European Journal of Engineering Science and Technology
ISSN 2538-9181

Nonlinear Analysis of Tie Confined Columns

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ARTICLE INFO

Keywords:
ANSYS
Columns
Concrete
FEA
Lateral reinforcements

ABSTRACT

Columns, being a very important component of the building structure, are required to be strong enough and also sufficiently deformable to withstand all possible static and dynamic loads to maintain the integrity of the structure throughout their entire life. The strength and the deformability of the columns can be increased by confining the concrete with lateral reinforcements provided in the form of the spirals, hoops or ties. Several experimental and analytical studies have been carried out by various researchers over the years to determine the extent of improvement that can be made to the strength and ductility of the columns, subjected to concentric loading, by confining them using lateral reinforcements. In the present study three-dimensional finite element models of confined concrete columns have been made using ANSYS and analyzed under the application of static concentric loading to find out the effects of lateral confinement. Suitable material models for both concrete and steel have been chosen and nonlinear finite element analysis (FEA) of laterally confined three-dimensional concrete column models have been carried out. The numerical methodology, at first, has been verified against previous experimental results. Then different types of lateral confinements have been modeled and the stress-strain responses and the complex stress distribution patterns have been studied and compared to find out the better type of confinement.

1. Introduction

Over the past few decades the major advancement and refinement in the field of the analysis of various structural systems has taken place based on the use of finite element method. A parallel and simultaneous improvement in the computing systems and the close symbiosis between computers and structural theories resulted in the development of various software packages for finite element analyses of various structural systems. These software packages are made capable of analyzing the most difficult and complex structural models, thereby saving huge amount of time and effort and improving the accuracy of the analyses results, which otherwise would have been very difficult with the use of the ordinary programs. Since the analyses results are mainly influenced by both the geometric and material characteristics of the structural system, it is important that the software is capable of simulating both the geometric and material nonlinearities. The materials commonly used for building structures like concrete and steel exhibit nonlinear characteristics almost from the beginning of the load application. Concrete is basically a brittle material and when combined with reinforcements it

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exhibits inelastic behavior even at a very early stage of loading and becomes more and more pronounced near the later stages. Therefore, due to such obvious reasons of analyzing complex three-dimensional structural models, in the present study of the confined concrete columns the general-purpose finite element analysis software ANSYS has been chosen for performing the nonlinear analysis of the concrete columns.

Concrete is a brittle material and weak in tension. Therefore, concrete can take sufficient amount of compression without much effect but fails quickly when subjected to tensile stresses. To prevent such early failure concrete elements have been strengthened by the addition of steel reinforcements, which arrests the tensile stresses. In case of the columns the reinforcements carry sufficient amount of compression also thereby increasing the overall load carrying capacity. As, in real situations the structural elements are not only subjected to concentric loading but also significant eccentric and cyclic loading, they are required to withstand sufficient compressive and tensile stresses. Extensive amount of research works, over the years, have led to the conclusion that strength and the deformability of the columns can be increased by confining the concrete with lateral reinforcements provided in the form of the spirals, hoops or ties. Concrete under compressive loading undergoes volumetric changes with a lateral increase in dimensions due to Poisson's effect and transverse reinforcement, when provided in the form of hoops, spirals or ties, resist the tendency of lateral expansion of concrete by developing tensile forces itself and consequently exerting a compressive force on the concrete core and thereby confining the concrete and increasing the deformability and strength. Numerous experimental works have been conducted over the years to study the confining effect and several empirical confinement models have been proposed for the prediction of the stress-strain response of the column's behavior under concentric loading [(Kent & Park, 1971), (L'egeron & Paultre, 2003), (Mander et al., 1988), (Richart et al., 1928), (Scott, 1980)]. Some numerical simulation works have also been carried out in recent years to study the confining effect of lateral steel on columns [(Bhargava et al., 2004), (Foster & Liu, 1998)]. However, the amount of numerical works done is still much less than the experimental works. As numerical simulations give much greater insight into the development of stresses and strains in the concrete and steel, more efforts are required to deeply explore this field. And for such cause it is essential to determine suitable numerical simulation procedures with proper geometric and material modeling which would properly reflect the behavior of reinforced concrete columns subjected to concentric loading at in situ conditions.

In this present study an approach has been made to prepare three-dimensional finite element models of isolated reinforced concrete columns subjected to concentric loading and carry out non-linear finite element analyses till failure using the FEA software ANSYS. Suitable three-dimensional elements have been chosen for geometric modeling of concrete and reinforcement and three-dimensional finite element models were prepared. Suitable material models for concrete and steel have also been chosen and finite element analyses have been carried out. The finite element model is at first validated against past experimental results. Then a comparative study has been carried out for different patterns of tie confinements. Some important observations have been obtained about the behavior of the tie confined concrete columns.

2. Numerical Simulation

Reinforced concrete exhibit inelastic behavior at different stages of loading and therefore it is necessary to develop proper geometric and material models of concrete and steel to carry out a nonlinear finite element analyses of the columns subjected to concentric loading to find its deformational characteristics.

For concrete applications in general, hexahedral elements are found to be more stable and efficient in convergence than the tetrahedral elements [(Chen, 1982), (Chen & Saleeb, 1982)]. Therefore eight-noded isoparametric Solid 65 element, having translations at each node in x, y and z directions have been used for the modeling of concrete. This element allows cracking at tension, crushing at compression, plastic behaviour and creep. A discrete approach, using two-noded three-dimensional isoparametric Link element having translations in x, y and z directions at each node, has been adopted for the modeling of reinforcements. A total adhesion between reinforcement and concrete and complete strain compatibility between the reinforcement elements and the concrete elements has been assumed.

ANSYS proposes the use of William-Warnke five-parameter model with the Solid 65 element for the modeling of brittle materials like concrete. ANSYS also provides option of combining William-Warnke five-parameter model with any of several other nonlinear material models such as Kinematic Hardening Model, Isoparametric Hardening Model, Anisotropic Model, Drucker-Prager Model, Nonlinear Elasticity Model and Multilinear-Elastic Model. In our present study the William-Warnke model has been combined with the Multilinear Elastic model. Although William-Warnke model allows both cracking and crushing of concrete, in the present analysis crushing capabilities have been kept inactive and concrete is allowed to crack only (Bhowmick, 2018). The nonlinearity of reinforcement behavior is modeled using the elasto-plastic Bilinear-Kinematic Hardening model available in ANSYS.

The numerical procedure involved geometric modeling of the reinforced concrete column and carrying out nonlinear finite element analysis. For the validation example complete model and for the comparative study $1/8^{th}$ of the structure consisting of reinforced concrete column has been modeled.

The boundary conditions have been applied by providing suitable restraints to the nodes. The nodes at the top of the concrete column have been restrained for translations in x- and z-directions. For the comparative study the nodes on the symmetry planes of concrete column had been restrained for translations perpendicularly to the symmetry planes i.e. in x-, y- and z-direction. In case of the validation example the load has been applied at the top nodes of the column as concentric load directed downward and in increments of smaller load value until the failure load is reached. The solution scheme has been the Newton-Raphson iterative scheme with a force based convergence criteria.

It has been observed that the covers of the concrete columns start spalling as the load levels are increased. This phenomenon is more pronounced in high strength concrete than normal strength concrete. This behavior is taken care of in the analyses by setting the cover elements to a low stiffness once a threshold tensile strain value is attained (Foster & Liu, 1998).

3. Numerical Example

B. D. Scott tested thirty nos. 450 mm square and 1200 mm high columns cast with varying amounts of longitudinal and lateral steel, under concentric or eccentric axial loads (Scott, 1980). One test specimen (Specimen 6), selected from the experiments carried out by Scott et al. has been modeled and three-dimensional nonlinear finite element analysis has been carried out to observe the behavior of the specimen under concentric loading and the results of the analysis are then compared with the test results. The property details of the column tested are summarized in Table 1 and the reinforcement arrangements are given in Fig 1. The test set-up is shown in Fig 2.

Table 1.
Material Properties of the Columns Tested by Scott

Batch No, And (MPa) Cylinder Strength	Specimen Number	Number and Diameter of Longitudinal Bars (mm)	Yield Strength (MPa)	Hoop Diameter and Spacing (mm)	Yield Strength (MPa)	Volume of Hoop Steel	Hoop Type
1 ~ 25.3	1	0		0		0	
	2	12 ~ 20	434	10 ~ 72	309	.0182	
	3	"	"	"	"	"	
	4	"	"	"	"	"	
	5	"	"	"	"	"	
	6	8 ~ 24	394	"	"	.0174	
	7	"	"	"	"	"	
	8	"	"	"	"	"	
	9	"	"	"	"	"	
	10	"	"	"	"	"	

Source: Scott, 1980

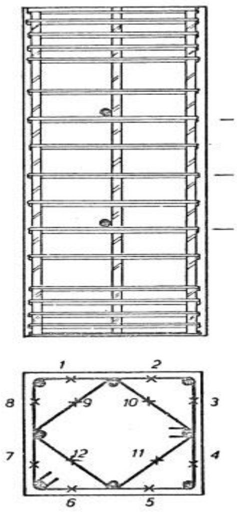


Fig 1. Reinforcement Arrangements

For the purpose of analysis the complete experimental set up has been modeled. Concrete has been modeled using 8-noded isoparametric Solid 65 elements and the reinforcements have been modeled using 2-noded three dimensional isoparametric Link elements. Complete strain compatibility has been assumed between the reinforcement and the concrete elements. The finite element mesh is shown in the Fig 3. The material properties of concrete and steel used, for the analyses, are summarized in Table 2. After applying proper boundary conditions, as discussed before, load is applied in the form of nodal loads at the top of the column. The load has been increased gradually from 0 to 7000 kN.

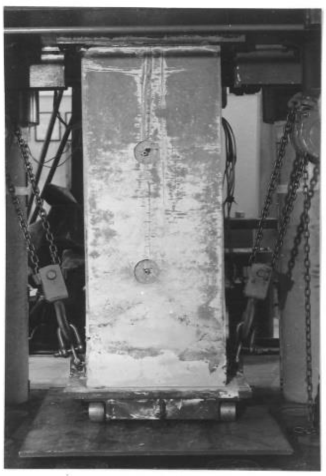


Fig 2. Test Set-up
Source : Scott, 1980

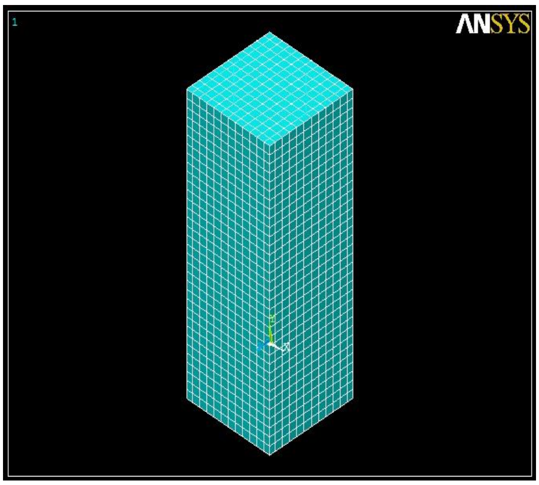


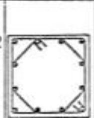
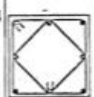
Fig 3. Finite Element Mesh of Tested Column

Table 2.
Material Properties of the Concrete and steel used for the Finite Element Analysis

Material	Properties				
	Linear Properties			Non-Linear Properties	
	Modulus of Elasticity (Mpa)	Density (kN/m3)	Poisson's Ratio		
Concrete	27278	25	0.2	Multilinear Elastic Model & Five – Parameter Model	
Steel	205500	78.5	0.3	Bilinear Kinematic Hardening	
				Yield Stress (Mpa)	Tangent Modulus of Elasticity (Mpa)
				394	20550
Steel	185500	78.5	0.3	Bilinear Kinematic Hardening	
				Yield Stress (Mpa)	Tangent Modulus of Elasticity (Mpa)
				309	18550

Scott tested the column and found out that the column could sustain a peak load of about 6720 kN with a corresponding peak strain of 0.0041 [Table 3]. The load – strain and the stress – strain curves for the experiment is given in Fig 4. In the numerical study the column failed at a peak load of about 6210 kN. The stress – strain curves obtained from the analyses are given in Fig 5a & 5b. The column had 216 mm length at top and bottom reinforced with lateral ties having spacing of 36 mm c/c. And the central portion of 792 mm of the column was reinforced with lateral ties having spacing 72 mm c/c. Therefore, in case of the numerical analysis, the plots of stress – strain curves are obtained one at 216 mm (A region) and the other at 432 mm (B region - central region) from top. Simultaneously the stress distribution patterns at two levels are obtained and given in Fig 6a & 6b. The results of the numerical analysis indicate that the peak stress reaches at 31.68 Mpa at a strain of 0.00237 for 'A region' [Fig 5a] and for 'B region' peak stress reaches at 37.05 Mpa at a strain of 0.0041 [Fig 5b]. The results clearly indicate a good agreement between experimental and numerical results.

Table 3.
Results of the experiments by Scott

BATCH NUMBER AND CYLINDER STRENGTH (MPa)	UNIT NUMBER	NUMBER AND DIAMETER OF LONGITUDINAL BARS (mm)	HOOP DIAMETER AND SPACING (mm)	VOLUME OF HOOP STEEL	HOOP SET SHAPES	TYPE OF LOAD	RATE OF LOADING Strain/s mm/s / 1200	PEAK LOAD (MN)	AVERAGE STRAIN AT PEAK LOAD	MAXIMUM CORE STRESS $\frac{f_{cc}}{f'_c}$	STRAIN AT MAXIMUM CORE STRESS	AVERAGE STRAIN AT FIRST HOOP FRACTURE	PEAK COMP'N STRAIN AT FIRST HOOP FRACTURE
1 — 25.3	1	0	0	0		Concentric	.000033	4.38	.0018	0.86	.0018	~	
	2	12 ~ 20	10 ~ 72	.0182		"	"	7.07	.0036	1.24	.0052	.0052	
	3	"	"	"		"	.0167	8.41	.0030	1.54	.0040	.0215	
	4	"	"	"		Eccentric	.000033	5.49	.0027			.0274	.0743
	5	"	"	"		"	.0167	6.40	.0033			.0188	.0609
	6	8 ~ 24	"	.0174		Concentric		6.72	.0041	1.22	.0044	.0325	
	7	"	"	"		"	.0167	7.85	.0032	1.47	.0038	.0271	
	8	"	"	"		Eccentric		5.54	.0044			.0206	.0649
	9	"	"	"		"	.0167	6.65	.0026			-	-
	10	"	"	"		Not Tested	~	-	-	-	-	-	-

Source : Scott, 1980

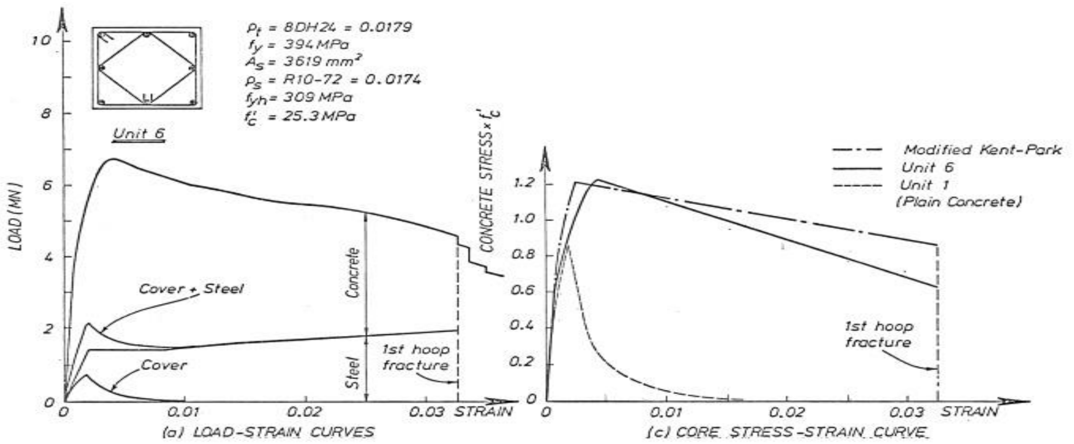


Figure 4. Load-Strain & Stress-Strain curves of the experiments by Scott (Source: Scott, 1980)

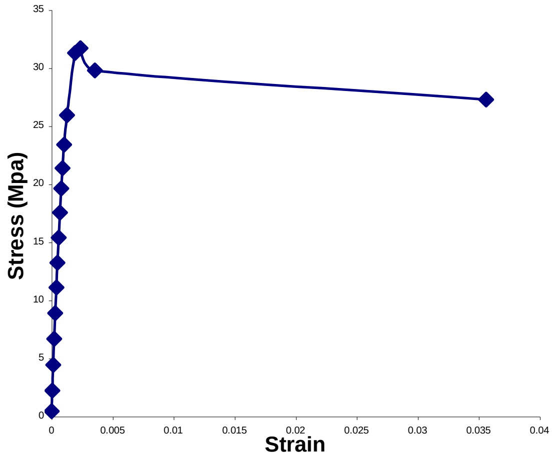


Figure 5a: Stress-Strain response at 216 mm from top

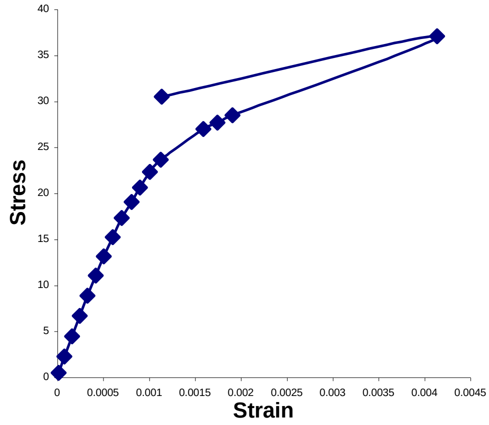


Figure 5b: Stress-Strain response at 432 mm from top

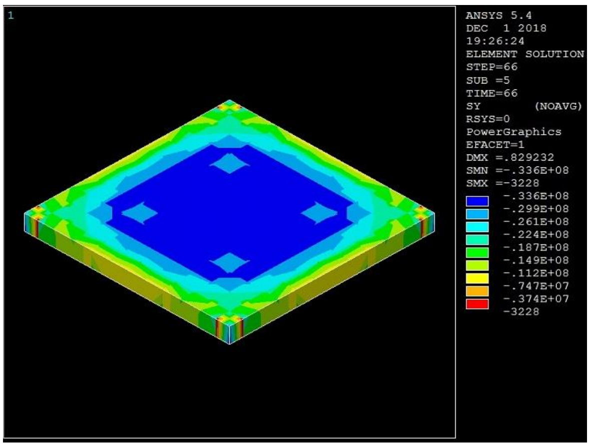


Figure 6a. Stress distribution pattern at 216 mm from top

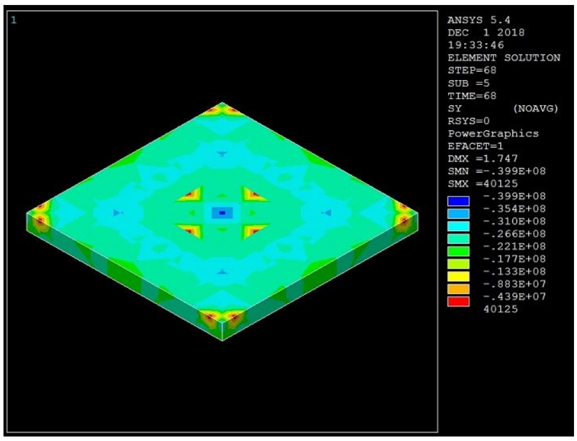


Figure 6b. Stress distribution pattern at 432 mm from top

4. Comparative Study

A comparative study has been carried out to find out the effect of different tie arrangements on the strength and ductility of columns. Square columns of 200 mm side dimension and 1000 mm length are considered for the study. In order to avoid complexity of the analytical procedure the columns are modeled without cover. Columns under study have been reinforced with four 12 mm dia longitudinal bars and 8 mm dia tie bars. The arrangements of tie steels are shown in Fig 7 (a,b,c). Three different types of arrangements are considered i.e.

A, B & C. In the case of A, the tie bars are spaced at 40 mm c/c keeping the central region of 200 mm without any tie steel in that region. In the case of B, one tie bar of same diameter of 8 mm is placed horizontally in the central region. And in the case of C, tie bars of equal volume of steel, as that of the horizontal tie bar of case B, are placed diagonally in the central region. The aim is to find out the effect of different tie arrangement in controlling the failure of the columns.

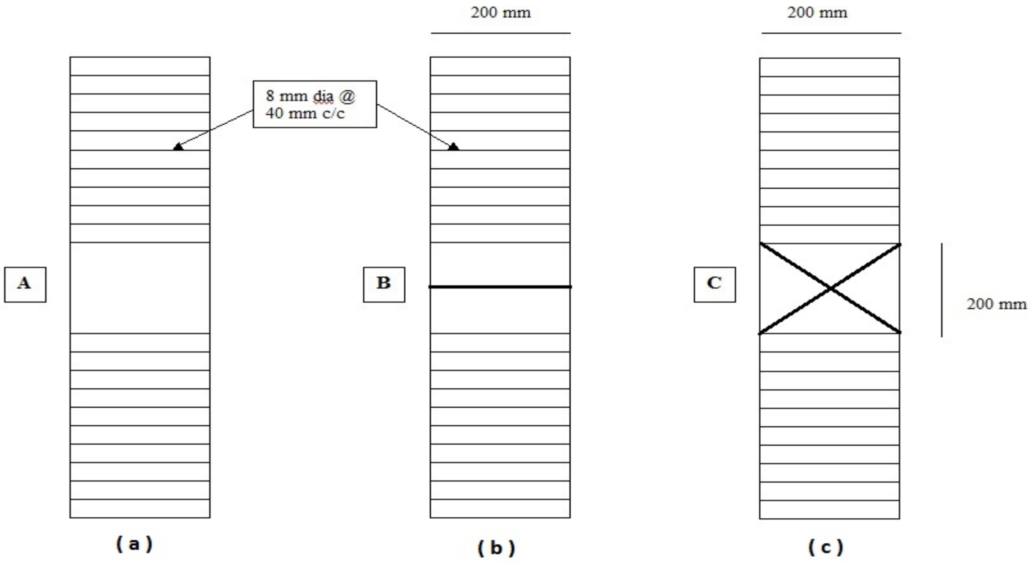


Figure 7. Columns with different tie - arrangements selected for comparative study

For the purpose of numerical analyses, as before, concrete has been modeled using 8-noded isoparametric Solid 65 elements and the reinforcements have been modeled using 2-noded three dimensional isoparametric Link elements. Complete strain compatibility has been assumed between the reinforcement and the concrete elements. The material properties of concrete and steel used, for the analyses, are summarized in Table 4. After applying proper boundary conditions, as discussed before, load is applied as concentric load directed downward and in increments of smaller load value until the failure.

Table 4.
Material Properties of the Concrete and steel used for the Comparative Study

Material	Properties				
	Linear Properties			Non-Linear Properties	
	Modulus of Elasticity (Mpa)	Density (kN/m3)	Poisson's Ratio		
Concrete	27278	25	0.2	Multilinear Elastic Model & Five – Parameter Model	
Steel (Long.)	205500	78.5	0.3	Bilinear Kinematic Hardening	
				Yield Stress (Mpa)	Tangent Modulus of Elasticity (Mpa)
				394	20550
Steel (Tie)	185500	78.5	0.3	Bilinear Kinematic Hardening	
				Yield Stress (Mpa)	Tangent Modulus of Elasticity (Mpa)
				309	18550

The comparative study reveals that addition of tie steel definitely has a beneficial effect on the strength and deformability of the columns. The stress-strain responses obtained at the middle of the central region and at the edge of the central region are given in Figure 8 & Figure 9. The figures indicate that the addition of a horizontal bar [B] in the central region have more influence than the addition of ties in the form of cross bars [C] as it increases both the peak stress and the peak strain more. The peak stress for case B reaches at about 34.3 Mpa with a peak strain of 0.0024. The peak stress for case A is 32.15 Mpa and the corresponding strain is 0.002.

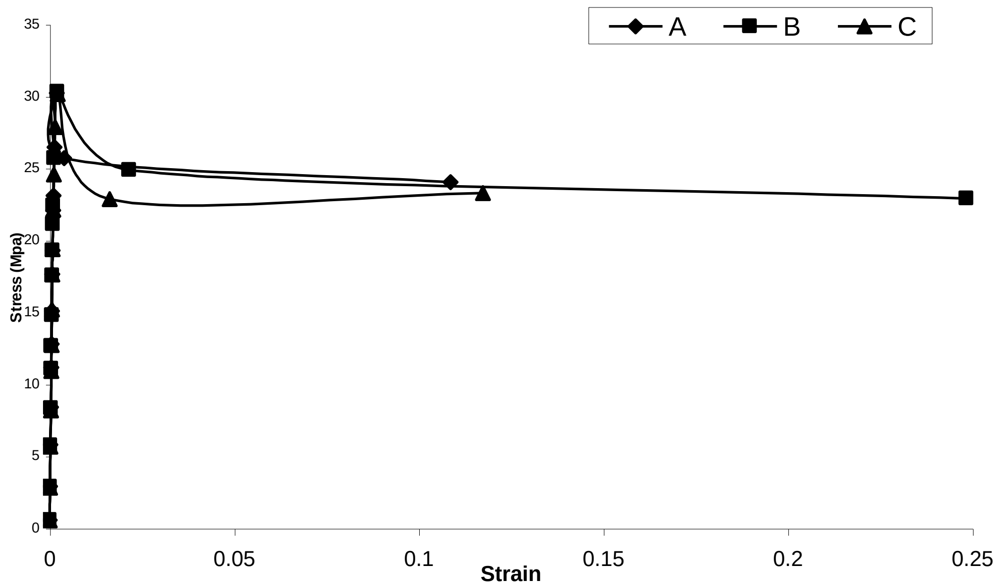


Figure 8. Stress – Strain responses for different tie arrangements at middle of central region

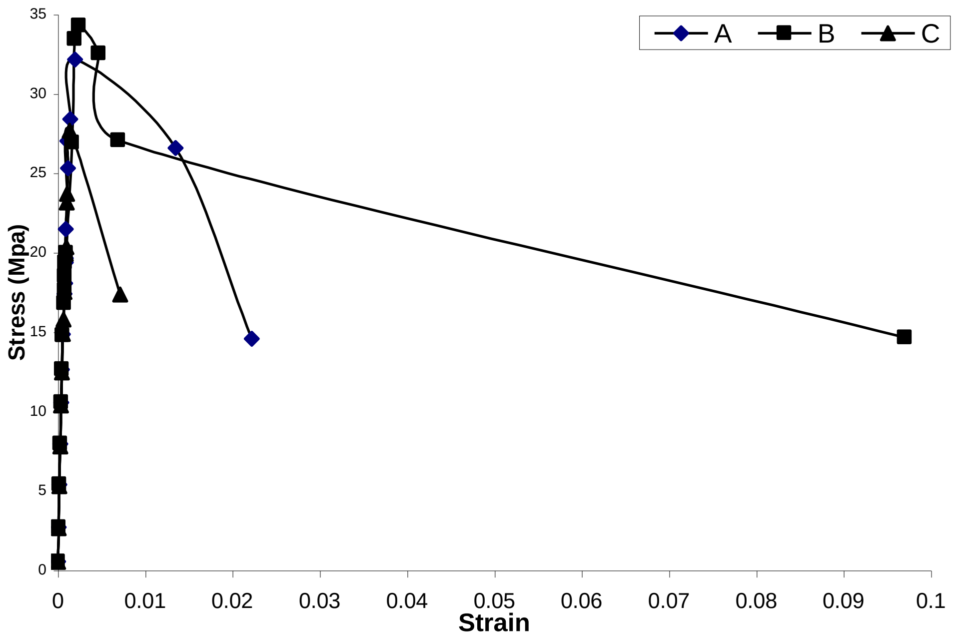


Figure 9. Stress – Strain responses for different tie arrangements at the edge of central region

5. Conclusions

The aim of the study has been to find out a suitable numerical procedure to obtain realistic response of concentrically loaded reinforced concrete columns and to determine the effects of different tie arrangements on the strength and deformability of them. For such purpose, material behavior of concrete has been modeled by combining the William – Warnke model with the Multilinear Elastic model and that of steel has been modeled using Bilinear kinematic hardening model of ANSYS. The finite element model gave results that had good agreement with the results of experiments from past research work. Subsequently, a comparative study had been carried out to determine the effects of different tie arrangements using the same material models. The results indicated that the horizontal form of tie steel improves the performance of the columns more than the other forms. However, it should be noted that other types of tie arrangements requires to be studied in more detail to be absolutely sure about their effectiveness or uselessness.

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