Investigating of Seismic Behavior of The Innovative Exoskeleton Structural System in Reinforced Concrete Tall Buildings

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SUMMARY:
The resistance of tall buildings to earthquakes is the main determinant in the devising of new structural systems that evolve by the continuous efforts of structural engineers to increase building height while keeping the deflection within acceptable limits and minimizing the amount of materials. Nowadays, the new structural system developed for reinforced concrete tall buildings in which the exterior shell is the primary structure of the building and acts as a perimeter tube. This system is categorized as an exterior structure that the major part of the lateral load-resisting system is located at the building perimeter so that this structural system is named "Exoskeleton". The exterior shell has many openings and openings layout creates a diagonal grid. This paper presents analysis of five concrete exoskeleton structures under seismic loads. In order to predict their seismic response; 20-story structures with plan dimensions of 30m × 40m have analyzed and designed. The overall void ratio created by openings is approximately constant between structures, but openings's layout, locations and configuration are changed. Three dimensional analysis and design of these structures is carried out. Lateral resisting system of strutures is interactive system with reinforced concrete core and exoskeleton system. Several analytical studies were conducted, then some selected results obtainded and compared. The comparison of analytical results indicate that this system can provide the required lateral stiffness and strength for resisting the lateral loads due to earthquakes. Moreover this paper presents description of exoskeleton structural system and the manner of its connection to interior structure. Also the focus of this paper will be on some specifications of structures alike drift, the shear absorbing percent, performance and interaction of interior core and exterior shell and stresses values.

Keywords: Tall Buildings, Exoskeleton, Reinforced Concrete, Seismic Behavior, Exterior Shell

1. INTRODUCTION OF EXOSKELTON STRUCTURAL SYSTEMS

Structural systems for tall buildings have undergone an evolution throughout the previous decades. From the structural point of view, a building is considered as tall when its structural analyses and design are affected by the lateral loads, particularly sway caused by such loads. Then the effets of these items had to be considered at the beginning of design procedure [1].

In these days, Structural system of tall buildings has been a continuously evolving process. In 1969 the late Dr.Fazlur Khan classified structural systems for tall buildings relating to their heights with considerations for efficiency in the form of "*Heights for Structural Systems*" diagrams. Later, he developed these schemes for both steel and concrete structures [2]. As time passes, classification of tall Building structural systems accomplished and structural systems of tall buildings can be divided into two broad categories: *interior structures* and *exterior structures*. This classification is based on the distribution of the components of the primary lateral load-resisting system over the building. A system is categorized as an interior structure when the major part of the lateral load resisting system is located within the interior of the building; alike Rigid Frame, Braced Frame, Outrigger and Belt trusses and Core structures. Likewise, if the major part of the lateral load-resisting system is located at the building perimeter, a system is categorized as an exterior structure; alike Framed Tube, Braced Tube, Tube in Tube, Bundled Tube and Diagrid systems [3].

Recently the *Exoxkeleton system* is exhibiting for tall buildings. In the Exoskeleton system, structural system located in perimeter of building and out of the building's primary skeleton and acts as a perimeter tube. The exterior shell has many openings that size and location of openings were carefully coordinated in order to make the wall effective in channeling both gravity and lateral loads down to the base of building. Openings layout in exterior shell creates a diagonal grid to enable its use both as gravity and lateral support. Generally the structural system such as exoskeleton system, can be said "Out of The Box". Using Exoskeleton system, provides column-free open spaces between core and exterior system which is effective from the viewpoint of architecture and makes flexible floors. Additionally by moving the lateral bracing for the building to the perimeter, the core which is traditionally enlarged to receive lateral loading in most towers, can be minimized for only vertical loading. This quality represents concrete at its best; because maintaining a minimum structural member, adding material locally where necessary and taking away where possible. This new structural system has unique architectural and structural feature and is the best lateral resisting system for concrete tall buildings [4].

2. Slab Connection to the exterior wall

One of the important points for design of this structural systems is the manner of connection between the plane of the floor plate and the exterior shell's vertical opening. Considering that Exoskeleton system located out of the buildings, had to be appropriate connection between exterior and interior skeleton. For this purpose, each slab edge is set back from the shell. So this connection would be done by tongues extending through the gap (see Figure 1). Approximately one-meter gap was needed between the main enclosure and exterior shell. Thus, the length of the gap between slab and shell had to be carefully monitored and controlled for deflection [5].

3. Openings Layout

Special attention was given to the detailing of the reinforcement so that each individual element's reinforcement could be integrated into the greater system. On the other hand, elements between the openings form a quasi-diagonal grid pattern and are reinforced accordingly to address shear stresses (see Figure 2). According to Figure 2, edges of the openings were ringed with edge reinforcement for crack control [6].

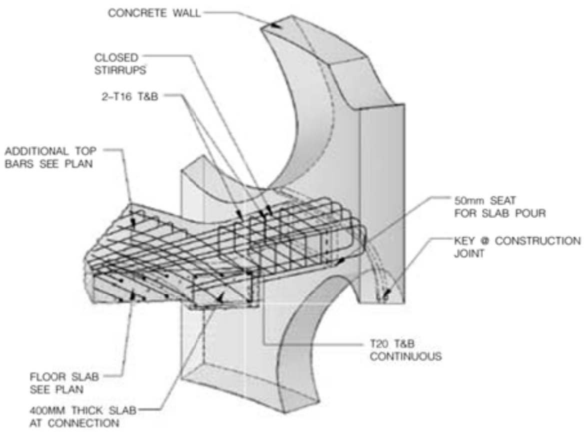


Figure 1. Typical slab connection to the exterior wall [6]

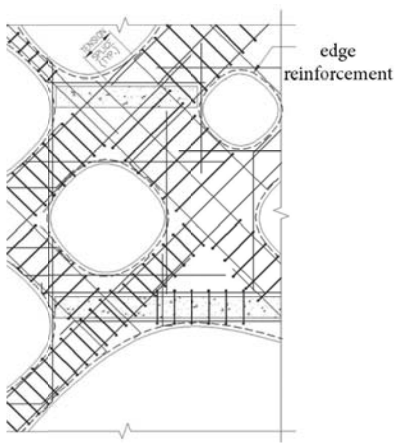


Figure 2. Typical reinforcement layout [5]

4. Specifications of analysis models

The analysis models are 20-story concrete exoskeleton structures with plan dimensions of 30m × 40m and story height of 4m. Aspect ratio (height to length) of these structures is equal to 2, so that exhibit High-Rise buildings. Figure 3 plotted the floor plan of these structures. This plan makes the exterior of the building curvilinear. This unusual external appearance makes it very distinctive. According to figure 3, centeral core is of rectangular shape and measures approximately 10m × 20m. In this system, openings Layout, openings location and overall void ratio created by the openings are important. It was decided that electing five models in which openings Layout and openings location are changed but overall void ratio created by the openings is constant between structures. The diameter of openings is 3 meters and percent of openings in exterior shell wouldn't be changed and is equal to 20% between structures.

The models are classified into five different types based on their openings Layout and openings location. The openings in exterior shell of first model, located randomly, throughout the whole building's façade. In other models, the whole building's façade is divided to four parts along their height; first part is along the first story to fifth story, second part is along the sixth story to tenth story, third part is along the eleventh story to fifteenth story and fourth part is along the sixteenth story to twentieth story. In second model, most of openings are located in first part and in third model to fifth model, respectively, most of openings are located in second part, third part and fourth part. Specifications of all models are mentioned in table 1.

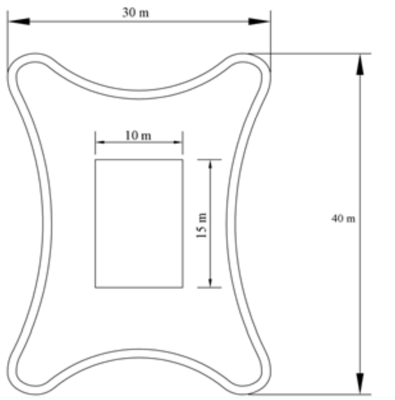


Figure 3. Floor plan of structure

Table 1. Specifications of models

Number of model	Openings locations
Model 1	located randomly, throughout the whole building's façade
Model 2	From first story to fifth story
Model 3	From sixth story to tenth story
Model 4	From eleventh story to fifteenth story
Model 5	From sixteenth story to twentieth story

The gravity loads are consisting of a 6 KN/m^2 dead load and a 4 KN/m^2 live load. The design seismic load was computed using the International Building Code 2006 (IBC, 2006) [6]. According to this code, following factors were chosen for structure. Importance factor in this structure was considered as I=1. Structure was located in a site with soil classification of type (C) and Site coefficient F_a and F_v are 1.2 and 1,7 respectively. In calculating the static seismic load, the response modification factor of 4.5 was applied for the exoskeleton system because there is no available response factor for this system in IBC-2006 and the ductility of the exoskeleton system is not clear. R=4.5 equal to the response modification factor of Shear wall-frame interactive system with ordinary reinforced concrete moment frame and ordinary reinforced concrete shear wall. This response modification factor makes this system behave safely for seismic loads, Therefore R=4.5 is applied. Also in this type of structure, system over strength factor and deflection amplification factor are respectively $\Omega_0 = 2.5$ and $C_d = 4$ [7].

Analysis and design of structure was carried out using SAP 2000 [8]. The design procedure of structure was started by satisfying ACI 318-05 requirements [9] and followed by checking satisfaction of maximum allowable drift by IBC2006. Compression strength of concrete is 70MPa (700 Kg/cm^2) for exterior shell and is 40MPa (400 Kg/cm^2) for shear walls and slabs. The yield stress of reinforcement is 350 MPa and the ultimate strength is 450 MPa. For exterior shells and shear walls, cracked section was respectively assumed with an effective stiffness equal to 35% and 70% of gross section.

5. Structural system of analysis model

The lateral resisting system of this model combines shear walls in centeral core and exoskeleton system. Thus lateral system of the building consists of shear walls surrounding centeral core and exterior shell. The main purpose of this paper is to investigate the behavior of exoskeleton system under seismic loads and interaction performance between centeral core and exterior shell. Also main characteristics like drift, value of shear stress in exterior shell and shear absorbing percent between exterior shell and centeral core are investigated. Then other influential parameters like percent of openings and the gap between slab and exterior shell should be stand constant. An isometric view of first model with Slabs removed for clarity and view of its exterior shell are shown in Figure 4. Also exterior shell of other models are shown in figure (5-a-d).

Typically shear walls are approximately 30 cm thick at the 11th story and above, and 40 cm thick at the 10th story and below. Also exterior shells are approximately 30 cm thick at the 11th story and above, and 50 cm thick at the 10th story and below. A conventional flat plate system, with thicknesses varying from 30 to 40 centimeters is used for the floor system. These thickness would be thickened after analyses and design to bear lateral loads.

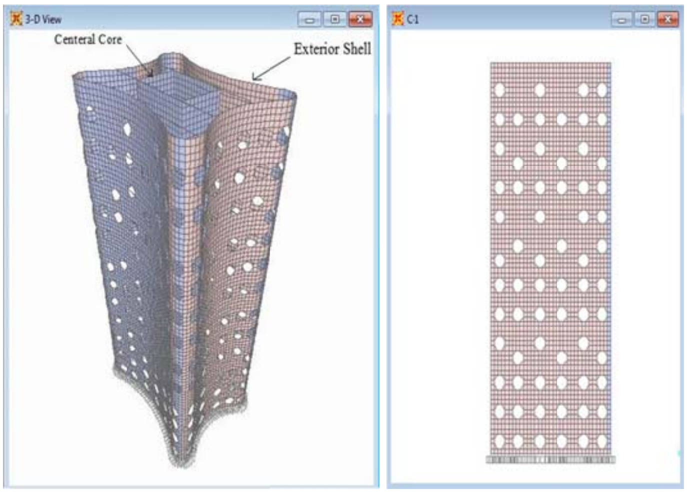
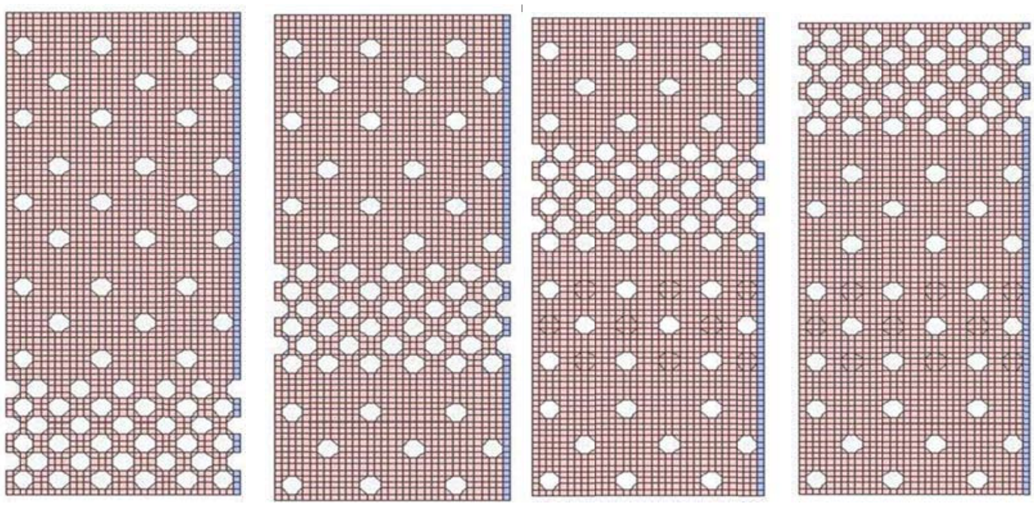


Figure 4. Left: 3D view of first model with exoskeleton system created in SAP2000, Right: Exterior shell with openings modeling in SAP2000



(a) (b) (c) (d)

Figure 5. a) Model 2, b) Model 3, c) Model 4, d) Model 5

6. Modeling Techniques

Modeling and analyzing the exterior shell was one of the biggest challenges in the design of the whole building. This process began with a 3D model of the shell in Auto CAD 3D. Then using analysis software SAP2000, could apply gravity and lateral forces to the model. This procedure took several iterations until the final elements and grid pattern fulfilled the structural requirements. The exterior shell was modeled using a fine mesh. Concerning this fact that plan of this model is curvilinear and the exoskeleton system has its difficulties, meshing had to be done in Auto CAD 3D before impotring this model to SAP2000.

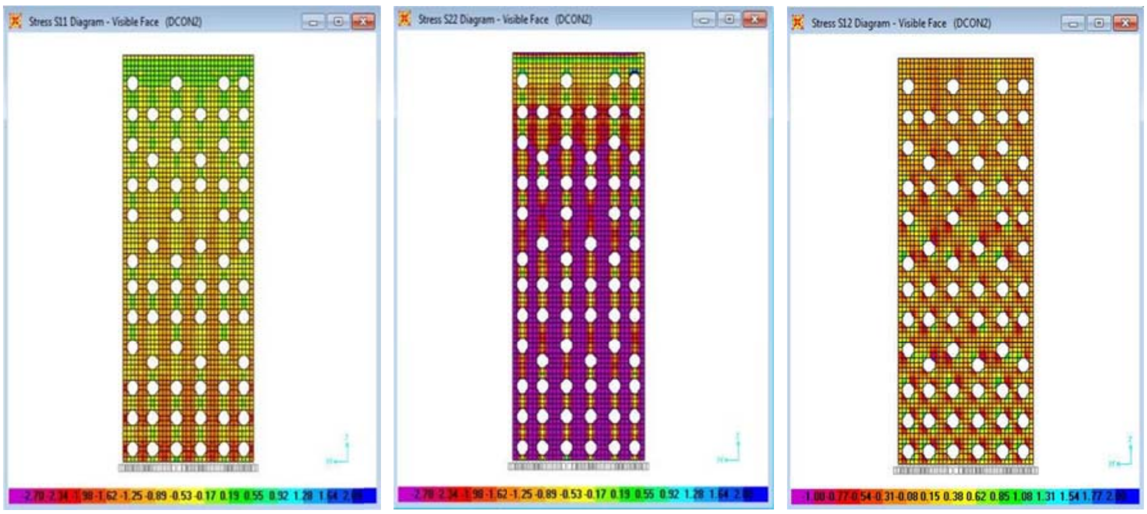
As mentioned previously, appropriate connection between exterior and interior skeleton is needed. Therbey modeling gap between exterior shell and interior skeleton is important. This connection would be done in not hollow shell. In order to provide appropriate connectivity, slabs at the floor level extending on the side of the shell without any opening through the gap. Since meshing this gap had to be conformed with meshing of shell. This connection was modeled in Auto CAD 3D and meshed according to mesh of exterior shell.

Eventually, final model exports to SAP2000. After importing this model to SAP2000, openings would be drawn in appropriate location. Then drawing of slabs and shearwalls of centeral core would be accomplished and the appropriate cross-sectional properties were assigned to all elements.

7. Analysis in SAP2000

As mentioned, using analysis software SAP2000, could apply gravity and lateral forces to the model in order to identify stresses in the elements between the openings. Thick shell elements were utilized to model the exterior shell, shearwall and slab. Therefore walls were modeled as shell elements without any nonlinearity.

The result from the SAP2000 analysis for exterior shell of first model is shown in Figures 6. According to Figure 6, σ_x stresses vary from -21 to 8.2 MPa and for σ_y from -37.43 to 13.9 MPa where negative values are compression stresses. As seen from the Figures the most critical stresses in x and y direction are at initial stories and around the openings. Therefore, thickness of shell was changed to 60 centimeters from the ground to the 10th level and 40 centimeters from the 10th level to the roof level and extra reinforcement was needed around openings. Also figure 6 shows the shear stresses in the shell and in the same way as for the stresses an average value is found to calculate the necessary reinforcement in the shell. The shear stresses change from -11.53 Mpa to 12.67 MPa and its value is bigger surrounding openings. In the region around of openings where shear stresses are more, edge reinforcement is needed. Resultes of other models are similar to first model so they don't mentioned.



(a) (b) (c)

Figure 6. a) Normal stresses from analysis in SAP2000, σ_x, b) σ_y, c) Shear stresses, τ_{xy}

It is necessary to mention that a concrete slab and connections between exterior shell and interior slab, without strengthening under tension will not provide much ductility. If the slab provides restraint to the exoskeleton and contribute to the stability of the system, the stiffness related to the stress level of the slab must be carefully considered.

8. Comparison of Relative Lateral Deflection

Three dimensional computer analyses using program SAP2000 is utilized for final assessment of drift. Figure 7 is a plot of the relative lateral deflection versus story number above the base for all models. In this plot the relative lateral deflection is caused by earthquake in X direction. Also a plot of the lateral deflection for all models is shown in figure 8. The maximum lateral deflection and the minium lateral deflection of the structures analysis is within 2.99 centimeter and 2.22 centimeter respectively. Maximum lateral deflection belongs to model 2 and minium lateral deflection belongs to model 5. For clarity, Maximum lateral deflection of all model is seen in figure 9. Lateral deflection in model 3 and 1 is similar and best model from lateral deflection point of view is model 5. Besides the deflected shapes show reasonable correlation near the base and verify cantilever behavior of buildings.

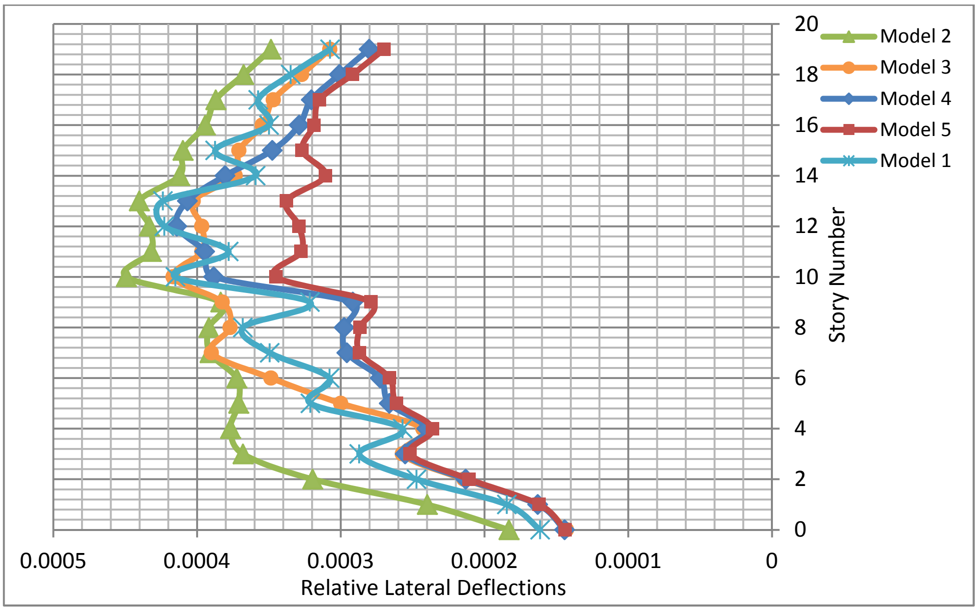


Figure 7. Relative Lateral Deflection vs. Story Number

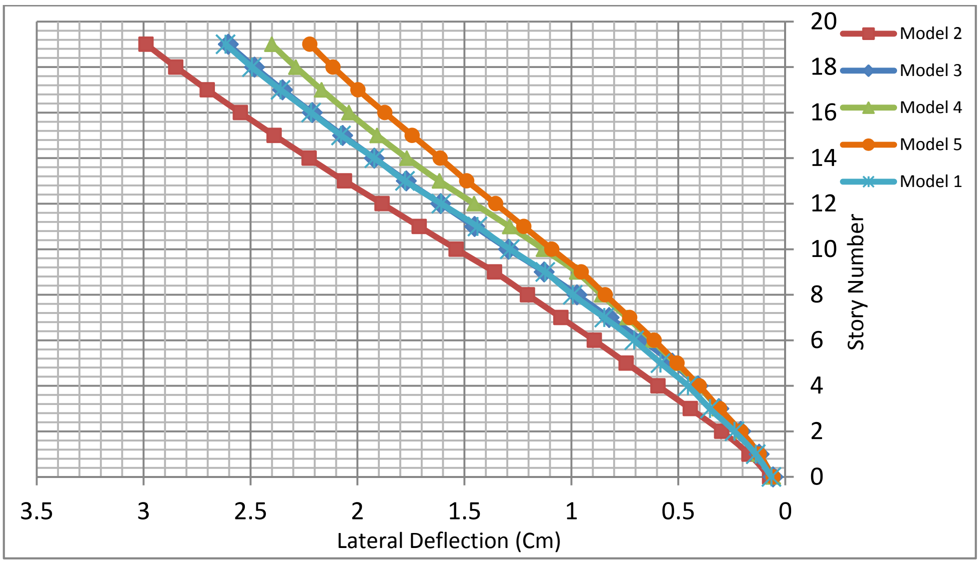


Figure 8. Lateral Deflection vs. Story Number

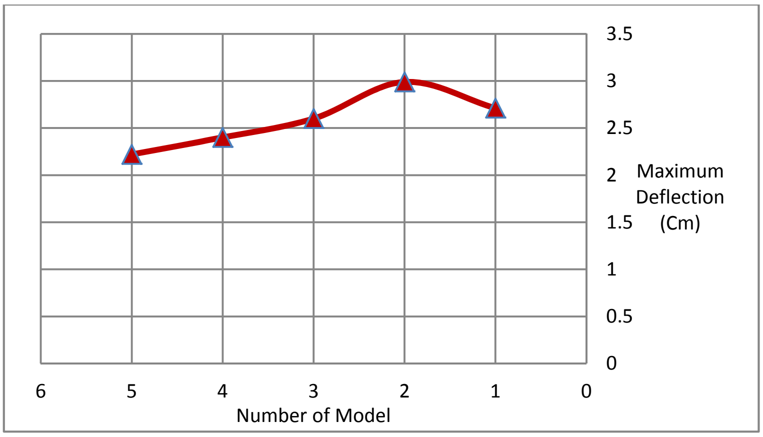


Figure 9. Maximum Lateral Deflection vs. Number of Model

9. Comparison of Shear Absorbing percent

As mentioned, in this building the main structure is composed of RC core and the concrete exoskeleton system. In this system, the RC core behaves like a cantilever and the exoskeleton resists shear actions. These two structural elements act together and make the building stiff. For this dual system, there is an interaction between the core shear wall and the exoskeleton system under lateral load. The shear transfer is usually not very large unless there is a significant change in lateral stiffness of either system. In this paper, in order to capture the centeral core-exterior structure interaction, a plot of the shear force and shear absorbing percent versus story number is sketched according to Figure 10 and 11. These results are related to earthquake in X direction. The shear walls deflects in a flexural mode with a maximum slope at the top, while the exterior shell deflects in a shear mode a maximum slope at the base. As illustrated, when both of them are connected together and subjected to earthquake loading, the deflected shape of structure has a flexural profile in the lower part and a shear profile in the upper part.

The shear absorbing percent is ratio of shear force that is carried by centeral core or exterior structure to total shear force at every level. Owing to this fact that, shearwalls of centeral core has a cantilever behavior, at upper stories internal core would be assisted by exoskeleton system. In table 1, date for shear absorbing percent in shear wall of centeral core is mentioned. For model 1, shear absorbing percent of interior core at top of building is -49.55% that indicates centeral core not only absorbs earthquake force, maybe make forces in earthquake direction.

Due to this cause, exterior shell at 20th story, absorbs 149.55% of earthquake shear force that is not appropriate. One manner to correct this deficiency is decreasing thickness of shear wall. As shown in figure 10 and 11, from 18th story, 72 meters elevation shear force would be negative and then shear walls had to be omitted after 18th story (after 68 meters). With trial runs, suitable thickness obtained equal to 5 centimeter that isn't executive. Consequently, shearwalls had to be omitted where produced negative shear force. Comments on the neglecting of shearwalls at three upper stories, optimized ratio of height for omitting shearwalls achieved $\frac{h}{H} = 0.9$ where h and H are height of existed shearwalls and height of omitted shearwalls respectively. This ratio is applied for all model except model 4. As shown in figure 10 and 11, in model 5, from story 17, 68 meters elevation shear force would be negative and then shear walls had to be omitted after 17th story (after 68 meters). therbey optimized ratio of height for omitting shearwalls achieved $\frac{h}{H} = 0.85$ where h and H are height of existed shearwalls and height of omitted shearwalls respectively. Additinally, As illustrated in table 1, shear absorbing percent of exterior shell at model 5 is the least that indicates model 5 is the best from the shear absorbing point of view.

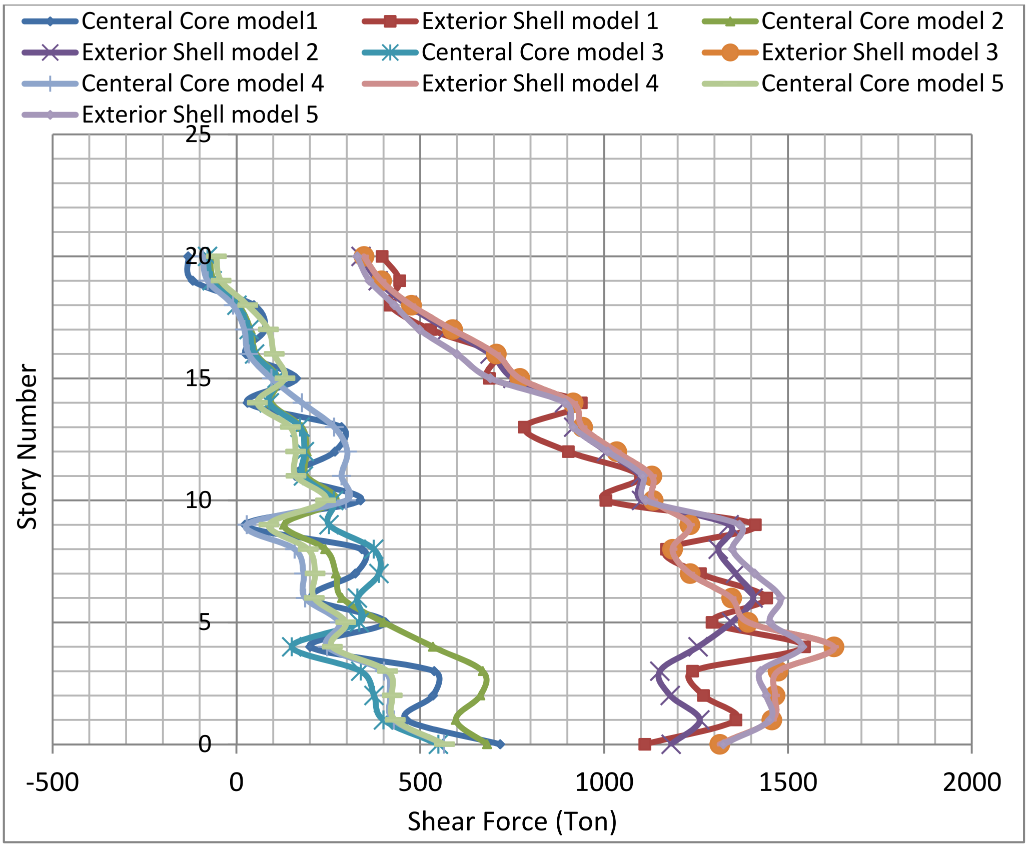


Figure 10. Shear Force Exterior Shell-Centeral Core vs. Story Number Diagram

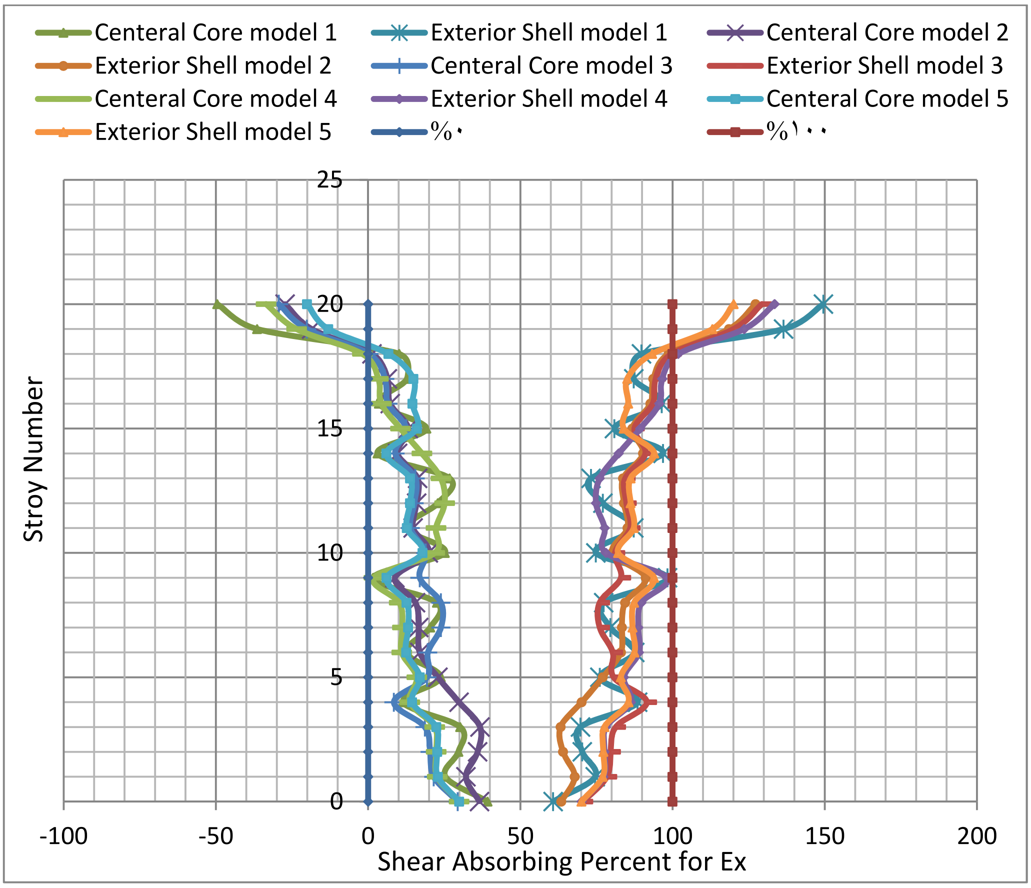


Figure 11. Shear Absorbing Percent Exterior Shell-Centeral Core vs. Story Number Diagram

Figure 1. Date for shear absorbing percent in shear wall of centeral core

Number of model	**Number of story with negative shear absorbing percent**	**Maximum negative shear absorbing percent**
Model 1	2	-49.55
Model 2	2	-27.30
Model 3	2	-29.33
Model 4	3	-33.51
Model 5	2	-20.06

10. CONCLUSIONS

As a result of our study, the exoskeleton system is recommended for architectural planning, structural efficiency and stability. This system resists lateral forces efficiently by its bending or shear action. Recently the exoskeleton system has been applied to tall concrete buildings because of its structural efficiency. More checks and researches are required to ensure the stability of the building and efficiency of construction because few have been built. If the exoskeleton system is selected for this building, it could become a landmark because of its unique external appearance and structural system. Furthermore, Applying the exoskeleton system could make singular building because of its unique structural system and external appearance.

Analytical results indicate:

1. The maximum and minium lateral deflection is within 2.99 centimeter and 2.22 centimeter. Maximum lateral deflection belongs to model 2 and minium lateral deflection belongs to model 5. Lateral deflection in model 3 and 1 is similar and best model from lateral deflection point of view is model 5. Besides the deflected shapes show reasonable correlation near the base and verify cantilever behavior of buildings.
2. The shear absorbing percent by interior core at top of building vary from -49.55% to -20.06%. Since exterior shell absorbs 149.55% to 120.06% of earthquake shear force. The maximum of negative shear absorbing is for model 1 and best manner to correct this deficiency is omitting shearwalls where produced negative shear force. Comments on the neglecting of shearwalls, optimized ratio of height for omitting shearwalls achieved $h/H=0.9$ where h and H are height of existed shearwalls and height of omitted shearwalls respectively.
3. The minimum of shear absorbing percent is for model 5 and optimized ratio of height for omitting shearwalls achieved $h/H=0.85$ where h and H are height of existed shearwalls and height of omitted shearwalls respectively.
4. Optimized model is the fifth one. So best location for openings is upper stories.
5. This study is done for 20-story buildings that suggests to predict their seismic response in a taller building when subjected to sereve ground motion.

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