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Effect of out of Frame Positioning of Shear walls in Steel Frames

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Abstract

Shear walls are straight external walls that typically form a box which provides all of the lateral support for the building and are constructed to counter the effects of lateral load acting on a structure. Shear walls are designed to resist the horizontal forces due to their strength and stiffness. Thus shear walls are one of the most effective building elements in resisting lateral forces during earthquake and high winds. In this paper we propose a way to optimized positioning of shear walls in steel structures to withstand seismic forces. Three positions will be considered for placing shear wall inside the steel frame: inside frame and interacting with columns, inside frame and non-interacting and eccentric shear wall with an offset equal to thickness of the wall from the frame . These positions are investigated in 4, 10 and 16 story buildings subjected to linear static loading according to Iranian building code (2800). The additional parameter of wall thickness is taken into account for having better point of view. The shear walls are designed according to ACI318-05 and the most cost effective design will be mentioned as optimized design.

Keywords: Effect, frame, positioning, shear, walls, steel, frames.

Introduction

In building construction, a rigid vertical diaphragm capable of transferring lateral forces from exterior walls, floors, and roofs to the ground foundation in a direction parallel to their planes. Lateral forces caused by wind, earthquake, and uneven settlement loads, in addition to the weight of structure and occupants; create powerful twisting (torsion) forces. These forces can literally tear (shear) a building apart. Some type of walls that call Shear walls are designed to resist gravity / vertical loads (due to its self-weight and other living / moving loads), and they are also designed for lateral loads of earthquakes / wind. Shear walls are vertical elements of the horizontal force resisting system that their supporting area (total cross- sectional area of all shear walls) with reference to total plans area of building, is comparatively more, unlike in the case of RCC framed structures. Shear wall buildings are commonly used for residential purposes and can house from 100 to 500 inhabitants per building. Shear walls resist both shear forces and uplift forces. Shear forces that generated by accelerations resulting from ground movement and by external forces like wind and waves create shear forces throughout the height of the wall between the top and bottom shear wall connections. In the other hand Uplift forces exist on shear walls because the horizontal forces are applied to the top of the wall. These uplift forces try to lift up one end of the wall and push the other end down.

In this paper proposed a way to optimized positioning of shear walls in steel structures to withstand seismic forces and three positions will be considered for placing shear wall inside the steel frame including, inside frame and interacting with columns, inside frame and non-interacting and eccentric shear wall with an offset equal to thickness of the wall from the frame. These positions are investigated in 4, 10 and 16 story buildings subjected to linear static loading according to Iranian building code (2800). The additional parameter of wall thickness is taken into account for having better point of view. The shear walls are designed according to ACI318-05 and the most cost effective design will be mentioned as optimized design.

Shear walls Specification: Shear walls provide large strength and stiffness to buildings in the direction of their orientation, which significantly reduces lateral sway of the building and thereby reduces damage to structure and its contents. These walls should be provided along preferably both length and width. However, if they are provided along only one direction, a proper grid of beams and columns in the vertical plane (called a moment-resistant frame) must be provided along the other direction to resist strong earthquake effects.

Shear walls are easy to construct, because reinforcement detailing of walls is relatively straight forward and therefore easily implemented at site. In the other hand these walls are cost effective and minimize earthquake damage in structural and nonstructural elements like glass windows and building contents.

Due to carrying large horizontal earthquake forces, the overturning effects on the shear walls are large and the design of their foundations requires special attention. There are three types of design method for shear walls. The first method is the segmented shear wall method which uses full height shear wall segments that comply with ratio requirements and are usually restrained against overturning by hold down devices at the ends of each segment. The second method force transfer-ground openings method considers the entire shear wall with openings and the wall piers adjacent to openings are segments. The method requires the forces around the perimeter of the openings to be analyzed, designed, and detailed. With this method, the hold-down devices generally occur at the ends of the shear wall, not at each wall pier, and special reinforcement around the opening is often required. The third and newest method is the perforated shear wall method which is an empirical approach that does not require special detailing for force transfer adjacent to the openings. The perforated shear wall method, however, specifically requires hold-down devices at each end of the perforated shear wall[1].

Review of literature

Reinforced concrete (RC) shear walls are common structural components used in tall buildings for efficiently resisting lateral loads. Because of low tensile strength of concrete, reinforced concrete shear walls tend to behave in a nonlinear manner with a significant reduction in stiffness, even under service load. According to Fintel[2] and many other researches[3] shear wall type building structures have better performance in earthquake and have the advantage as less distortion, less damage on non-structural elements and Robustness. A typical failure of shear walls that occurs during the Chilean Earthquake of 1985 is reported. As seen in figure 1 despite of local damage, the walls fulfilled their structural function[4].

Figure-1
Failure of shear wall observed after Chilean Earthquake 1985[4].

Pauly et al[5] reviewed Mechanisms of flexural and shear resistance of squat shear walls with emphasis on aspects of sliding shear. For this purpose, investigated the response of four test walls with rectangular or flanged cross sections to simulated seismic loading and demonstrated detrimental effects of sliding shear together with improvement achieved by use of diagonal wall reinforcement. It is postulated that critical parameters of sliding gear during inelastic seismic response are ductility demand, vertical web reinforcement in providing dowel shear resistance, and aspect ratio h/L. They concluded that with suitably arranged diagonal wall reinforcement a predominantly flexural response mode with good energy dissipating characteristics can be received in squat shear walls. Results of an experimental investigation of isolated structural walls subjected to inelastic load reversals were discussed and evaluated by Oesterle et al[6]. They also used an analytical model based on truss analogy was to evaluate the experimental results and to obtain a design equation that predicts web crushing strength. Web crushing strengths of structural walls were then described as a function of concrete strength, axial load, and lateral interstory drift. Paulay and Priestley[7] made a recommendation for the prediction of the onset of out-of-plane buckling Based on the observed response in tests of rectangular structural walls subjected to severe simulated earthquake actions and theoretical considerations of fundamental structural behavior.

They conclude that major sources of instability of the compression zone of the wall section within the plastic hinge region are inelastic tensile steel strains imposed by preceding earthquake-induced displacements. Siao[8] test shear behavior specimens of short reinforced concrete walls like deep beams and corbels (H/L is not > 1) to predicted shear capacity of reinforced concrete wall. They use formulas that established for top-loaded deep beams and corbels, and observed good agreement between analyses and experimental results. Gupta, and Rangan[9] test longitudinal reinforcement ratio, transverse reinforcement ratio and axial load in eight high-strength concrete (HSC) structural walls under plane axial and horizontal loads. The theoretical predictions compared with the test results showed good correlation with the test strengths.

Zhang and Hsu [10] have tested fourteen full-size reinforced panels (membrane elements) made of 100 MPa high-strength concrete. For the first time, they correctly measure the three-dimensional (3-D) stress-strain curves of panels and the descending branches of the compressive stress-strain curves of concrete. Five 100 MPa concrete panels in the study were Subjected to biaxial tension-compression. By comparing the behavior of panels with those of 42 and 65 MPa tested previously, they evaluate the effect of concrete strength on the constitutive laws of concrete in compression. A total of four reinforced concrete structural shear wall models were subjected to seismic-type lateral forces by Tasnimi[11]. The only variable was the type of slow reversed cyclic lateral displacement which was affected with no axial load.

Results of this experimental investigation are presented in the form of load-displacement plots and compared with the values calculated on the basis of ACI recommendations. Zhang and Wang[12] discussed the results of an experimental study that investigated the failure mechanism and ductility of rectangular reinforced concrete shear walls subjected to high axial loading and found that Axial-load ratio have a significant effect on the cracking pattern, flexural strength, failure mode, and ductility of reinforced concrete shear walls. Riva, and Franchi[13,14] showed that walls reinforced by means of hot-rolled (HR) mesh exhibit ductility properties comparable to those reinforced with ordinary reinforcement only. Sittipunt et al.[15] evaluate the influence of diagonal web reinforcement on the hysteretic response and indicated that the diagonal web reinforcement was effective in transferring shear force to base of walls, especially during load reversals when most diagonal cracks in concrete remained open and compressive struts in concrete were not effective in transferring shear force. The behavior of reinforced concrete walls that exhibit the shear mode of failure was studied by Hidalgo, et al.[16]. They showed that deformation capacity, energy absorption, dissipation characteristics and strength deterioration after maximum strength shown by the walls and the influence of vertical distributed reinforcement on the seismic behavior of walls.

Oh et al.[17], investigated the effect of boundary element details of structural walls on their deformation capacities. They found that the deformation capacities of walls, which are represented by displacement ductility, drift ratio and energy dissipation capacities, are affected by the boundary element details. Salonikios[18] suggested a general method to estimating sliding shear strength takes into account the presence or not of bidiagonal reinforcement at the critical area of R/C walls.

The seismic behavior of shear walls is investigated in the framework of the study focusing on seismic evaluation of existing buildings by Greifenhagen, and Lestuzzi[19]. It was observed that lightly reinforced shear walls can have significant deformation capacity that is not affected by the ratio of horizontal reinforcement. It was also found that the flexural strength governs the observed strength in the tests while ultimate drift was limited by shear failure. Su, and Wong[20] develop an experimental study to investigated Seismic behavior of slender reinforced concrete shear walls under high axial load ratio. For checking global dynamic performance of shear walls, there is need for efficient numerical models so it is necessary to model structural elements based on realistic material behavior and element response to loading to study based on a solid theory.

Kabeyasawa, et al[21] performed Pseudo-dynamic earthquake response tests of a full-scale seven-story reinforced concrete wall-frame structure. Hsu and Mu[22] derived a truss model theory to predict the strength and behavior of low-rise reinforced concrete shear walls Based on equilibrium and compatibility conditions, as well as a new stress-strain relationship for softened concrete. Mander et al[23] developed a stress-strain model for concrete subjected to uniaxial compressive loading and confined by transverse reinforcement. Their model allows for cyclic loading and includes the effect of strain rate. Lefas and Kotsovos[24] investigated the effect of loading history and repair methods on the structural characteristics of reinforced concrete walls. They found that, while repairing only the damaged regions of the compressive zone, and were sufficient to fully restore wall strength.

Cheng, et al.[25] introduced a technique of calculating inelastic deformation of low-rise shear walls having height-width ratios of 0.5 and 0.75 without boundary elements with consideration of the coupling effect for bending and shear deformations as well as the deformation due to base rotation; and developed a computer program for structural system analysis subjected to seismic excitations

Model Descriptions

Model description and design methodology is described in this section. For the numerical analyses the commercially available computer program named ETABS was chosen. ETABS is a special purpose computer program for the linear and non-linear, static and dynamic analysis of buildings. ETABS is a special purpose computer program for the analysis of building systems. Due to performing this paper to studying effect of wall positioning in various building heights and how does wall thickness affects the design forces, we used three groups of parameters include building height (story count), wall position and wall thickness. Wall positioning regulation is as follow: RC shear wall is inside steel frame and are interacting with each other (CPL= coupled). RC shear wall is inside steel frame and are isolated from each other (NCP models = non- coupled). RC shear wall is outside steel frame with eccentricity of half of its thickness (ECCmodels= eccentric).

Story counts are taken into account to study if the reinforcement requirement for shear buildings differs from flexural buildings or not. To reach this aim, building with 4, 10 and 16 levels of stories were considered and modeled. Finally, the wall thicknesses of 20, 30, 40 cm were used as common shear wall thickness ranges to consider the effect of thickening the walls in the analyses. In general, modeling and design process can be done in 3 general steps: Geometrical modeling, Loading and design. The aim of the geometrical modeling is to define positioning of columns and beams; length of them, drawing of area properties such as decks, slabs, walls, openings, etc. Defining grid is first step in almost every modeling procedure. The aim of this step is to determine the coordinate of column, beams, etc.

For the steel frames Steel material is used. The most common used steel in steel structures is ST37 or steel with isotropic mechanical properties. Elasticity modulus of steel is 200 GPA, with a mass per volume of 7850 kg/m3, a Poisson's ratio of 0.3, yield stress of 240 MPa and ultimate stress of 370 MPa. Concrete material also defined as an isotropic material with modulus of elasticity of 25 GPa, Poisson's ratio of 0.2 and specified compression strength of 25 MPa. The yield stress of longitudinal reinforcing bars of concrete is defined 400 MPa and the transverse reinforcement strength of concrete is defined 300 MPa.

The steel beam / column sections for the models have been defined separately for each count of stories but it remind unchanged in wall positioning in same story level models to have an appropriate behavior in steel frame and providing a reasonable framework to validate comparison between structural systems. For 4 story models, 300x10 mm and 300x8 mm columns are used in first and top 2 stories respectively where number is width of the profile and the second number is thickness of the profile. Also used profiles for these models in beams are standard IPE330 profiles. 350x20 mm columns are used in 3 first stories in 10 story models. Consequently, 350x15 mm profiles are used in 3 middle stories and finally 350x10 mm columns are used for last 4 stories. IPE 400 is used for story beams while for roof story, IPE300 profiles are used. 16 story models are divided into four story types: in first 4 stories, 350x30 mm columns are used. 350x20mm profiles are assigned for second 4 stories (story 5-8). In stories 9 to 12, 350x12 mm columns are used and finally in 4 most upper stories, columns of dimensions 350x10 mm are assigned. IPE 450 beams are used in first 8 stories plus A2-A3 axis in stories up to roof level. In the roof level, IPE 300 profiles are used and in the rest of the elements, IPE 400 sections are used. Areas in these models consist of decks and walls. Deck profiles are not considered in calculations directly and are used to define one way load bearing floor system and defining rigid diaphragm over them to have a realistic behavior in structures. But wall sections have direct effect in building output results because they affect lateral stiffness of the structure. They defined in two stages: The first stage is to define geometry of the sections. The program will not consider reinforcing of shear walls in analyses of the structure but it will be calculated in second stage after obtaining wall design forces. The plate bending behavior includes two-way, out-of-plane include plate rotational stiffness components and a translational stiffness component in the normal direction to the plane of the element. By default, a thin-plate (Kirchhoff) formulation is used that neglects transverse shearing deformation. Optionally, one may choose a thick-plate (Mindlin/Reissner) formulation which includes the effects of transverse shearing deformation.

Generally, typical loads imposed to the structure are categorized in two main types: gravity loads that are in vertical direction and are steady loads and lateral loads like seismic or wind load. In Iran, the probability of occurring earthquake and peak wind is so little amount. So, the structures are generally analyzed subjected to seismic or wind load separately and the more efficient load specifies the design lateral load.

In regions with a higher seismic hazard, the seismic load is dominant. So in this project, the seismic load is taken into account in opposition to wind load. Gravity load consisted of combination of dead and live load. In this paper, dead load imposed to the structure is equal to amount of 700 kg/m2 in stories and 600 kg/m2 in roof. The amount of live load in stories is 200 kg/m2 and in the roof level, this amount is reduced to 150 kg/m2. An infill load equal to 1180 kg/m is imposed in the type of the dead load. Seismic load was imposed to the structure according to Iranian building code (2800). According to this code, there is 3 ways for analyzing of the structure subjected to seismic loads such as Equivalent static analyses, Response spectrum analyses and Time history analyses[26].

Our models are hybrid models with combination of steel frames plus reinforced concrete shear walls. All structural elements should meet Iranian building code criteria, but there is no such design method in ETABS program. To overcome this issue, some changes should be performed in design methods to reach a design that meets used standards. The best design method that is compatible with Iranian code is AISC ASD 89 and UBC ASD 97.

Results and Discussion

The analyses results for all models have been illustrated and discussed. The results are containing wall design forces (P, V2, V3, M2, and M3) and column forces (P, V2, V3, M2, and M3) for the attached column to shear wall in the first story in various placements of shear wall inside frame to comparison between systems.

From the result of 4 story building it is concluded that frames with outsider shear walls have periods greater than frames with walls inside. Moreover in the frames with coupled shear walls, periods are slightly less than non-coupled walls. Also by increasing wall thickness, the periods decrease. In the other hand coupled frames are slightly stiffer than non-coupled frames and both of them are moderately stiffer than eccentric frames. Similarly by increasing wall thickness, stiffness of the structure increases too.

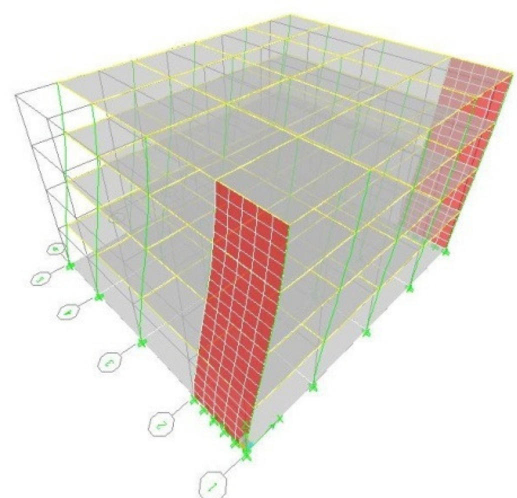


Figure-2
For 4 story buildings mode 1 shear wall design forces

The shear walls in all models are divided into 5 piers and results of the first story piers are mentioned here.

It is concluded that design axial forces for coupled and non-coupled shear walls are slightly differ and less than eccentric wall. In other word, placing wall inside frame causes decreasing in design force and leads to a more cost efficient design. The effect of wall placing on the major shear forces are discussed in incoming diagrams.

The effect of wall placement in columns of structures, are related here. To see effect of wall placing in structure the two columns in end and beginning of shear wall in first story are compared to each other.

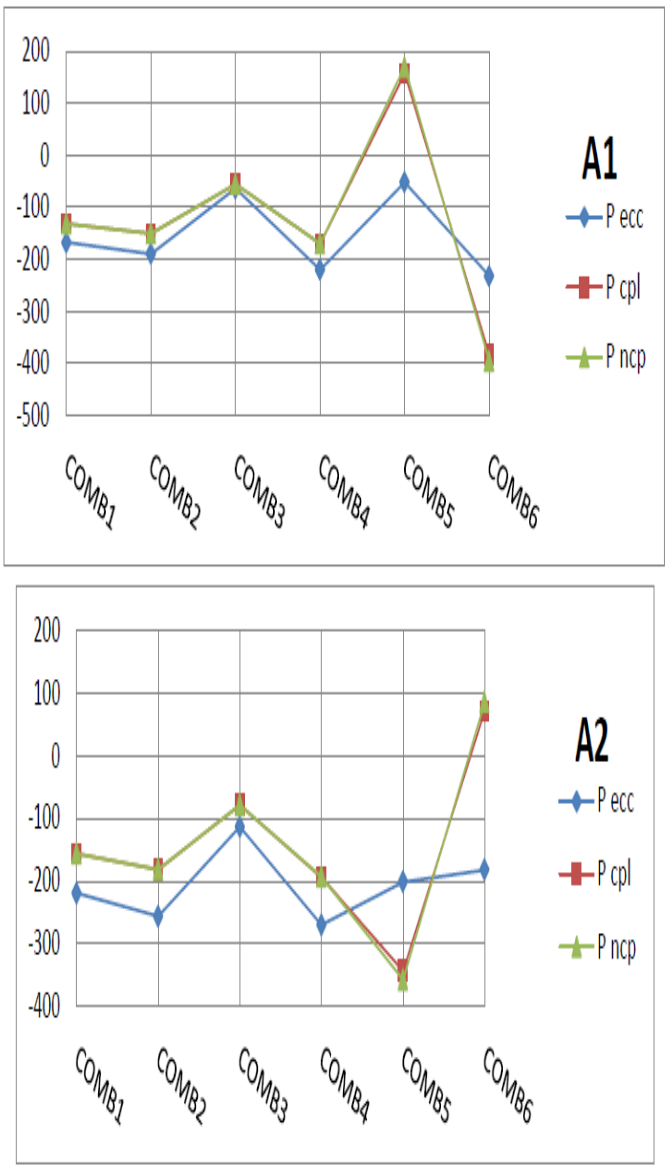


Figure-3
Comparison of design axial forces in columns for 20 cm wall in 16 story models

Design forces for column don't change with change of wall thickness but for eccentric wall, design force is less than other two methods.

The design moment slightly decrease by thickening shear wall. All models have same design forces except eccentric in certain combination. And non-coupled system requires more attention in design because of having more design force than other systems. Results are shown in figure-3 to 8.

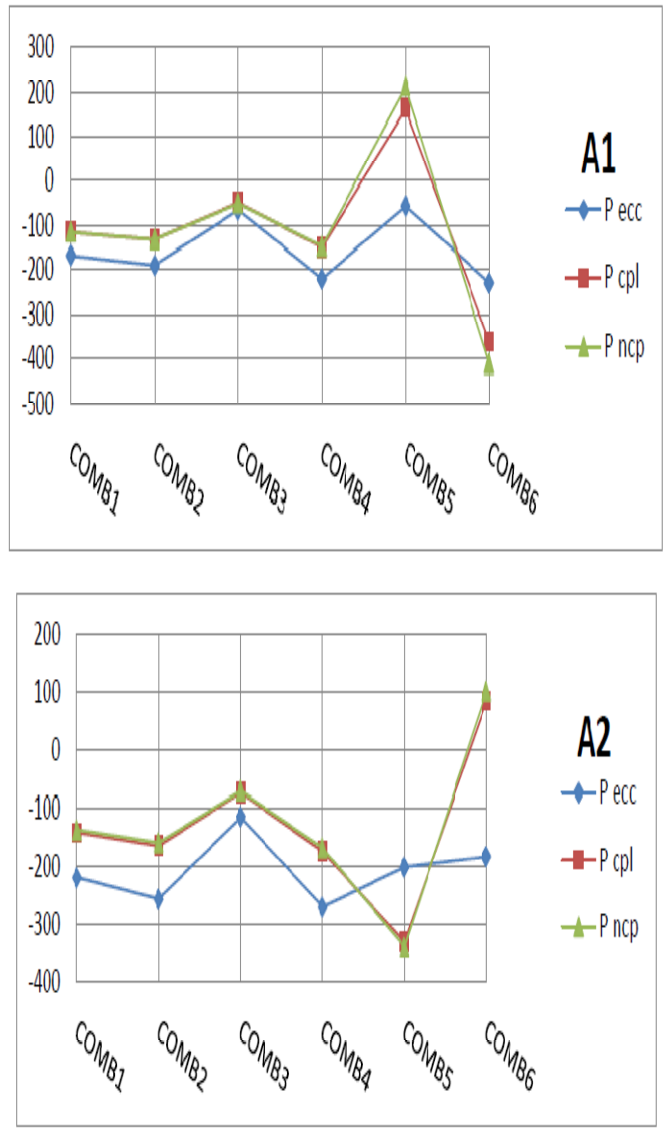
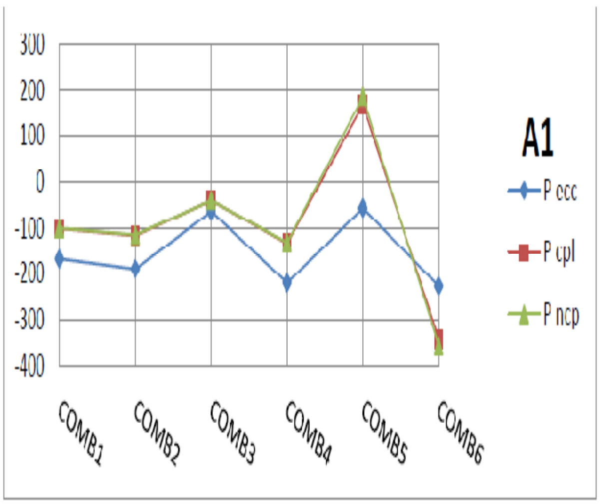


Figure-4
Comparison of design axial forces in columns for 30 cm wall in 16 story models

According to design forces, some reinforcing ratios are applied to walls. Here, design results for first 4 stories of models are mentioned and compared: It is seen that required reinforcing ratio for non-coupled and coupled systems are the same and less than eccentric system in all conditions like 4 and 10 story models. In some cases, when ratio is more than maximum reinforcement ratio, the thicker wall should be used. Also, reinforcing in boundary elements in eccentric models is more than the other systems and it shows that boundary elements in eccentric walls are more critical than other systems.

From above result it can concluded that thickening the shear wall affects stiffness of the structure. Also coupled and non-coupled system has more stiffness than eccentric systems. In the other hand design forces for coupled frame systems are slightly less than other systems. Design charts for shear walls show that there is no difference between design of coupled and non-coupled system and these two require less reinforcement than eccentric wall system to have an appropriate design.



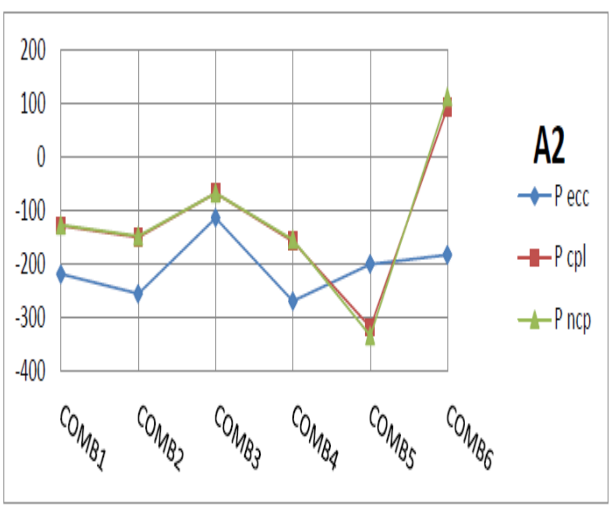


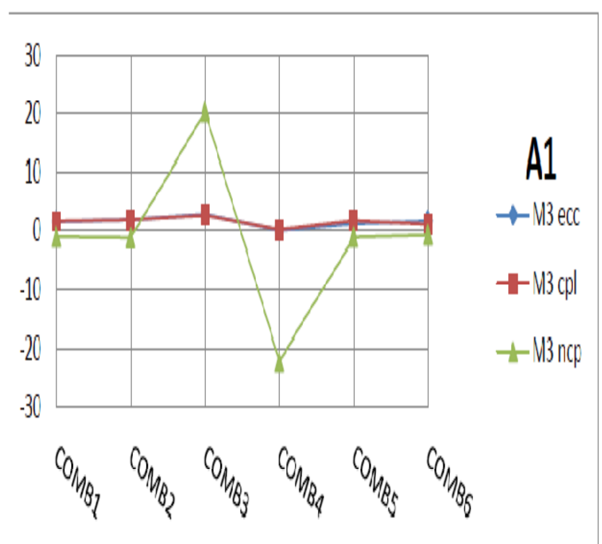
Figure-5
Comparison of design axial forces in columns for 40 cm wall in 16 story models

Conclusion

In this study, positioning of shear walls in steel structures to withstand seismic forces has been investigated. Three positions have been considered for placing shear wall inside the steel frame: inside frame and interacting with columns (Coupled system), inside frame and non-interacting (Non-Coupled system) and eccentric shear wall with an offset equal to thickness of the wall from the frame (Eccentric system). Wall thicknesses of 20, 30 and 40 cm are taken into account for having better point of view. The shear walls are analyzed with etabs 9.5 software and designed according to ACI318-05 and the most cost effective design have been mentioned as optimized design.

According to the results we found that having a thick wall, leads to higher design forces because thicker walls are having more stiffness than thin walls and have more design forces than thin walls. In addition in 4 story models, increase of wall thickness in eccentric systems doesn't change axial design forces but decreases design moments and increases design shears. Axial force and moment of eccentric walls is less than “in frame” walls in many combinations, but in some combination, their forces are maximum amount. Design of these walls is according to this maximum amount and because of this, their design requires more reinforcement ratio than other systems.

In 16 story models, increase of wall thickness in eccentric systems doesn't change axial design forces but decreases design moments and increases design shears and increase of wall thickness in coupled and non-coupled systems decreases axial design forces. But design shear forces and moments didn't show a dramatic change.



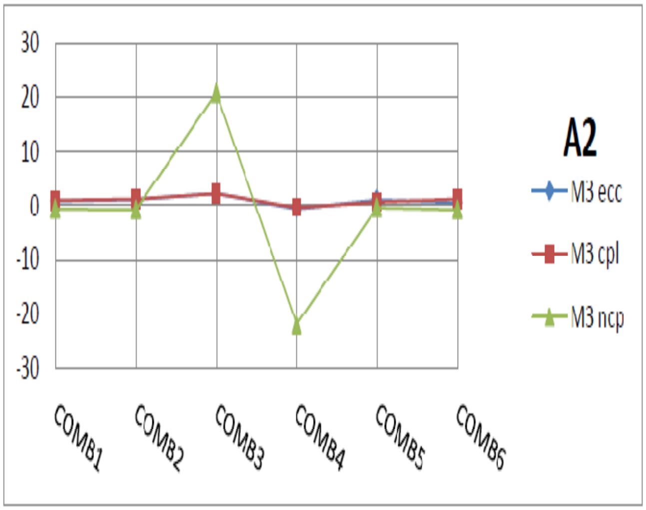


Figure-6
Comparison of design moment in columns for 20 cm wall in 16 story models

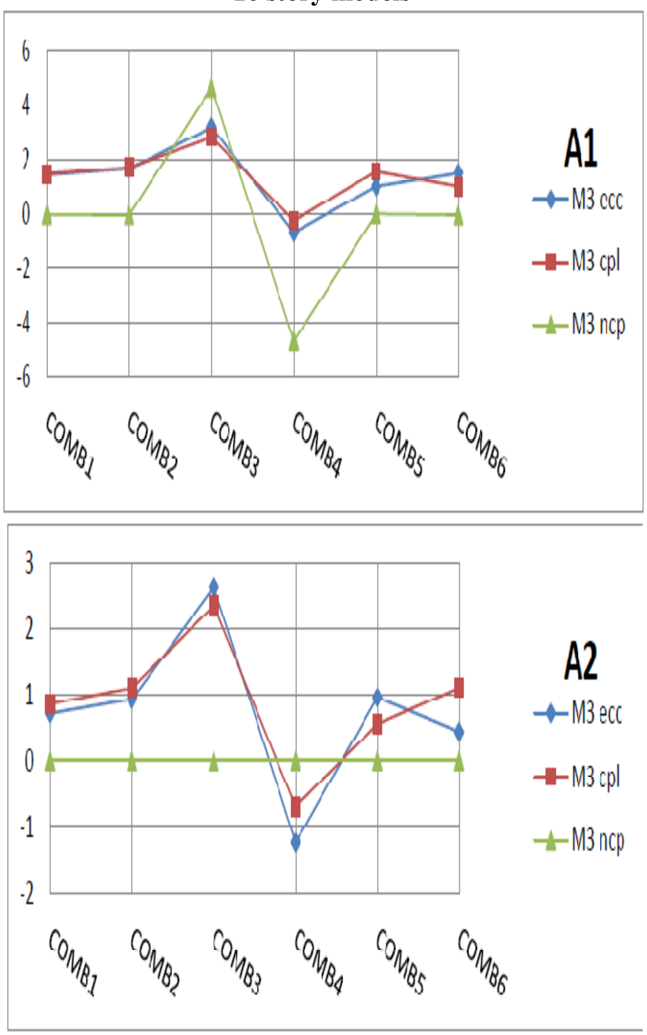


Figure-7
Comparison of design moment in columns for 30 cm wall in 16 story models

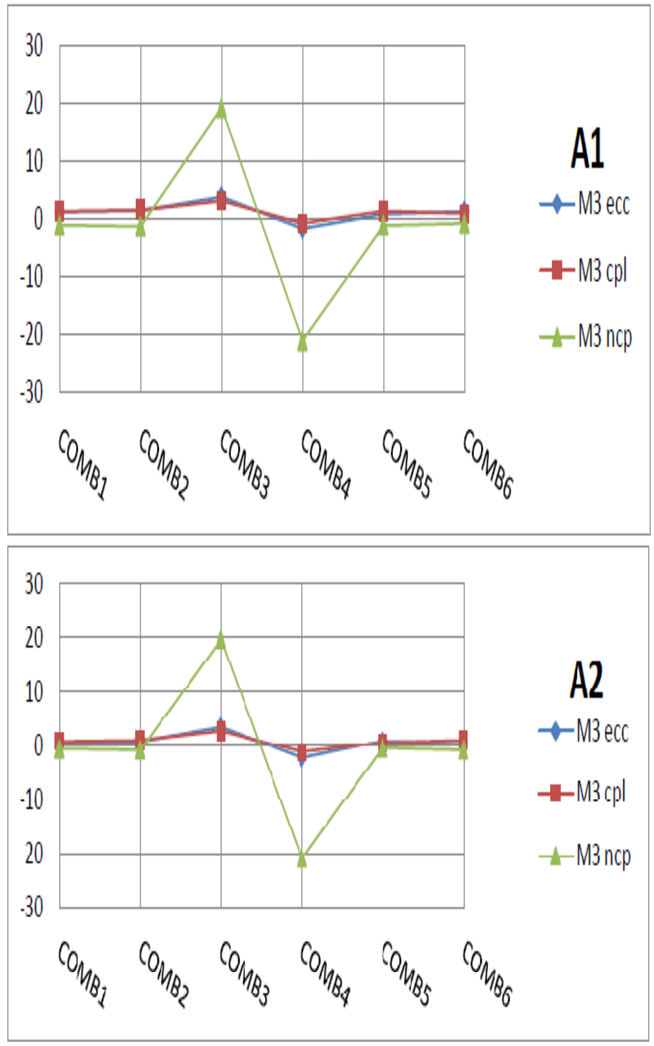


Figure-8
Comparison of design moment in columns for 40 cm wall in 16 story models

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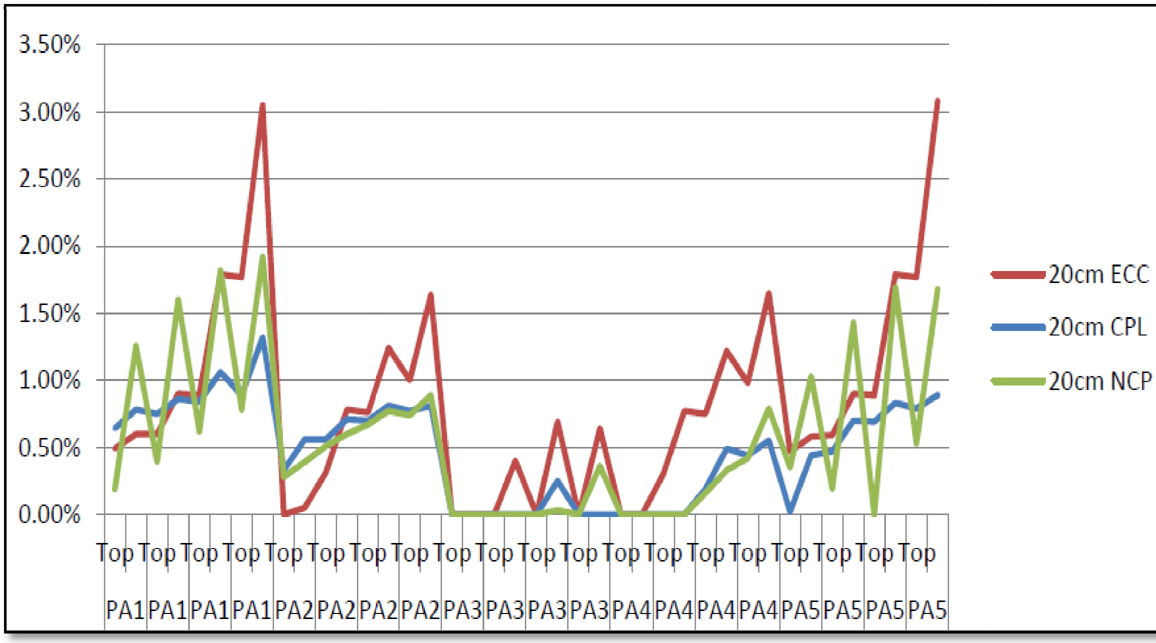
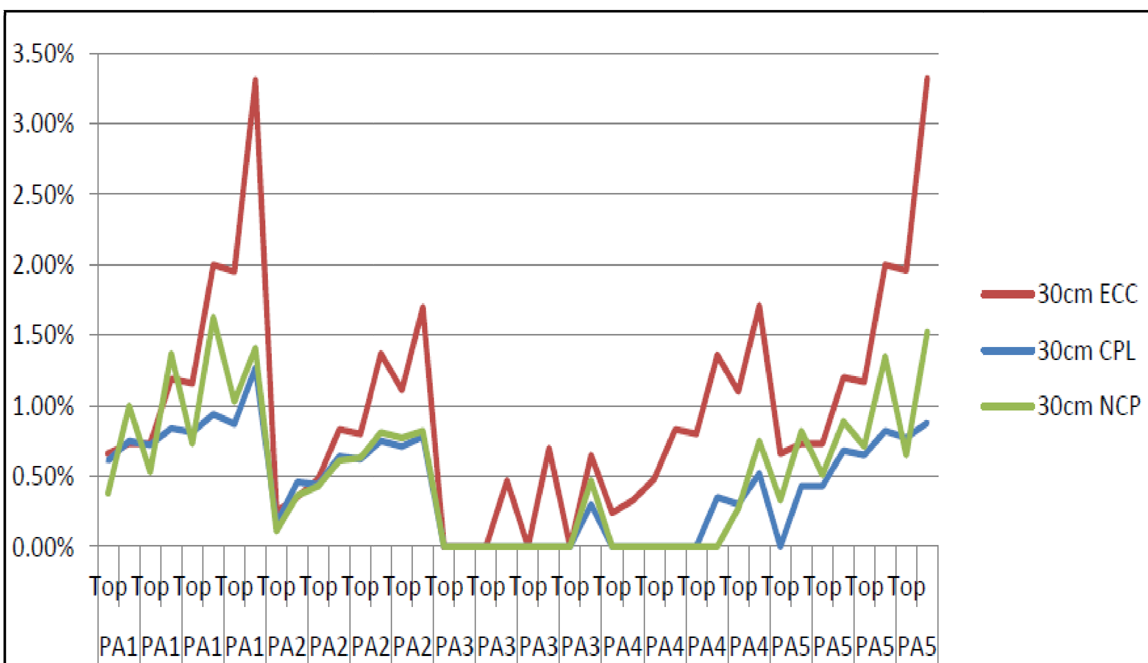




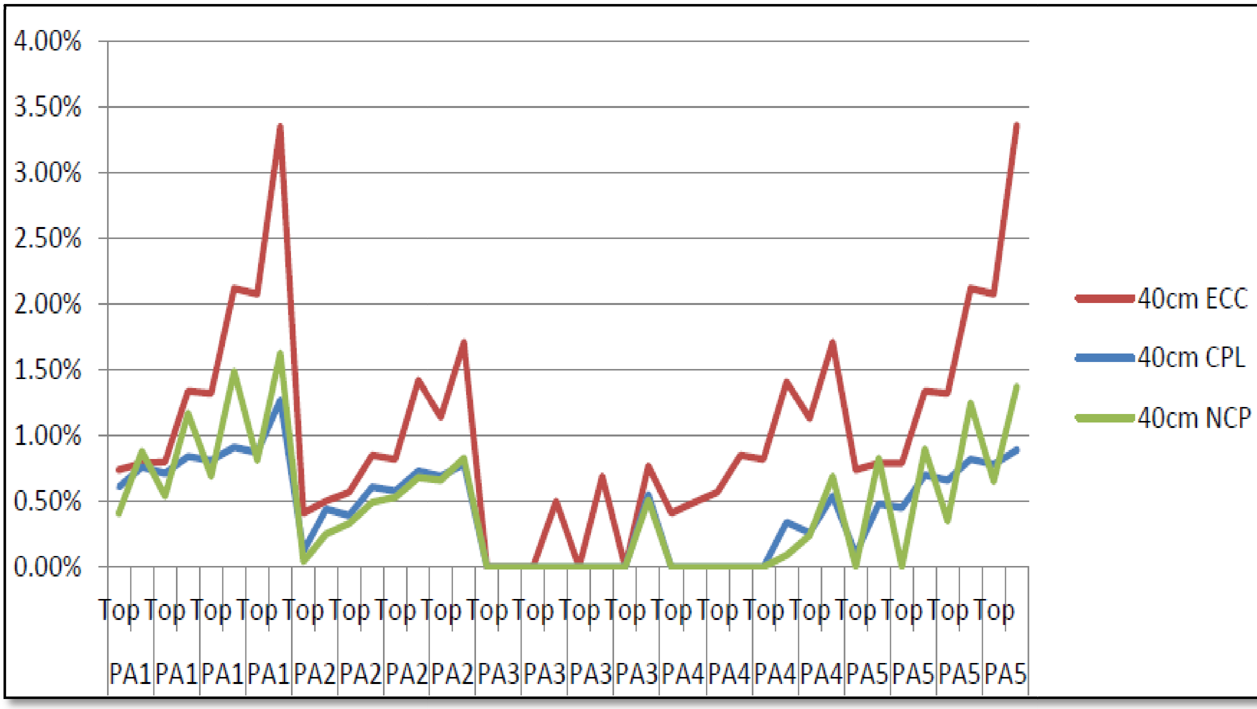
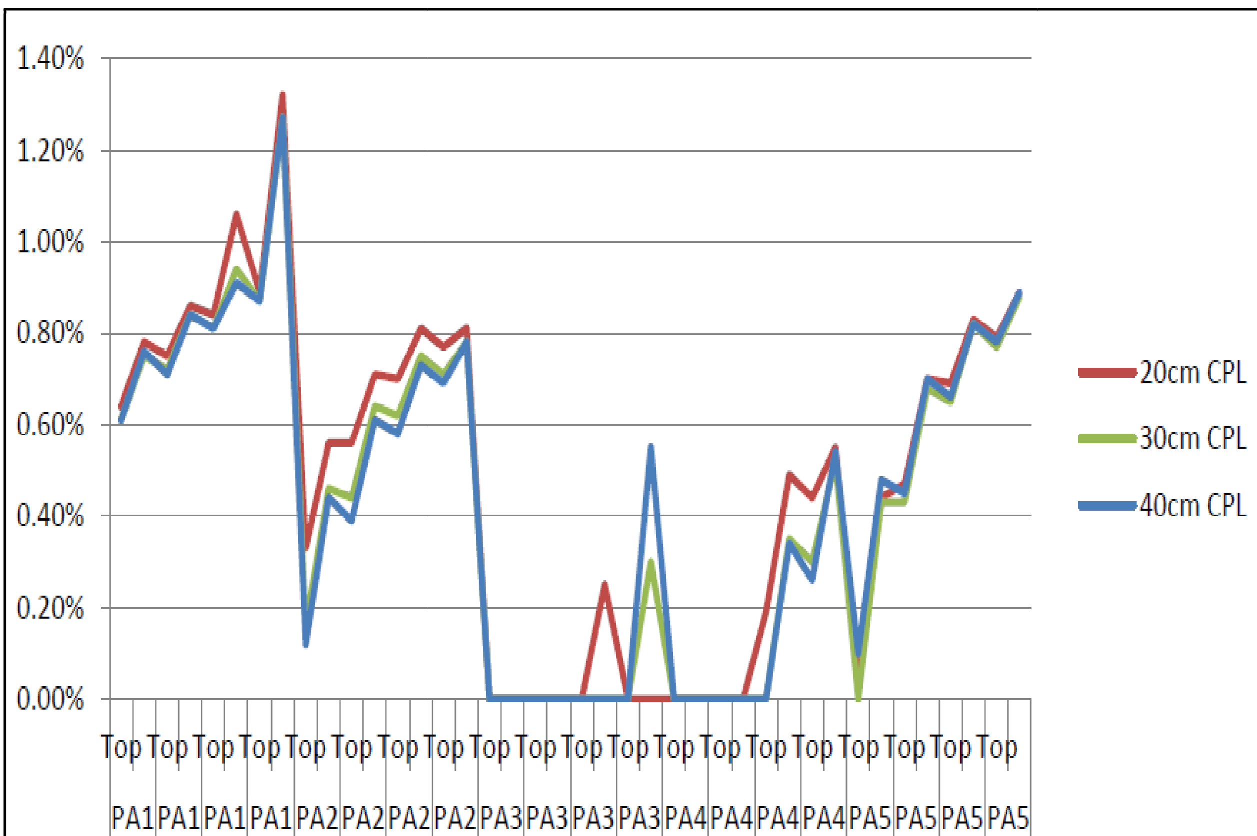
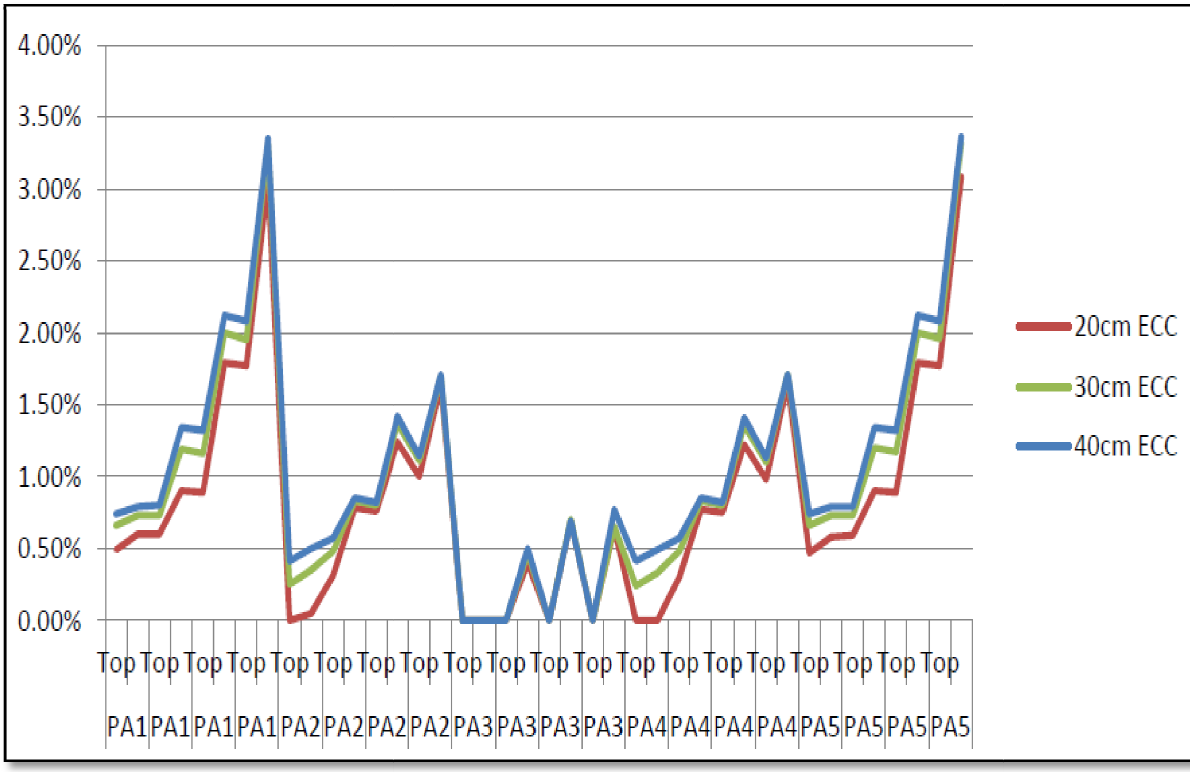


Figure-9
Comparison of required reinforcement ratio for 16 story models by shear wall placement and constant wall thickness





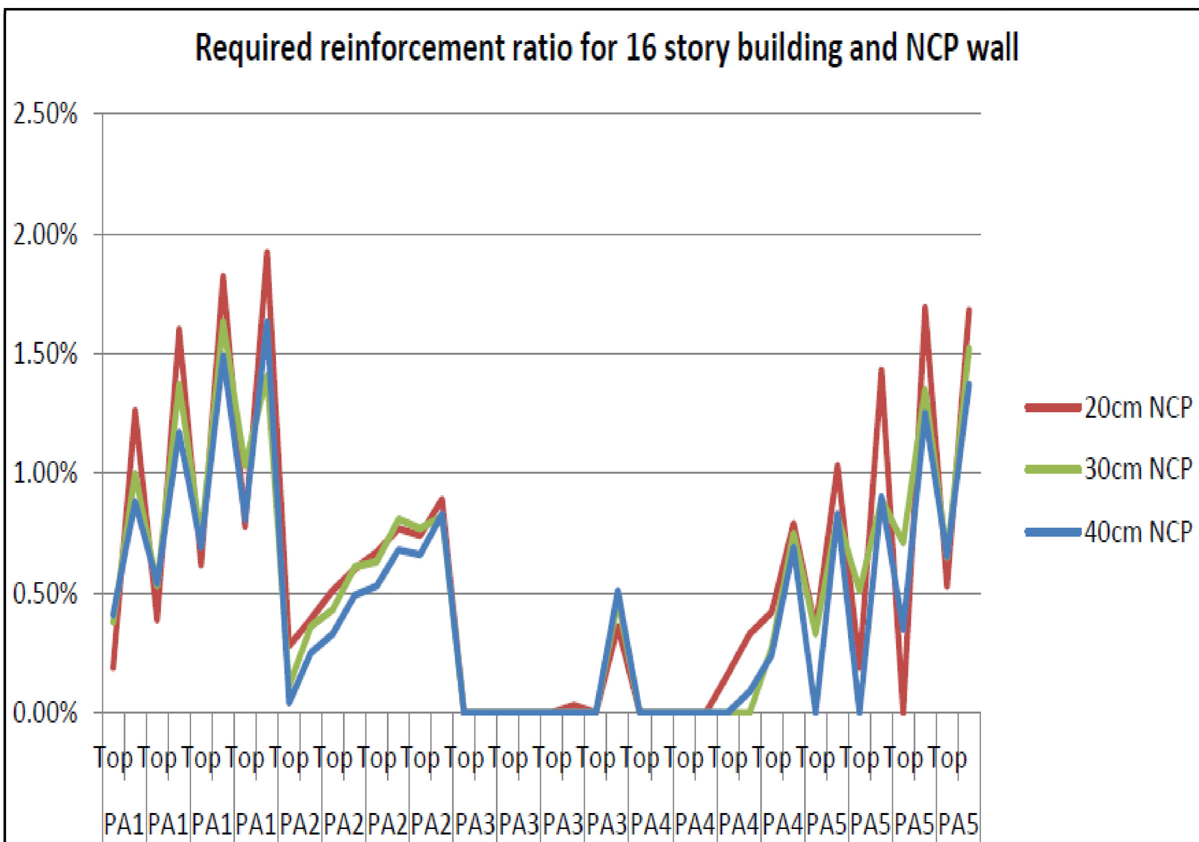


Figure -10
Comparison of required reinforcement ratio for 16 story models by shear wall thickness and constant placement

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