Study of Structural RC Shear Wall System in a 56-Story RC Tall Building

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ABSTRACT:
In recent decades, shear walls and tube structures are the most appropriate structural forms, which have caused the height of concrete buildings to be soared. So, recent RC tall buildings would have more complicated structural behavior than before. Therefore, studying the structural systems and associated behavior of these types of structures would be very interesting. Here in this paper; we will study the structural aspects of one of the tallest RC buildings, located in the high seismic zone, with 56 stories. In this Tower, shear wall system with irregular openings are utilized under both lateral and gravity loads, and may result some especial issues in the behavior of structural elements such as shear walls, coupling beams and etc. To have a seismic evaluation of the Tower, a lot of non-linear analyses were performed to verify its behavior with the most prevalent retrofitting guidelines like FEMA 356. In this paper; some especial aspects of the tower and the assessment of its seismic load bearing system with considering some important factors will be discussed. Finally after a general study of ductility levels in shear walls; we will conclude the optimality and conceptuality of the tower design. Finally, having some technical information about the structural behavior of the case would be very fascinating and useful for designers.

KEYWORDS:
Tall Building, Reinforced Concrete, Shear wall system

1. INTRODUCTION

In many respects concrete is an ideal building material, combining economy, versatility of form and function, and noteworthy resistance to fire and the ravages of time. The raw materials are available in practically every country, and the manufacturing of cement is relatively simple. It is little wonder that in this century it has become a universal building material.

Tall buildings are the most complex built structures since there are many conflicting requirements and complex building systems to integrate. Today's tall buildings are becoming more and more slender, leading to the possibility of more sway in comparison with earlier high-rise buildings. Thus the impact of wind and seismic forces acting on them becomes an important aspect of the design. Improving the structural systems of tall buildings can control their dynamic response.

With more appropriate structural forms such as shear walls and tube structures, and improved material properties, the maximum height of concrete buildings has soared in recent decades. Therefore; the time dependency of concrete has become another important factor that should be considered in analyses to have a more reasonable and economical design.

In this paper, we introduce the highest reinforced concrete tower, located in high seismic zone. Having a general overview of the case, some especial aspects of the tower, and the assessment of its seismic load bearing system with considering some important factors will be discussed.

2. A GENERAL OVERVIEW OF THE TOWER

The tower is a 56-story tall building, located in Tehran, which is the most high seismicity zone of Iran and extensively populated nowadays (Figure 1, Table 1.1). As the policy of construction in Tehran is toward the vertical accommodation, so building such a tower would be helpful to approach this goal. The tower has three transverse main walls with the angle of 120° and multiple sidewalls perpendicular to each of them (Figure 1). It seems that this kind of architectural configuration is due to aesthetic considerations.

2.1. Structural system

Main walls are RC shear walls with regular staggered openings. Sidewalls are also RC shear walls, connected to the main walls with coupling beams. Some of sidewalls contain continuous column of openings and the rest are solid.

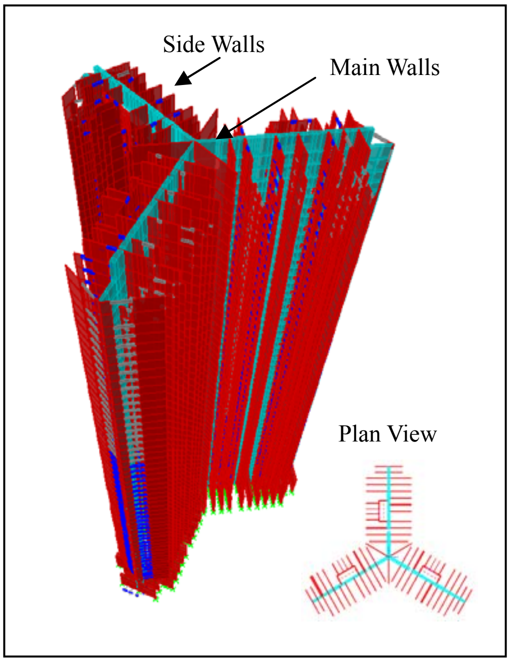

Figure 1 The view and structural system of the tower

Table 1.1 Summary of the tower properties

No. Elevations	56
Height	173 m
Typical floor area	3000 m^2
Effective residential area	126000 m^2
Structural system	Coupled shear wall
Volume of concrete	125’000 m^3
Weight of reinforcement	26’000 ton.
Steel weight per area	200 kg/m^2
Number of Individuals	571
Foundation	Mat

3. GENERAL CONSIDERATION IN THE TOWER

In the tower general considerations are the followings:

- Overall torsion

- Time-dependent effects
- Construction sequence loading

As the tower is located in a seismic dominant site, wind effects are neglected and the evaluation of the tower behavior is limited to seismic considerations only.

3.1. Overall torsion

In tall buildings, which have axisymmetrical lateral load resistant elements, here are three main walls; overall torsion should be considered as an important effective behavior. Regardless of the lateral in plane sidewall stiffness, the tower is not supposed to have any torsional stiffness. Therefore, not only the sidewalls are assumed to be a main gravity load bearing system of the tower, but also they are considered as a torsional resisting system. According to modal analysis results, tower's first mode shape is torsional with a period of 3.34 sec. (Figure 2). Despite of the fact that the dominant mode of the tower is torsional; the tower may not experience torsional excitation (torsional excitation is known as a characteristic of near fault ground motions).

3.2. Time dependent effects

In the design of high-rise concrete structures, a cumulative vertical non-uniform displacement in vertical elements is another subject that must be considered. Due to the elastic nature of concrete and its basic characteristics of initial shrinkage during curing process and creep, the high-rise structure will shorten during construction and for some period thereafter. Also, differential vertical displacements due to probable different loading patterns may cause a redistribution of forces in structural components. It is important that the designer should recognize the presence of time-dependent effects, and provide for them in the design. [9, 11, 12]

3.3. Construction sequence loading

Engineers have for long been aware of the inaccurate analytical demands in the upper floors of buildings due to the assumption of the instantaneous appearance of the dead load after the structure is built. In many cases the analytical results of the final structure can be significantly affected by the construction sequence of the structure and the manner in which the structure is built and activated and the incremental dead load gets applied. Tall buildings, which have structural elements with different longitudinal stiffness, are sensitive to these effects.

4. SEISMIC LOAD BEARING SYSTEM

4.1. General discussion

In this part, the seismic effectiveness of structural system will be explored. It should be investigated if the structure has enough level of ductility, as a seismic system, to satisfy the assumptions of the codes. Also, effective contribution of coupled walls, which essentially depends on the behavior of coupling elements (beams interconnecting main wall and sidewalls), is of the prime importance (Figure 2b).

4.2. Effect of axial load on shear wall ductility

According to the design codes, shear walls cannot be used as both gravity and seismic bracing systems; in fact, very tight criterions should be satisfied. A seismic bracing system, conceptually, should have a level of ductility; therefore the decrements of the bracing elements ductility under axial loads should be considered in conceptual design.

In this tower, it seems that designer assumed main walls as a seismic bracing system and sidewalls to carry gravity loads. This tower has a considerable behavior complexity because of its especial geometric specifications such as high aspect ratio of sidewalls (about 9), especial architectural plan form and some unknown facts about coupled wall system behavior. To quantify effects on gravity load distribution due to mentioned facts, numerical models of the tower assuming different number of stories over the foundation were developed.

Based on analysis results, main walls bear about 35% up to 60% of gravity loads varying with the story (Figure 3). It seems usual for a designer, to have an unreasonable judgment about gravity load distribution in the tower for example "main walls are a seismic bracing system and sidewalls are gravity load bearing system", but as it is mentioned above, not only main walls are assumed to carry seismic loads, but also they are going to bear a significant percentage of gravity loads.

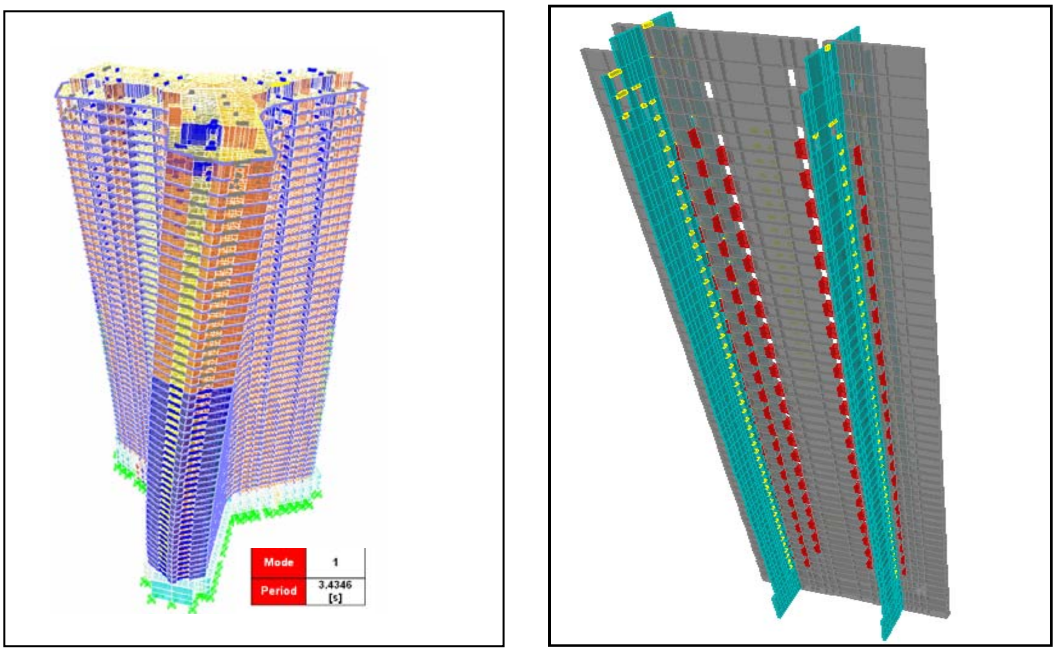

Figure 2 – (a) First mode of the tower, (b) Coupling beams in the main wall

According to these phrases, there is no straightforward design procedure, which may lead to build such a tower. In other words, a designer cannot choose a building with a same structural system following a design code. Then the trial and error approach would be the only way to achieve that.

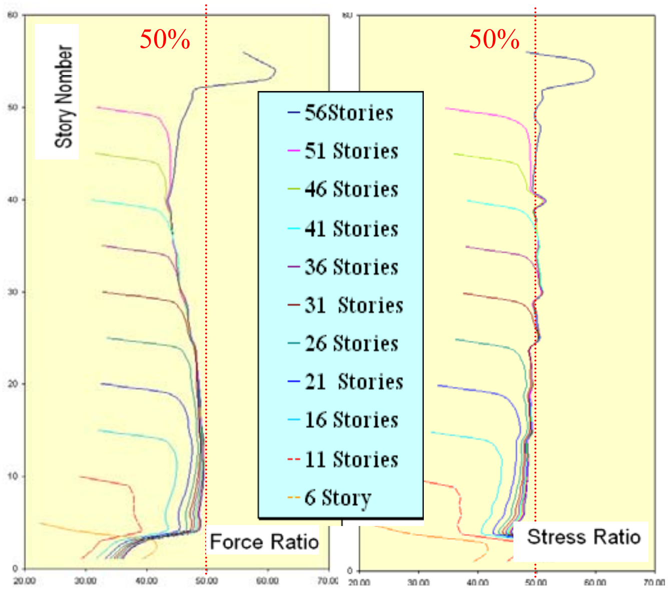

Figure 3 – Force and stress ratio diagrams in a main wall due to arrangement and geometric properties under floor loads only (Diagram is based on analyzing the tower assuming different number of stories over the foundation)

4.2.1 Numerical approach to shear wall ductility evaluation

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Nonlinear behavior of reinforced concrete sections is traditionally considered in evaluation of wall bracing systems.

Figure 4a shows the relation between axial force and ultimate curvature of the section based on Whitney block stress state. It is obvious that an increase in axial force, results the decrement of ultimate curvature, which implicitly means a decrease in section ductility ($\mu_\phi = \phi_u / \phi_y$). For an exact evaluation of curvature ductility, it is necessary to plot P-M-φ diagram representing true stress-strain behavior of concrete. In literature, idealized stress-strain curve of unconfined concrete looks likes Figure 4b. The behavior of reinforcements assumed to be elastic-perfect plastic. Assuming the values $\varepsilon_u = 0.003$, $\varepsilon_0 = 0.002$ and $\gamma = 0.15$, a computer program was developed to establish equilibrium in section and find M for given P and φ, which is shown in Figure 5a.

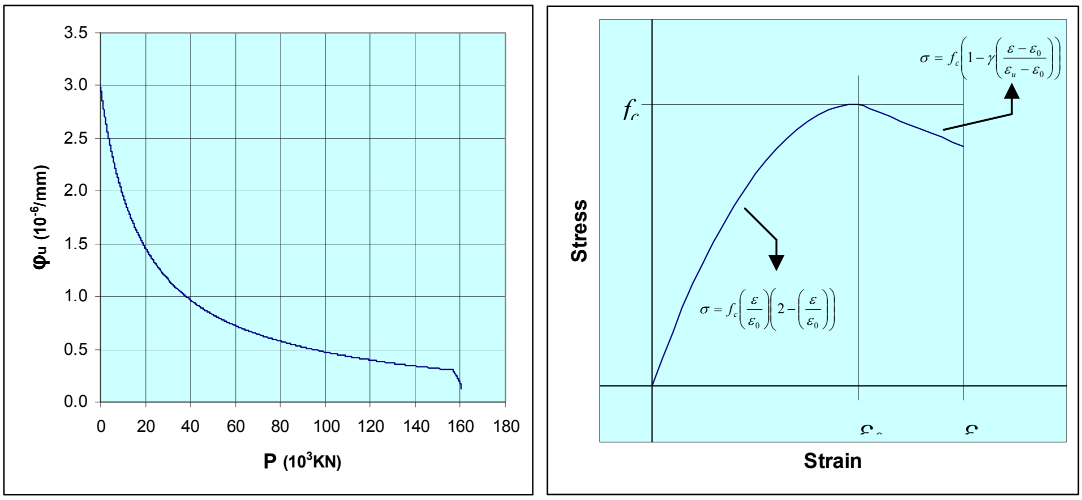

Figure 4 – (a) Ultimate curvature diagram for a 800x60cm RC section with 1% uniformly distributed reinforcement; f_c=35MPa, f_y=400MPa, (b) Idealized stress-strain diagram for unconfined concrete.

A variation of φ_y and φ_u versus P is shown in Figure 5b which proves that for $P/P_0 < 1/3$ the section is to some extent ductile, but for $P/P_0 > 1/3$, it collapses before yielding. Figure 6 shows curvature ductility for $P/P_0 < 1/3$.

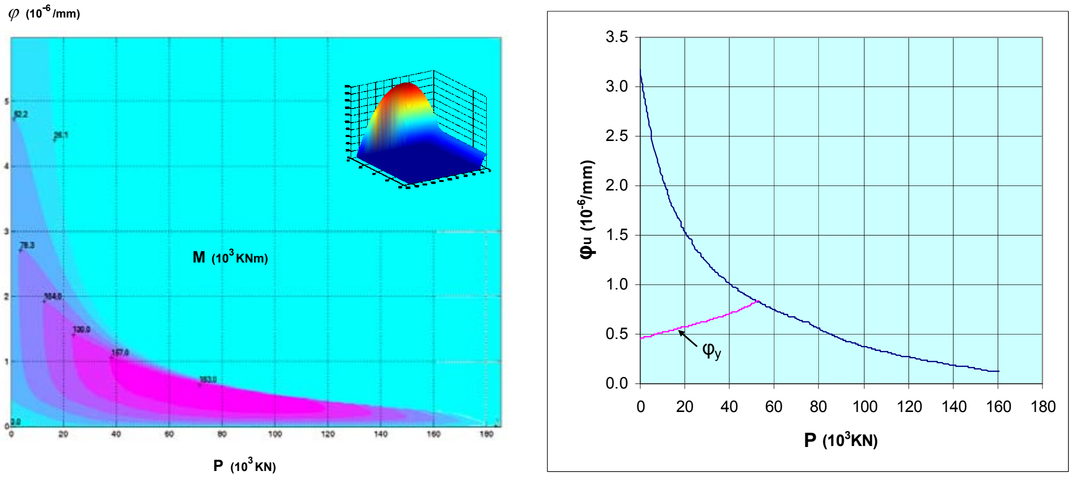

Figure 5 – (a) P-M-φ contour for a 800x60cm RC section with 1% uniformly distributed reinforcement; f_c=35MPa, f_y=400MPa., (b) φ_u and φ_y versus P diagram for a 800x60cm RC section with 1% uniformly distributed reinforcement; f_c=35MPa, f_y=400MPa.

Figure 6 states another interesting result that an over axial loaded wall cannot experience any plastification forever. In other words, it will bear seismic loads in elastic range or it will collapse. According to these results, using a wall system as both gravity load bearing system and seismic bracing one, leads to very non-economic designs, however it is not impossible. Increasing axial load level decreases R factor. So design base shear will be increased and moment of inertia of the section should be increased. In other hand, the lesser the axial load, the much more cross sectional area. Both approaches assure a non-reasonable and non-economic design.

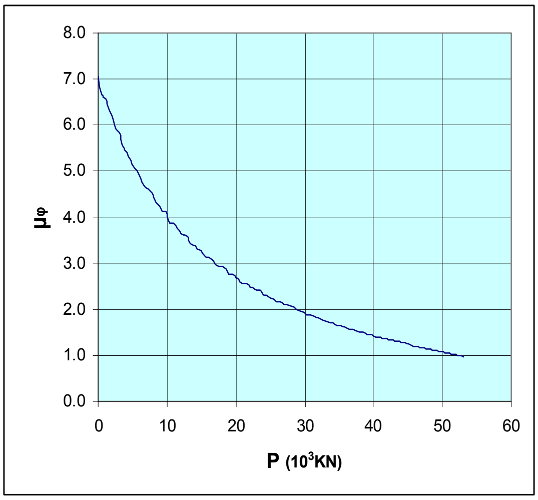

Figure 6 – μ_φ versus P diagram for a 800x60cm RC section with 1% uniformly distributed reinforcement; f_c=35MPa,f_y=400MPa

4.3. Effective contribution of coupled walls via coupling beams

Theoretical and experimental studies show that in coupled wall structures, plastic hinges are formed in the coupling elements before the walls yield and that such plastifcation can substantially increase the ductility of the structures. Within certain limits, the earlier the beams start to yield, the greater will be the increase in ductility. However, if the beams yield prematurely, the lateral strength of the wall structures might be severely impaired and the ductility of the beams might become exhausted when the walls start yielding. Thus for best overall performance, the beams should yield well before the walls do but not at so early a stage as to cause excessive reduction in lateral strength or breakage of the beams before the wall fails.

Despite the fact that coupling beams are assumed to be cracked prematurely in earthquake, this event might take place under permanent gravity loads as a result of concrete time dependency. According to above, some coupling beams, connecting main wall to sidewall, were found to be cracked (Figure 7).

It can be concluded that coupling beams are plastified under fixed moments due to non-uniform vertical displacement. Level of axial stresses associated with floor loads on sidewalls and main walls were the same (Figure 3) and only probable cause, might be time-dependent effects based on self-weight of walls. All of the walls have at least 0.7% of reinforcement so the shrinkage effect will be negligible.

Figure 7 – Structural cracking of a coupling beam in middle stories after sand blast

4.3.1 Tertiary Evaluation of time-dependent effects with consideration of construction sequence loading

According to ACI-209, followings are the most important parameters that should be considered in creep analysis [9]:

- Age of Loading
- Relative humidity
- Average thickness of element
- Slump of fresh concrete
- The ratio by weight of the fine aggregate to total aggregate
- Air content of fresh concrete

To consider these effects, a numerical code was developed to analyze the main wall and sidewall separately under their self-weight considering creep and construction sequence loading effects. In next part, the geometric properties of model and the analysis results will be presented (Table 4.1).
The results are presented in Figure 8, and significant differences are shown between sidewall and main wall displacements due to creep and construction effects.

Table 4.1 Properties of walls for creep effect analysis

Wall type	Length (m)	Thickness (cm)	Height (m)
Main wall	50	100	173
Side wall	12	30	173

Provided that the structure analyzed traditionally, not considering these facts, the critical demands due to cumulative differential displacements would be occurred in upper structural elements. If time dependencies of concrete and construction sequence loading were coupled in analyses, the critical demands would be descended to middle height of the structure (here is somewhere between 25~35th story).

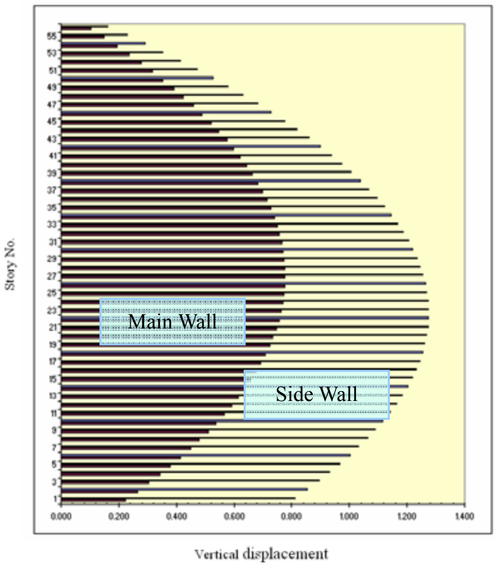

Figure 8 – Results with consideration of construction sequence loading plus creep effects for Main Wall and Side Wall.

4. CONCLUSION

Designer should recognize the presence of time-dependent effects, and provide for them in the design. Having concrete structural elements with different longitudinal stiffness makes the tower to be more sensitive to differential displacements due to concrete time dependency. A level of ductility for seismic bracing systems, conceptually, should be provided for energy absorption but axial loads have an adverse effect on their acceptable performance and this fact should be considered exactly.
As is proofed here, using shear walls for both gravity and bracing system is unacceptable neither conceptually nor economically. Not only main walls are assumed to carry seismic loads, but also they are going to bear a significant percentage of gravity loads.

Increasing axial load level decreases R factor. So design base shear will be increased and moment of inertia of the section should be increased. In other hand, the lesser the axial load, the much more cross sectional area. Confinement of concrete in shear walls is a good way to provide more level of ductility and getting more stable behavior. So, the designer would be allowed to bring up the level of axial stresses to have a reasonable design. Despite the fact that coupling beams are assumed to be cracked prematurely in earthquake, this event might take place under permanent gravity loads as a result of concrete time dependency. Redistribution of loads according to creep and sequential loading will intensely change the primitive assumptions on gravity load tributaries and consequently the level of ductility. By considering both time dependency of concrete and construction sequence loading simultaneously in analyses, the critical demands would be found to occur in the middle height of the structure (here is somewhere between 25~35th story).

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