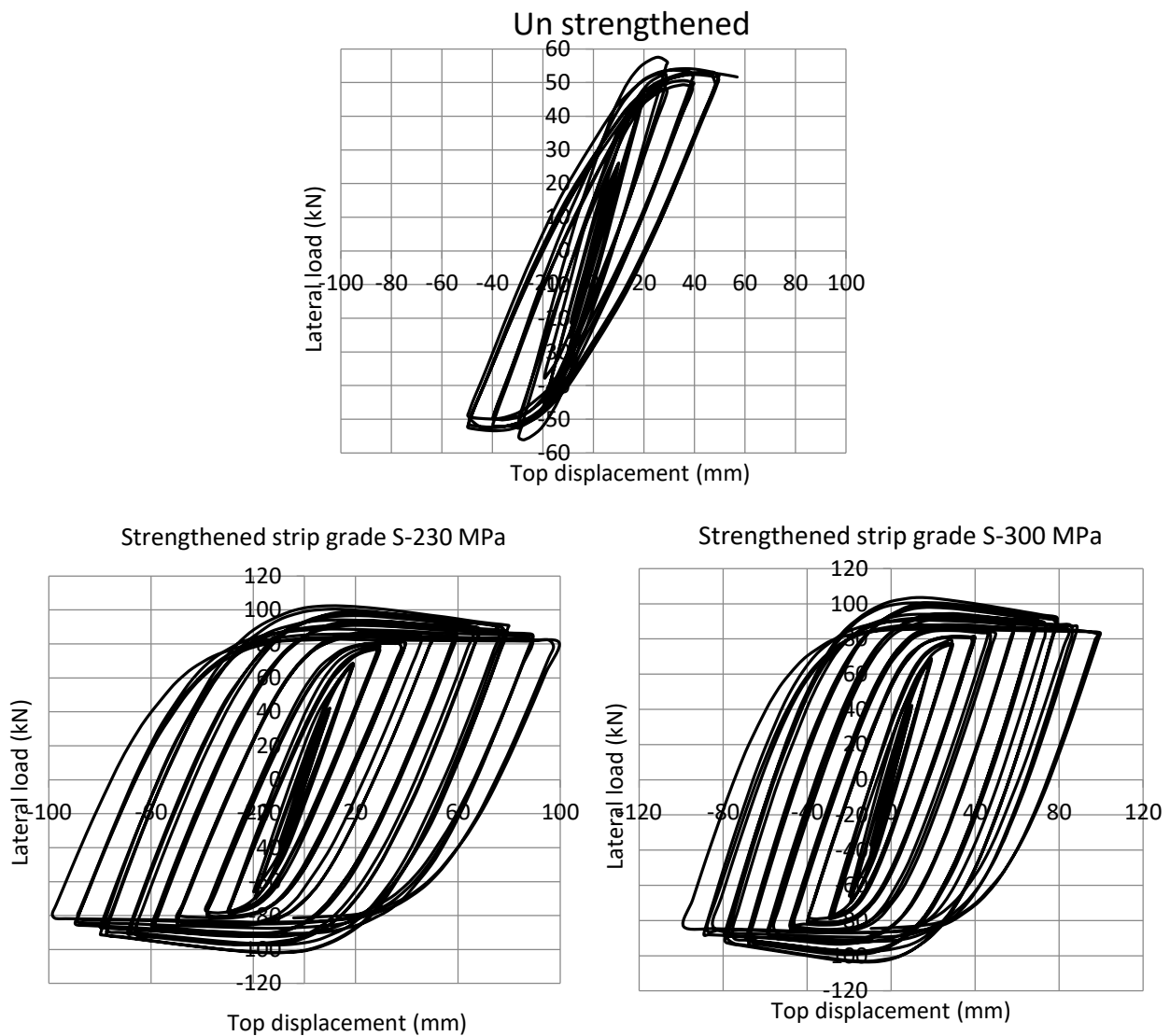


Figure 4-21 Hysteresis response of reference and strengthened with S-230& S-300 strip grade

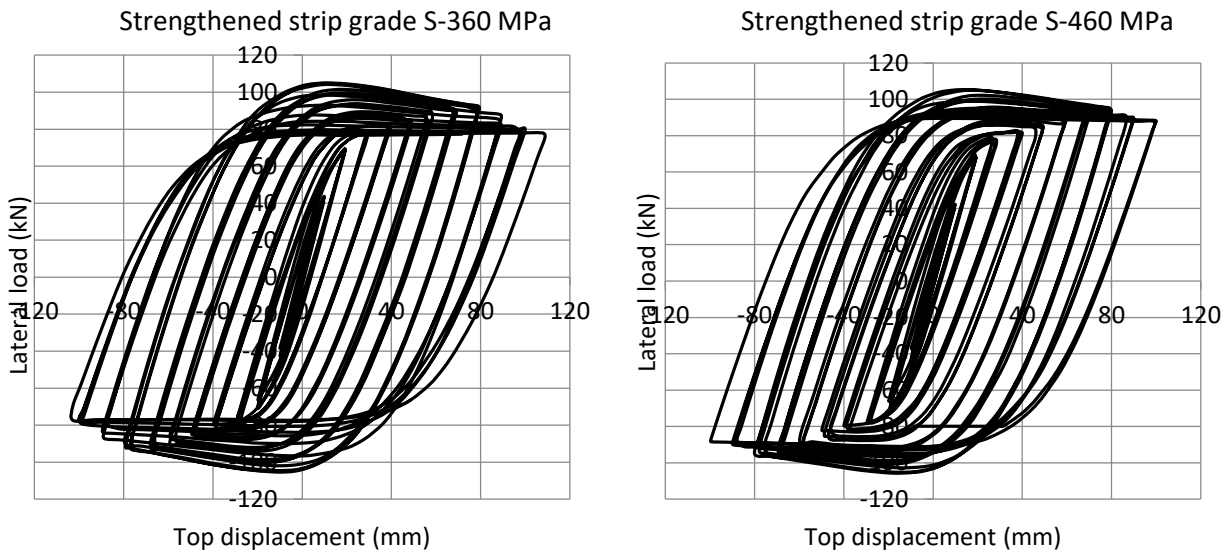


Figure 4-22 Hysteresis responses for S-360 and S-460 MPa strip grades

Table 4-14 Ultimate capacity of reference and strengthened column for different strip grades

	Ultimate capacity (kN)			
	Strengthened S-230 MPa	Strengthened S-300 MPa	Strengthened S-360 MPa	Strengthened S-460 MPa
Un-strengthened column	57.53			
Strengthened column	102.41	103.57	104.95	105.31
% increase with respect to un-strengthened column	78.01%	80.02%	82.43%	83.03%

#### 4.5.6. Effect of horizontal strip configuration

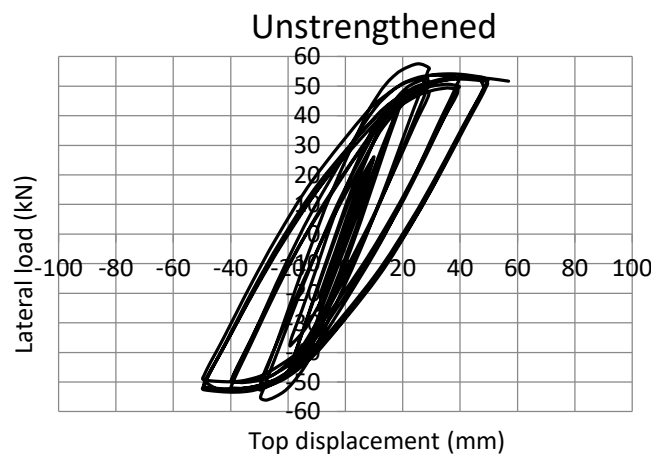


Figure 4-23 Hysteresis response of reference column

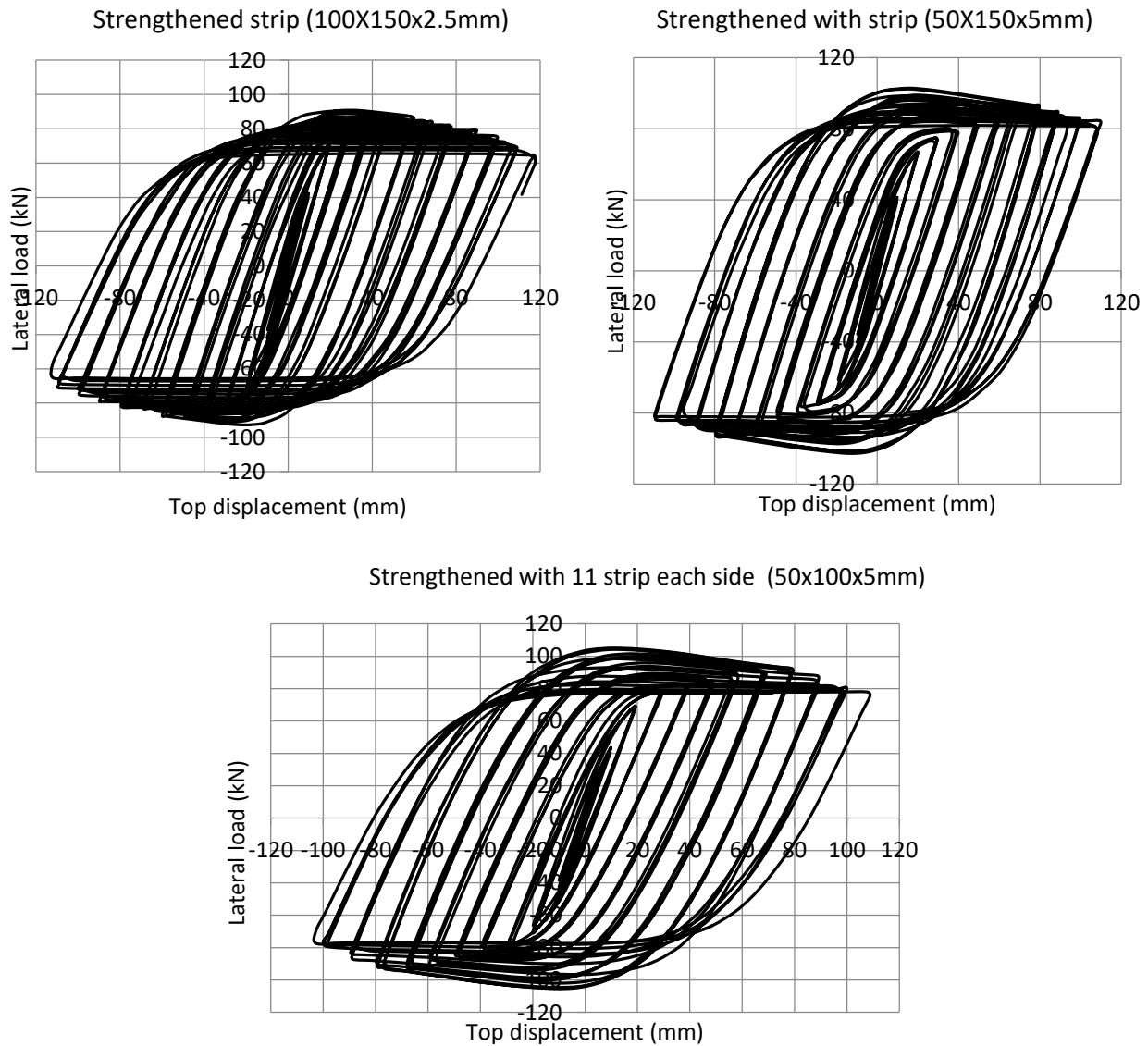


Figure 4-24 Hysteresis responses for different strip configuration

The maximum lateral capacity is obtained from the values of the hysteresis curve.

Table 4-15 Ultimate capacity for different strip configuration

	Ultimate capacity (kN)		
	Strengthened by 11 strip (100X150x2.5mm)	Strengthened by 6 strip (100X150x5mm)	Strengthened by 11 strip (50X150x5mm)
Un-strengthened column	57.53		
Strengthened column	90.83	104.95	102.86
% increase with respect to un-strengthened column	57.88%	82.43%	78.74%

### 4.6. Critical Parameter for cyclic load

A parametric study on the steel jacketed column for angle grade, strip grade and strip configuration is conducted by comparing with the un strengthened RC column under cyclic load.

Table 4-16 Ultimate capacity for angle grade, strip grade & strip configuration under cyclic load

		Ultimate capacity (kN)	
		Cyclic load	% increase with respect to un-strengthened column
	Un strengthened	57.53	
Angle grade	S-230	86.61	50.55%
	S-300	99.09	72.24%
	S-360	104.95	82.43%
	S-460	121.01	110.38%
Strip grade	S-230	102.41	78.01%
	S-300	103.57	80.02%
	S-360	104.95	82.43%
	S-460	105.31	83.03%
Strip configuration	11P100X150 t=2.5mm	90.83	57.88%
	11P50X150 t=5mm	102.86	78.74%
	6P100X150 t=5mm	104.95	82.43%

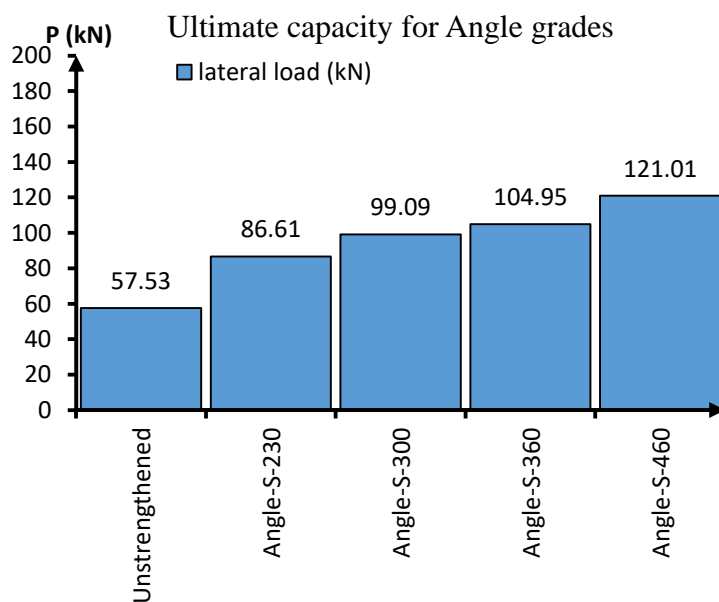


Figure 4-25 Maximum lateral load for angle grade

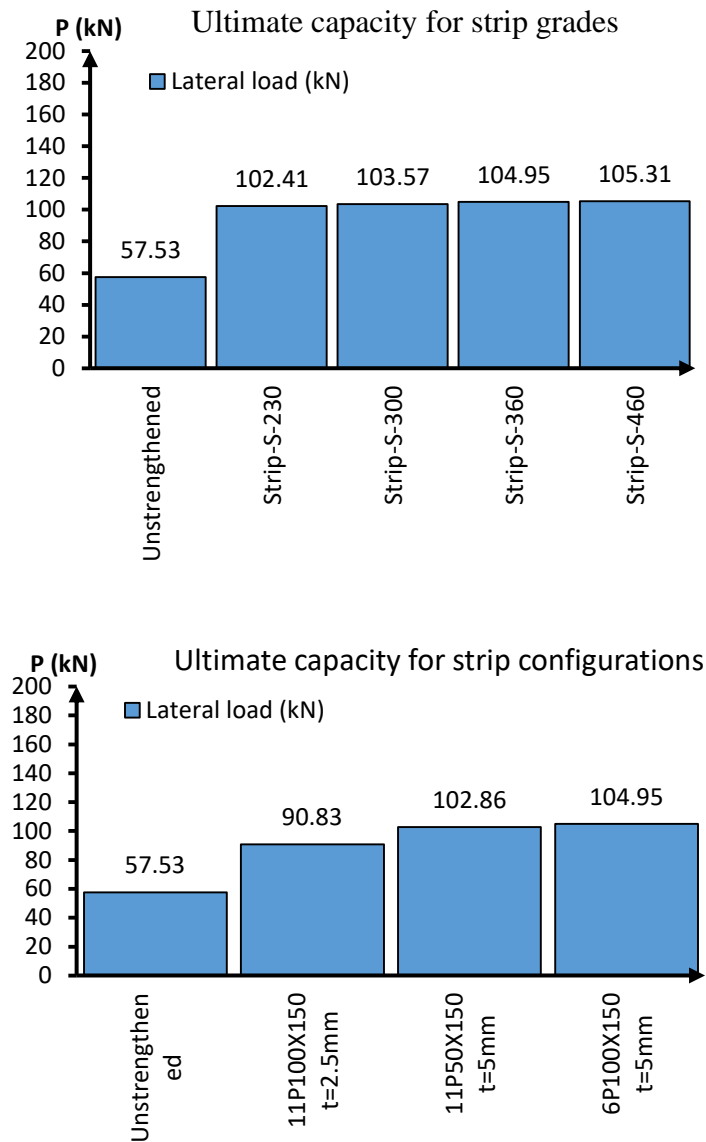


Figure 4-26 Maximum lateral load for strip grade and strip configurations

From the figures and tables above, we can see that angle grade is the most critical parameter when steel jacketed RC column (i.e. steel cage) is used because varying its steel grade critically influences the lateral load resistance of the column.

## 4.7. Comparison between monotonic and cyclic load

### 4.7.1. Effect of concrete grade

A comparative study for different concrete grades under monotonic and cyclic load is done by comparing the percentage increase of maximum capacity with respect to the un strengthened column

Table 4-17 Comparison between monotonic and cyclic load for concrete grade

		Monotonic-eccentric ultimate capacity (kN)					Cyclic ultimate capacity (kN)
		e = 0mm	e = 25mm	e =50mm	e =75mm	e =100mm	
C-15	Un strengthened	792.1	626.4	490.9	387.1	309.3	40.58
	Strengthened	1526.8	1294.3	1076.7	918.9	780.1	91.21
	% increase with respect to un-strengthened column	92.78%	106.62%	119.34%	137.43%	152.21%	124.71%
C-20	Un strengthened	973.4	769.9	603.7	471.7	366.6	46.24
	Strengthened	1615	1454.8	1189.7	1030.7	872.3	95.61
	% increase with respect to un-strengthened column	65.92%	88.95%	97.05%	118.51%	137.93%	106.73%
C-25	Un strengthened	1154.7	918.7	711.2	551.8	417.4	51.34
	Strengthened	1870.6	1602.9	1321.9	1133.7	956.7	100.39
	% increase with respect to un-strengthened column	62%	74.46%	85.88%	105.47%	129.21%	95.54%
C-30	Un strengthened	1281.3	1093.2	815.8	628.1	462.9	57.53
	Strengthened	2081	1749.9	1435.3	1233.8	1037.3	104.96
	% increase with respect to un-strengthened column	62.41%	60.06%	75.94%	96.46%	124.07%	82.43%
C-40	Un strengthened	1689.3	1331.4	1016.2	768.9	544.3	68.04
	Strengthened	2417.6	2029.1	1655.9	1423.2	1187.4	113.37
	% increase with respect to un-strengthened column	43.11%	52.41%	62.94%	85.10%	118.13%	66.61%

As concrete grade increases the ultimate capacity increment of the column decrease for both monotonic and cyclic load, therefore a column made with C-40 concrete provides minimum capacity increment for both loading conditions.

### 4.7.2. Angle steel grade

Table 4-18 Comparison between monotonic and cyclic load for angle grade

		Monotonic-eccentric ultimate capacity (kN)					Cyclic ultimate capacity (kN)
		e= 0mm	e= 25mm	e= 50mm	e= 75mm	e= 100mm	
S-230	Un strengthened	1281.32	1093.24	815.79	628.01	462.93	57.53
	Strengthened	1837.57	1519.65	1254.23	1067.28	892.16	86.61
	% increase with respect to un-strengthened column	43.41%	39%	53.74%	69.95%	92.72%	50.55%
S-300	Un strengthened	1281.32	1093.24	815.79	628.01	462.93	57.53
	Strengthened	1979.69	1643.62	1331.45	1160.16	973.41	99.09
	% increase with respect to un-strengthened column	54.50%	50.34%	63.21%	84.74%	110.27%	72.24%
S-360	Un strengthened	1281.32	1093.24	815.79	628.01	462.93	57.53
	Strengthened	2028.95	1749.87	1435.3	1233.77	1037.3	104.95
	% increase with respect to un-strengthened column	62.41%	60.06%	75.94%	96.46%	124.07%	82.43%
S-460	Un strengthened	1281.32	1093.24	815.79	628.01	462.93	57.53
	Strengthened	2204.45	1901.21	1579.51	1347.04	1132.38	121.04
	% increase with respect to un-strengthened column	72.05%	73.91%	93.62%	114.49%	144.61%	110.38%

As angle grade increases, higher structural capacity increments for both monotonic as well as cyclic loading are observed. Thus steel jacket (i.e. steel cage) made using S-460 steel angle grade provides the highest capacity increment for both monotonic as well as cyclic loadings.

### 4.7.3. Strip steel grade

For the strengthened RC column four steel grades are studied for the horizontal strip and a comparison is made between capacity increment under monotonic and cyclic loading.

Table 4-19 Comparison between monotonic and cyclic load for strip grade

		Monotonic-eccentric ultimate capacity (kN)					Cyclic ultimate capacity (kN)
		e=0mm	e=25mm	e=50mm	e=75mm	e=100mm	
S-230	Un strengthened	1281.32	1093.24	815.79	628.01	462.93	57.53
	Strengthened	2080.1	1698.71	1433.33	1230.32	1032.18	102.41
	% increase with respect to un-strengthened column	62.34%	55.38%	75.69%	95.91%	122.96%	78.01%
S-300	Un strengthened	1281.32	1093.24	815.79	628.01	462.93	57.53
	Strengthened	2095.95	1748.75	1434.96	1229.94	1033.87	103.57
	% increase with respect to un-strengthened column	62.41%	59.96%	75.89%	95.84%	123.32%	80.02%
S-360	Un strengthened	1281.32	1093.24	815.79	628.01	462.93	57.53
	Strengthened	2095.95	1749.87	1435.3	1233.77	1037.3	104.95
	% increase with respect to un-strengthened column	62.41%	60.06%	75.93%	96.45%	124.07%	82.43%
S-460	Un strengthened	1281.32	1093.24	815.79	628.01	462.93	57.53
	Strengthened	2095.95	1749.94	1435.31	1234.05	1027.68	105.31
	% increase with respect to un-strengthened	62.41%	60.06%	75.94%	96.51%	121.92%	83.03%

Varying strip grade does not help for capacity increment under monotonic loading, however, for cyclic load as we increase strip grade we get a capacity increment for a given eccentricity.

#### 4.7.4. Effect of plate configuration

Three types plate configurations are studied in the research namely 11P100X150 t = 2.5mm (11 plates of 100X150X2.5mm at each sides of the column), 11P50X150 t = 5mm (11 plates of 50X150X5mm at each sides) and 6P100X150 t = 5mm (6 plates of 100X150X5mm at each sides). A comparison is made with respect to percentage increment of maximum capacity for both eccentric and cyclic load.

Table 4-20 Comparison between monotonic and cyclic load for strip configuration

	Ultimate capacity (kN)					
	Monotonic-eccentric					Cyclic
	e= 0 mm	e= 25 mm	e= 50 mm	e= 75 mm	e = 100 mm	
Un Strengthened column	1281.32	1093.24	815.79	628.01	462.93	57.53
Strengthened 11P100X150 t =2.5mm	2059.57	1799.04	1492.32	1258.72	1055.9	90.83
% increase with respect to un-strengthened column	60.73%	64.56%	82.93%	100.43%	128.08%	57.88%
Strengthened 11P50X150 t =5mm	1854.41	1576.6	1321.34	1120.3	936.38	102.86
% increase with respect to un-strengthened column	44.72%	44.21%	61.96%	78.38%	102.33%	78.74%
Strengthened 6P100X150 t =5mm	2080.95	1749.87	1435.3	1233.77	1037.3	104.95
% increase with respect to un-strengthened column	62.41%	60.06%	75.93%	96.45%	124.06%	82.43%

From the above results, we can see that plate configuration 11P50X150 t =5mm provides lower capacity increment under all eccentric loadings when compared to other configurations. Similarly, plate configuration 11P100X150 t =2.5mm provides least capacity increment for cyclic load. When compared to other configurations.

## 5. CONCLUSION AND RECOMMENDATION

### 5.1. Conclusion

The finite element modeling findings for eccentric and cyclic loading are summarized as follows.

1. For both uni-directional and bi-directional eccentricity the strengthening method gives a significant capacity increment.
2. Bi directional eccentricity provides a higher capacity increment than a uni directional one. For a given eccentricity.
3. As eccentricity increases, the capacity increment for all concrete grades decreases. However, for a given concrete grade as eccentricity increases the capacity increases.
4. As strengthening angle grade increases the load resisting capacity increases. For a given angle grade as eccentricity increases the capacity increment also increases.
5. As strengthening strip grade increases the load resisting capacity increases however, for a given eccentricity as the strip grade increases the efficiency of the method remains constant.
6. Plate configuration 11Px100x150x2.5mm gives the best performance for 25, 50, 75 and 100 mm eccentricity and 11Px50x150x5mm gives the least performance for the considered eccentricity, however for specified plate configuration efficiency of the method increases as eccentricity increases for 25, 50, 75 and 100 mm.
7. The combination of Concrete grade and Angle grade provides higher capacity for Monotonic axial load.
8. As concrete grade increases the capacity increment of the method decreases under cyclic loading and C-15 concrete provides large capacity increment.
9. As angle grade increases the lateral load carrying capacity increases under cyclic load and hence S-460 MPa angle grade gives large increment.
10. As strip grade increases structural load resistance increases under cyclic loading

11. Plate configuration of 6P×100×150×5mm provides the highest capacity increment under cyclic load as compared with other configurations and 11P×100×150×2.5mm gives the least performance for cyclic load.
12. From the hysteresis curves we can see that the FEM tool does not fully reflect the stiffness degradation or pinching.

## **5.2. Recommendation**

The conclusions drawn from the thesis are limited for rectangular section and fixed column dimensions and hence for other conditions like slenderness effect, steel to concrete ratio and different loading conditions, an extensive experimental and finite element investigation is required to understand more about the performance of the method. Besides a simple precise analytical solution is for analysis and design are limited in number and in this part further analytical procedure for designing is required.

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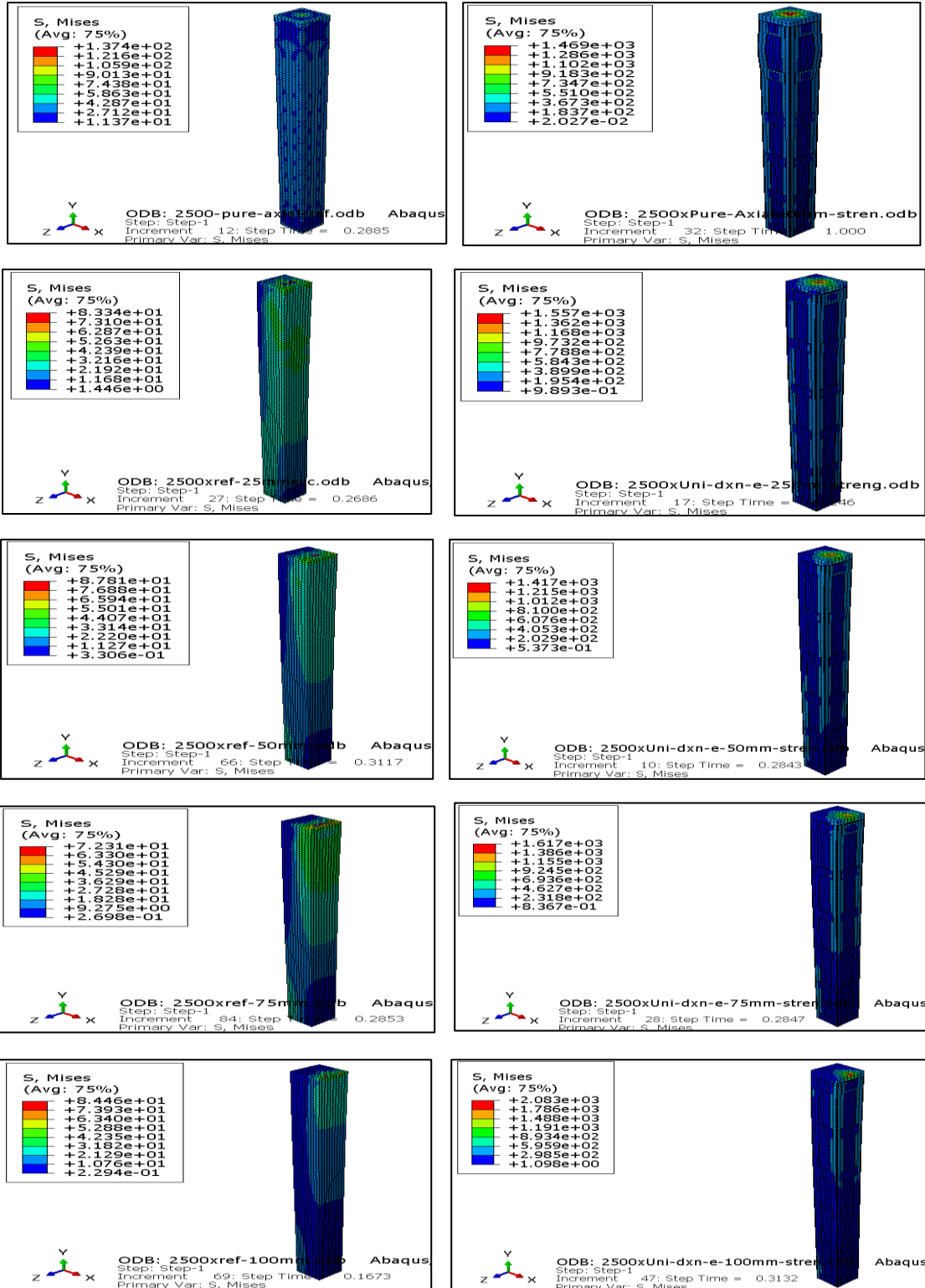
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APPENDIX A

Stress contours at ultimate capacity for eccentric load

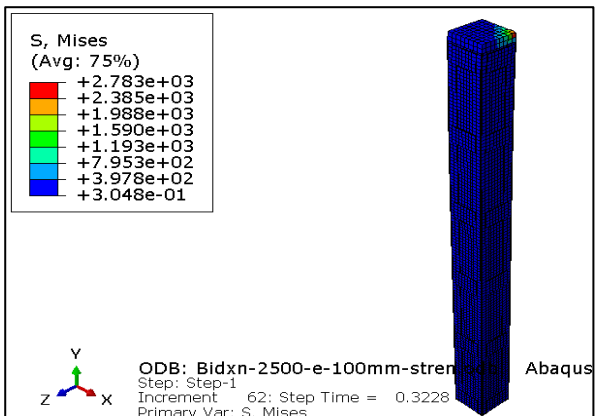
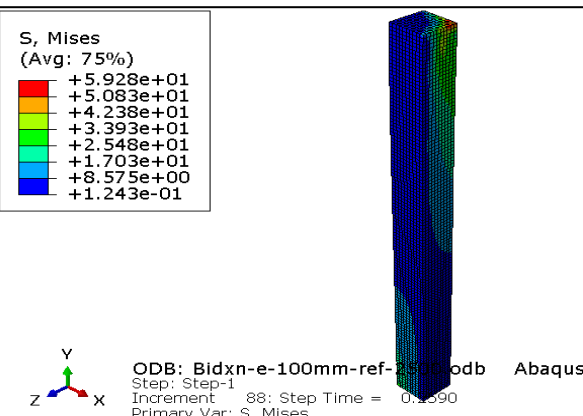
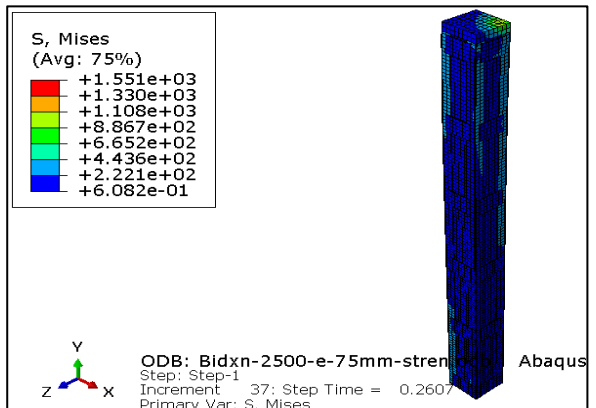
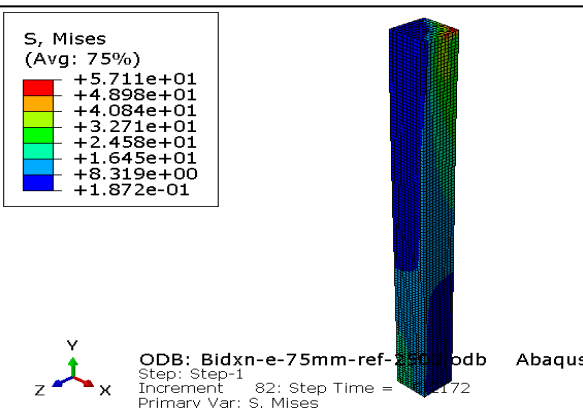
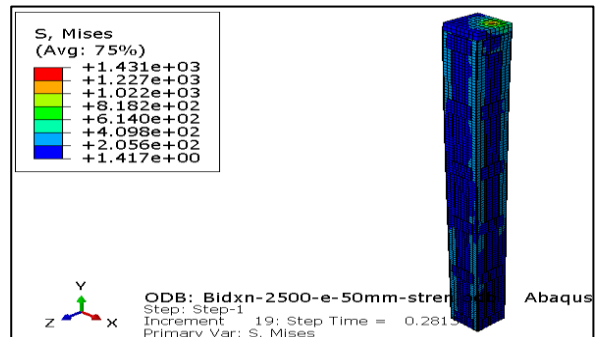
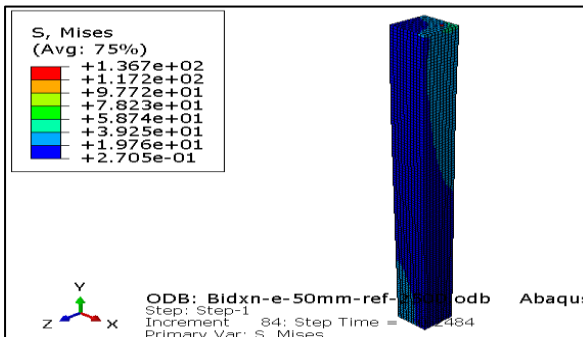
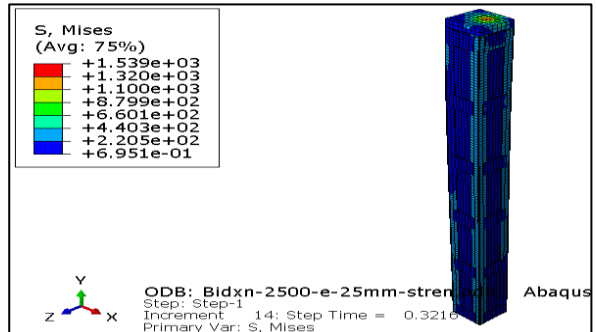
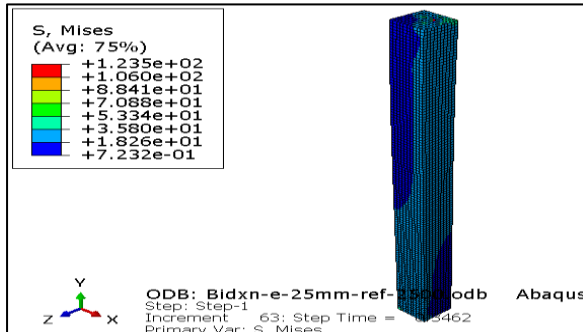
Stress contours at ultimate capacity for Uni directional eccentricity load

Stress at ultimate capacity for Uni directional eccentricity ( $e = 0, 25, 50, 75$  and  $100$  mm)



**Stress contours at ultimate capacity for Bi-directional eccentric load**

Stress contours at ultimate capacity for bi-directional eccentric load ( $e = 25, 50, 75$  and  $100$  mm) reference and strengthened.



## APPENDIX B

### Stress at ultimate capacity for cyclic load

#### Stress at ultimate capacity for concrete grade under cyclic load.

