Lateral Response Behavior of High-Rise Buildings in One Direction Eccentricity

Osama A. Kamal[1a], Ahmed H. Abdel-Kareem[2b], Hala M. Refat[3c] and Ahmed M. Abd El Salam[*4]

[1]*Department of Civil Engineering, Shoubra Faculty of Engineering,Benha University, Egypt*
[2,3, and 4] *Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt*

Abstract. This paper presents an approach for calculating a Cumulative Inertia Index (*CII*) in order to predict high-rise buildings response under lateral loads for cases ofmedium eccentricity(≥ 5%, and ≤ 10%) in one direction. Different distributions of columns, shear walls, and outriggers are considered. Plan layouts with different aspect ratios are studied. The main aim is to present an index for high-rise building structures subject to lateral loads, which is simplified, and gives results within an acceptable accuracy.Shear walls and tube-in-tube systems with and without outriggers are considered. A set of guide charts and equations for moments, shear, deflection, drift, and period are generated for each case. The utility and accuracy of this approachis be demonstrated by several case study examples.

Keywords:high-rise, lateral response, period of vibration, vibration period, drift, medium eccentricity

1. Introduction

The idea of high-rise buildings construction began in the 1880s. It had been largely spread for commercial and residential purposes.Emerging of these buildings was primarily a response to the demand by business activities to be close to each other and to the city center;thus leading to intense pressure on the available land space. High-rise commercial buildings are frequently developed in the city center as prestige symbols for organizations. With the increasing mobility, the tourist community has a need for more high-rise city center hotel accommodations.

From the point of view of the user of a high-rise building; the building should be stationary, and any displacement or lateral drift must be acceptable. Unacceptable motion results in acceptable building becoming an undesirable building;thus producing difficulties in living or working in that building or part of it. Any building must be capable of resisting the design loads and of preventing any excessive movement and damage to nonstructural elements. Therefore, provisions that control the response of the building such as period, displacement, drift, and vibration had been included in the design codes.

Approximate methodsare available to predict columns, shear walls, and footing loads under gravity loads. Experienced engineers judgeany computer output as being right or wrong depending on these approximate approaches.Similar simplified methods are also available toestimate shears and moments due to gravity loads in horizontal elements such as slabs and beams. However, there are no such "agreed upon" heuristic rules for predicting response due to lateral loads on columns, shear walls, and foundations. Therefore, similar judgment on the straining actions and deformations resulting from computer analysis for such cases becomes a harder task.

∗Corresponding author, Ph.D. Student, E-mail: ahmed.abdelsalam@bhit.bu.edu.eg
[a]Professor, E-mail: osama.kamal58@feng.bu.edu.eg
[b]Associate Prof., E-mail: ahmed.abdelkareem@bhit.bu.edu.eg
[c]Associate Prof., E-mail: hala.abusafa@bhit.bu.edu.eg

Design codes such as Uniform Building Code (UBC 1997), Egyptian Code of Practice (ECP201 20012), American Society of Civil Engineers (ASCE07-102010), International Building Code(IBC 2018), and other codesallow approximate and simplified methods for determining the vibration period for buildings. Newmark and Hall (1982) suggested a formulae for predicting the vibration period of the buildings.Hojjat Adeli (1985) derived approximate formulae for the vibration period for different building systems: frames, shear walls, diagonally braced frames, frames with cross bracing, and frames with k bracing.Peifu et al. (2014) adopted 414 high-rise buildings in China to explore a range for vibration periods.Alguhane et al. (2016) proposed two equations for calculation of the period of vibration. Pavan and Dhakal (2016) proposed an equation for calculation of the period of vibration.

Many researchers had developed simplified equations to estimate lateral response components such as drifts, periods, displacements, and base shear for different types of systems such as frames, shear walls, and dual systems of high-rise buildings. Algan (1982)investigated the role of drift and damage considerations in earthquake resistant design of reinforced concrete buildings. He used small-scale reinforced concrete structures (sixteen, ten, and nine-story) tested on the earthquake simulator at University of Illinois. The deformed shape and maximum drift were dependent on the type of structure (frame or wall). Hoedajanto (1983)developed a simple analytical procedure to calculate the response of reinforced concrete elements subjected to lateral loads. The main concern of his research was to develop a computer program to calculate the displacement of general reinforced concrete cantilever beam subjected to increasing load. Brownjohn et al. (2000)built six 3-D finite element models of one tall building, using finite element models with lumped masses and rigid floor diaphragms. The mode shapes and natural frequencies were obtained and compared by results from field measurements. Hoenderkamp and Snijder (2000)produced an approximate hand method for estimating horizontal deflections in high-rise steel frames in order to study the effect of beam-column connections on horizontal deflections. Kamal and Hamdy (2003)presented a simplified approach that reduces the size of the problem to a more viable size, for estimating straining actions and drift values for preliminary design against lateral loads.

Tarjan and Kollar (2004)produced a simple formulaefor calculating the period of vibration and internal forces of a building structure subjected to earthquakes. Meftah et al. (2007)produced a generalized hand method for seismic analysis of asymmetric structure braced by shear walls and thin–walled open section columns. Based on the continuum technique and d'Alembert's principle, simplified formulae are given to calculate the circular frequencies and internal forces of a building structure subjected to earthquakes. Bozdogan and Ozturk (2010)produced an approximate method based on the continuum approach and transfer matrix method for lateral stability analysis of building. Rahgozar et al. (2010)proposed a new and simple mathematical model that may be used to determine the optimum location of a belt truss reinforcing system on tall buildings.Panagiotis and Mehdi (2019) proposed a study that focuses on the determination of the vibration period of reinforced concrete infilled framed structures by using feed-forward artificial neural network models.

So far, it is seen that none of the presented work provides a unified approach for estimating lateral response behavior forhigh-rise buildings.This paper presents a method for predicting the high-rise building response under lateral loads for medium eccentricitiesin one direction (≥ 5%, and ≤ 10%). Different distributions of columns, shear walls, and outriggers are considered. Elevation layouts with different aspect ratios are studied.

2. Proposed Model

This study is designated for four structural systems. The first structural system consists of core walls only. The second structural system utilizescore wallswith outriggers.The third structural system adopts tube-in-tube.The fourth structural system usestube-in-tube with outriggers.

The study considers nine towers of different heights (thirty-two, thirty-six, forty, forty-four, forty-eight, fifty-two, fifty-six, sixty, and sixty-four floors). The study targets high-rise buildings with vertical regularity and with 'height to width' ratio lying between 2.5 and 5.As per some design codes, the response spectrum approach is best suited for such range of aspect ratios. Forsecond and fourthstructural systems, one outrigger in the middle of the building for forty-four to fifty-two story buildings, and two outriggers (at the first third and at the second third of the building) forfifty-six to sixty-four story buildings are considered in the configuration.

Figure1 shows the structural systemsusedfor shear wall case with 10% eccentricity in x and y direction,separately. The code used is (XW10):the first letter indicates the direction of eccentricity (X for x-direction and Y for y-direction), the second letter indicates the type of systems (W for shear wall and Tfor tube-in-tube,), and thethird number indicates the number of model.Models are divided into four models in order to allow for different layout wall arrangements (Fig. 1), and the final number indicates theexistence of outrigger (0 for no outrigger, and 1 for inclusion of outrigger).Figure 2manifests the different shapes of shear wall with outrigger systemswith 10% eccentricity in x and y direction,separately. In addition, Figure 3 presents the tube-in-tube structural systemswith 10% eccentricity in x and y direction,separately. Figure 4exhibits the shapes of tube-in-tube with outrigger systemswith 10% eccentricity in x and y direction,separately.

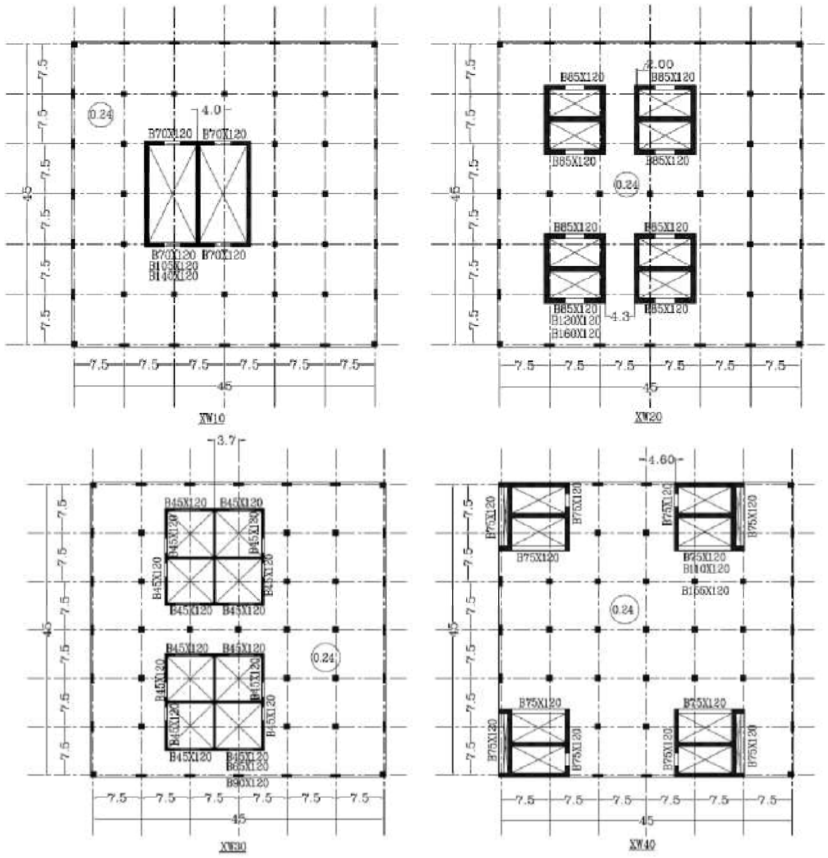


Fig. 1 Structural Systems used in Core (Shear Wall) Case

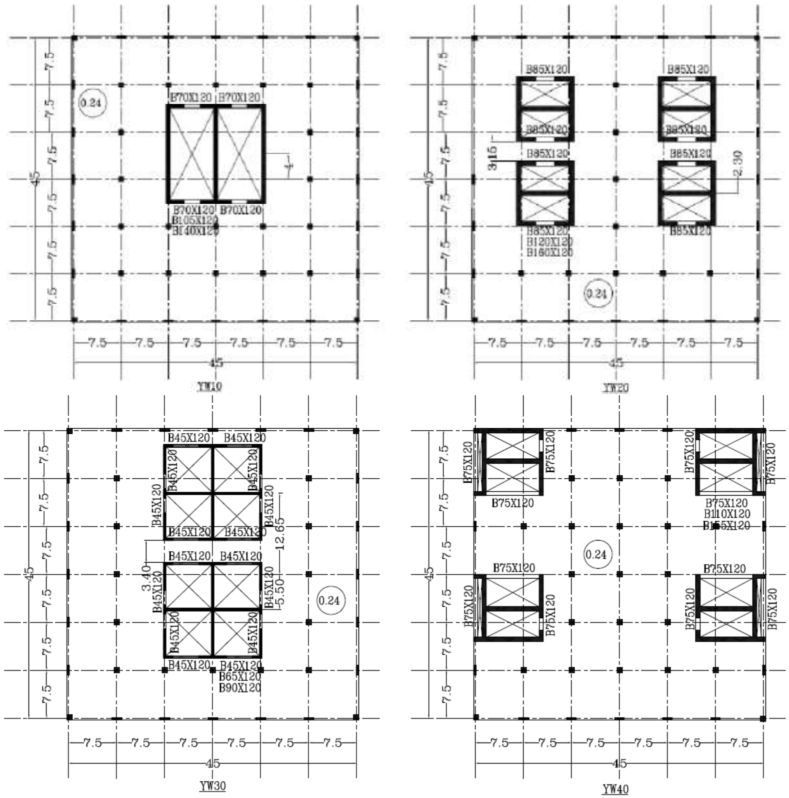


Fig. 1 (Cont.) Structural Systems used in Core (Shear Wall)Case.

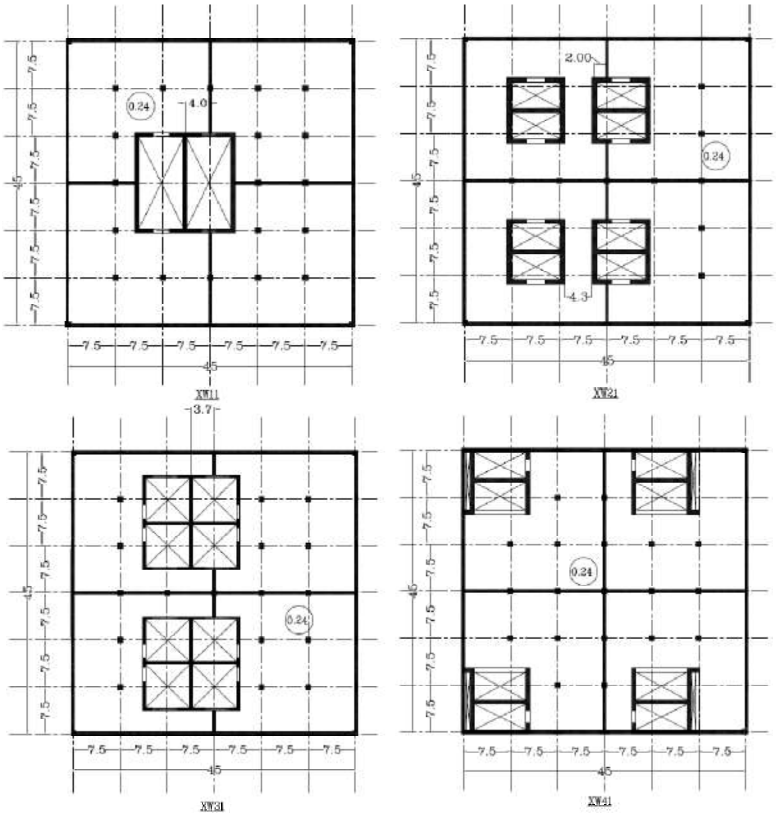


Fig. 2Structural Systems used in Core (Shear Wall) with Outrigger.

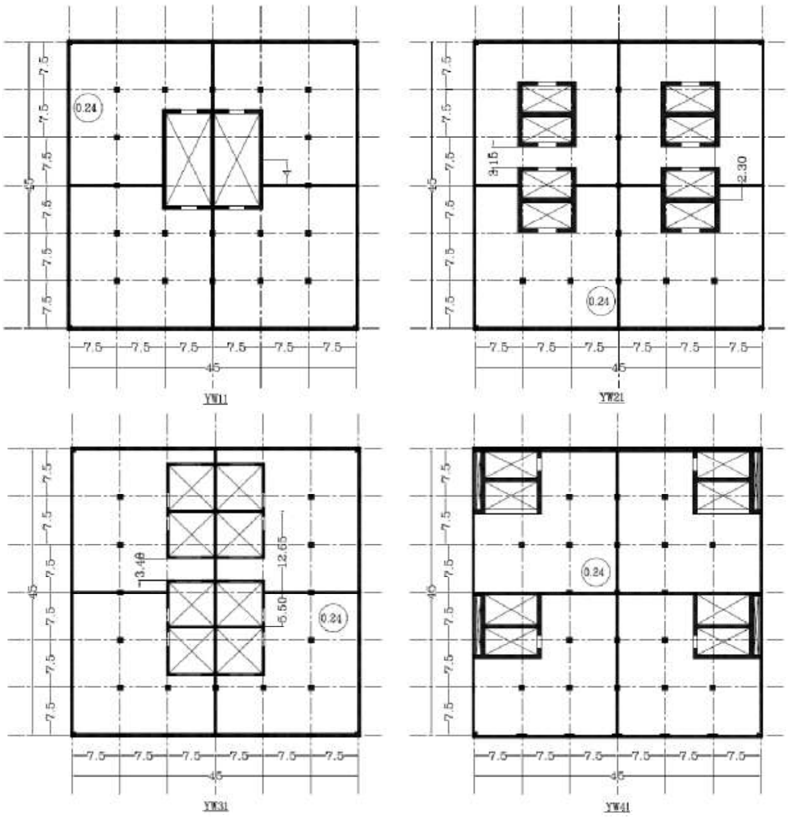


Fig. 2 (Cont.)Structural Systems used in Core (Shear Wall) with Outrigger.

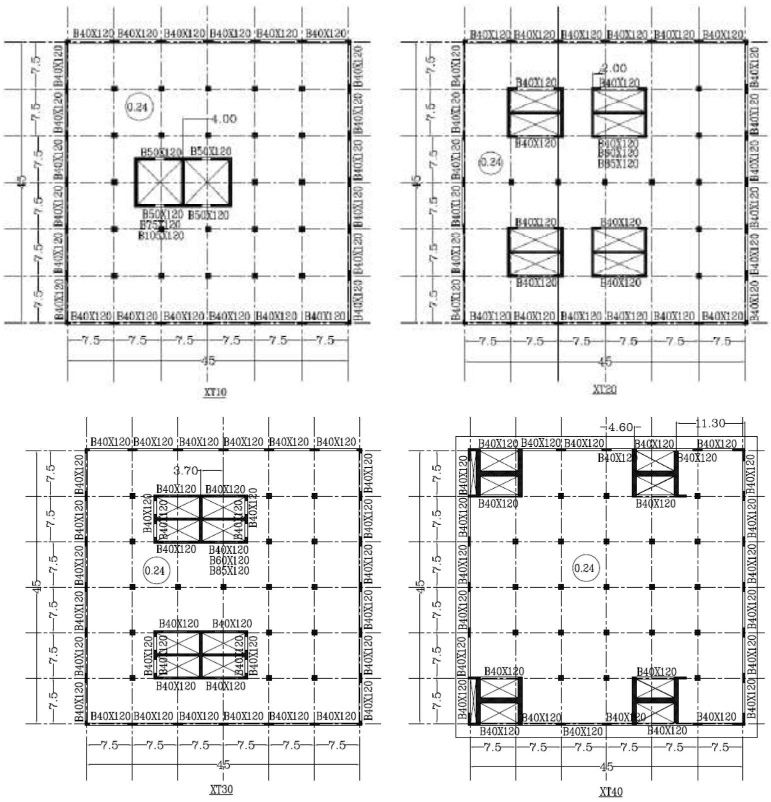


Fig. 3Structural Systems used in Tube-in-Tube.

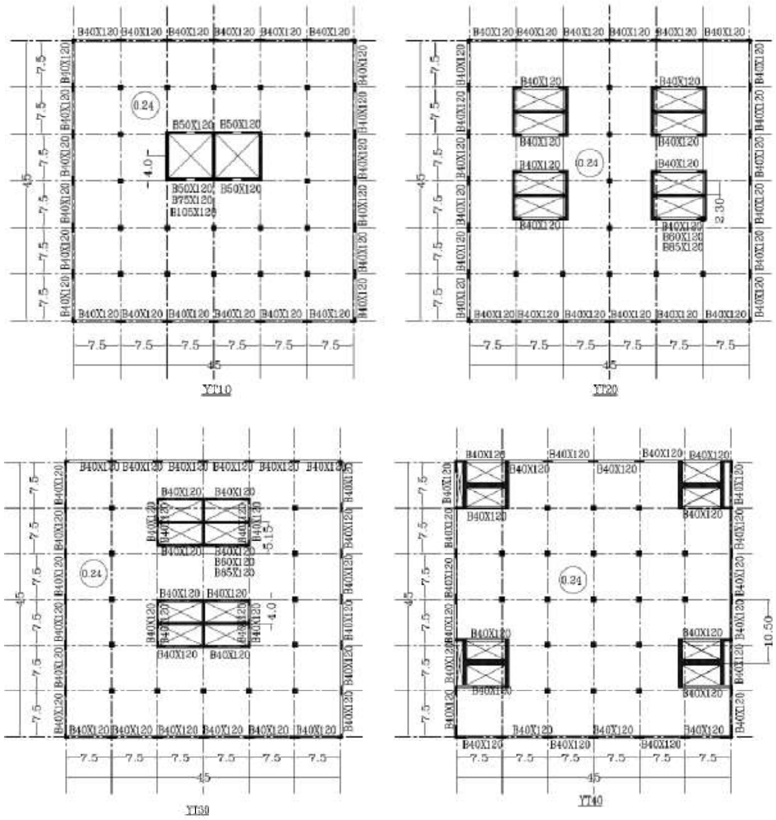


Fig. 3 (Cont.)Structural Systems used in Tube-in-Tube.

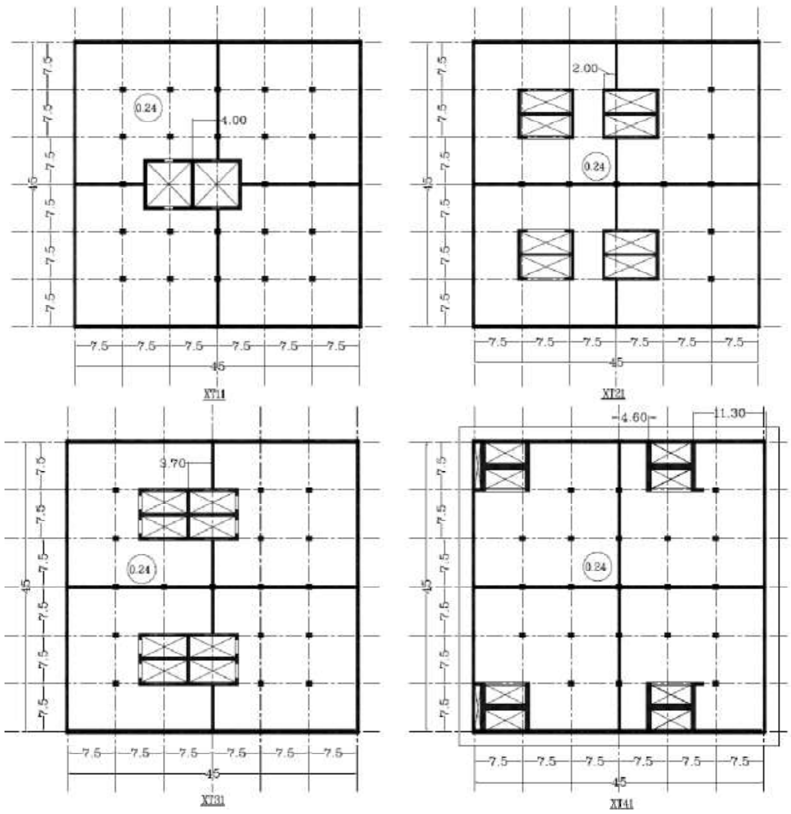


Fig. 4Structural Systems used in Tube-in-Tube with Outrigger.

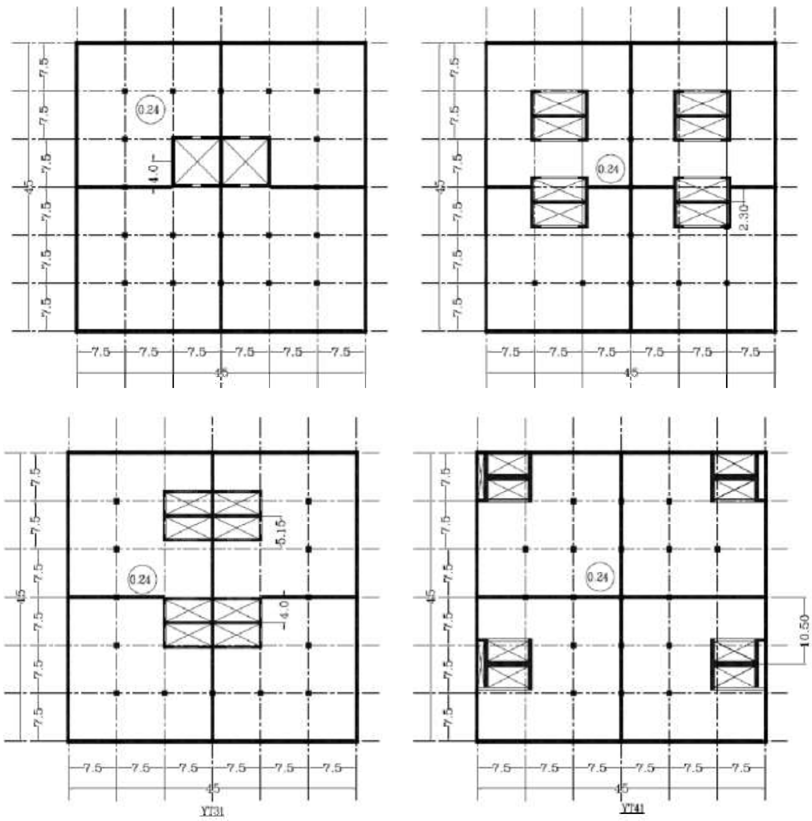


Fig. 4(Cont.) Structural Systems used in Tube-in-Tube with Outrigger.

Gravity loads include live loads,own weight, super imposed loads, interior wall loads, and cladding loads on external perimeter.All lateral loads are according to ASCE07-10 (2010). The analyses are carried out using *CSI-ETABS* software program.

3. Cumulative Inertia Index (*CII*)

The inertia for one floor is calculated according to Equation 1.Columns,shear walls, or coresinertiasare calculated separately about their own centroids.For frames,the inertia are be computed about its centroidal axes.For outriggers,the moment of inertia can be reckoned by equations 2 (Fig. 5). Therefore, the Cumulative Inertia Index *CII* is defined as:

$$I_{z,s}(single\ floor) = \sum_{i=1}^{n_1}\left(\frac{b_i h_i^3}{12}\right) + \sum_{j=1}^{n_2}\left(\frac{b_j h_j^3}{12} + b_j\, h_j d_j^2\right) + \sum_{k=1}^{n_3}\left(\sum_{l=1}^{n_{4k}}\left(\frac{b_{kl} h_{kl}^3}{12} + b_{kl}\, h_{kl} d_{kl}^2\right)\right) \quad (1)$$

where

s stands for single floor.
z is the direction considered for inertia (x or y).
n_1 is the number of non-frame columns.
b_i is the non-frame column dimension in the direction considered.
h_i is the non-frame column dimension perpendicular to the direction considered.
n_2 is the number of frame columns.
b_j is the frame column dimension in the direction considered.
h_j is the frame column dimension perpendicular to the direction considered.
d_j is the distance between centers of gravity of frame column (j) and the frame, perpendicular to the direction considered.

n_3 is the number of cores.
n_{4k} is the number of legs of core (k).
b_{kl} is the wall (l) dimension of core (k) in the direction considered.
h_{kl} is the wall (l) dimension of core (k) perpendicular to the direction considered.
$d_{kl}$is the distance between the centers of gravity of leg (l) and core (k), perpendicular to the direction considered.

For outriggers,the moment of inertia can be reckoned by Equation 2 (Fig. 5). Therefore, the Cumulative Inertia Index *CII* is defined as:

$$CII = I_{z,n}(building) = \sum_{s=1}^{n} I_{z,s} + \sum_{p=1}^{n_5}\left(\sum_{q=1}^{n_6} \frac{b_{pq}h_{pq}^3}{12}\right) \quad (2)$$

where

n is the number of stories.
n_5 is the number of outriggers in the building.
n_6 is the number of outriggers in a single plan.
b_{pq} is the outrigger (p) dimension of outrigger (q) in the direction considered.
h_{pq} is the outrigger (p) dimension of outriggers (q), perpendicular to the direction considered.

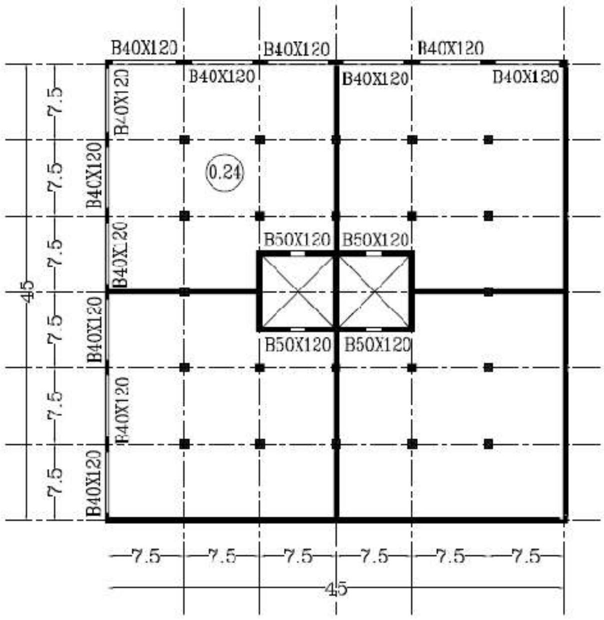
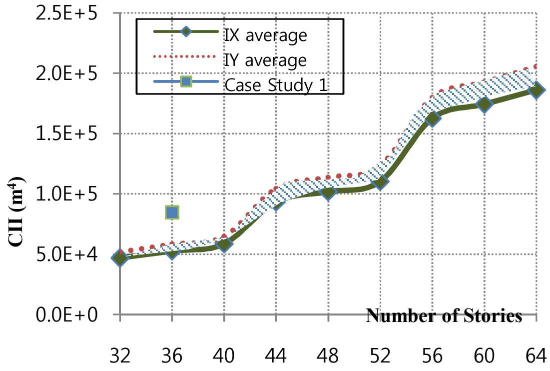
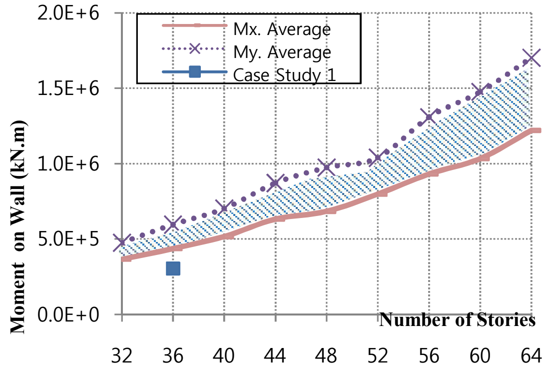


Fig. 5Building Layout.

3. Shear Wall Case

For all four models of Fig.(1), the average values of *CII* are calculated and presented in x-directions and y-directions (Fig. 6). The shaded area represents the calculated*CII* values, for which all response results are expected to be acceptable. Ifa building *CII* value lies within the shaded area, the response values are expected to be border line values. If a*CII* value lies below the shaded area,some of the lateral response values are expected to exceed limits. Otherwise, if a building *CII* value lies higher than the shaded area,the structure is expected to be overdesigned with respect to some of the response parameters.

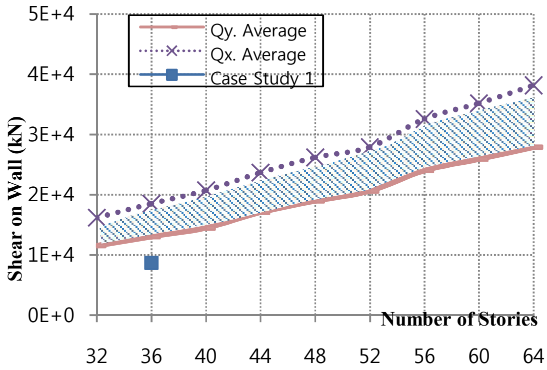




.Fig. 6Average Values CII for Shear Walls of Fig.1.

Fig. 7Average Moments for Shear Walls of Fig.1

Figure 7 shows the average predicted moments(sum of moments) on shear walls. Similarly, shear forceson shear wallsand displacements of building are presented in Figs. 8and 9, respectively.



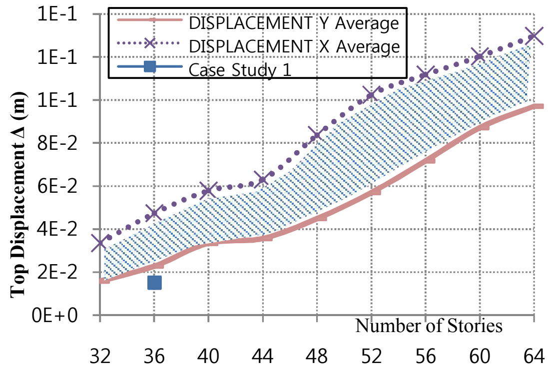
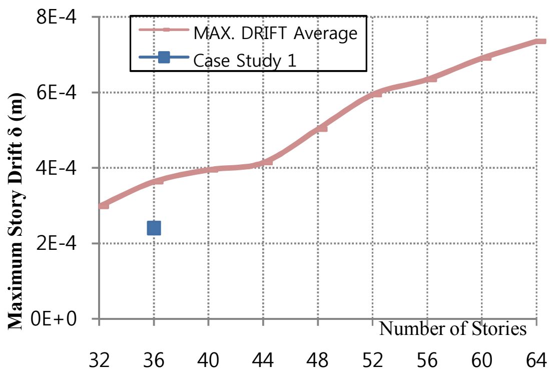


Fig. 8Average Shear Forces for Shear Walls of Fig.1.

Fig. 9Average Values of Top Displacements for Shear Walls of Fig.1.

Inter-story drift and computed vibration period for shear wall casesare shown in Figs. 10 and 11, respectively. The obtained curves help the structural engineer to choose a reasonable shear wall configuration for the building at hand.



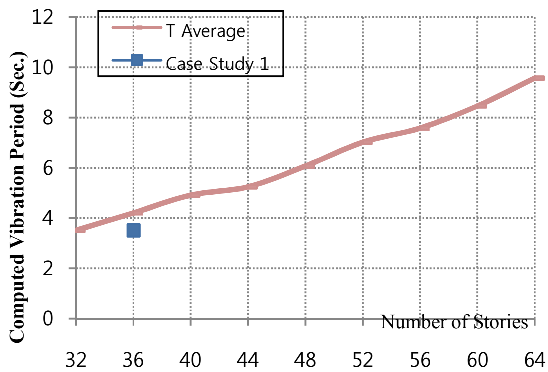


Fig. 10Average Drifts Values for Shear Walls of Fig.1.

Fig. 11 Average Values for Vibration Periods for Shear Walls of Fig.1.

As a summary for the shear wall case, the average values for the previous charts are presented by the following idealized equations:

$$CII = 5030N-125928 \quad (3)$$

$$M_{wall} \leq 427N^2-9449N+299826 \quad (4)$$

$$Q_{wall} \leq 609N-6364 \quad (5)$$

$$\Delta_{top} \leq 0.00002N^2+0.0012N-0.03 \quad (6)$$

$$\delta_{drift} \leq 0.00001N-0.0001 \quad (7)$$

$$T_c \leq 0.184N-2.55 \quad (8)$$

where N is the number of stories.

Case Study 1

Our case study is a building of total height 126 m (36 stories)designed and built in the Arabian Peninsula.The main system resisting the lateral loads is shear wall system (Fig.12).The building has9.8% eccentricity inx-axis.Therefore, the y-direction response is compared with the valuesobtained for shear wall case(*CII*, moment, shear, displacement, drift, and computed vibration period) as shown inprevious figures(labeled by ■). Figure 6 shows that, the inertia of building is greater than the average *CII*, which leads to acceptable response values for the building as shown in the previous Figs. 7-11, and the following Table 1.

Table 1: Case Study1 (N = 36)

Response	*CII* (m^4)	M_{wall} (kN.m)	Q_{wall} (kN)	Δ_{top} (m)	δ_{drift} (m)	T_c(Sec.)
Referenced Values (this work)	55152	303552	15560	0.039	0.00034	4.07
Case Study 1	84407	305825	8675	0.015	0.00024	3.5
Checks	EQ.(3) √	EQ.(4) √	EQ.(5)√	EQ.(6) √	EQ.(7)√	EQ.(8)√

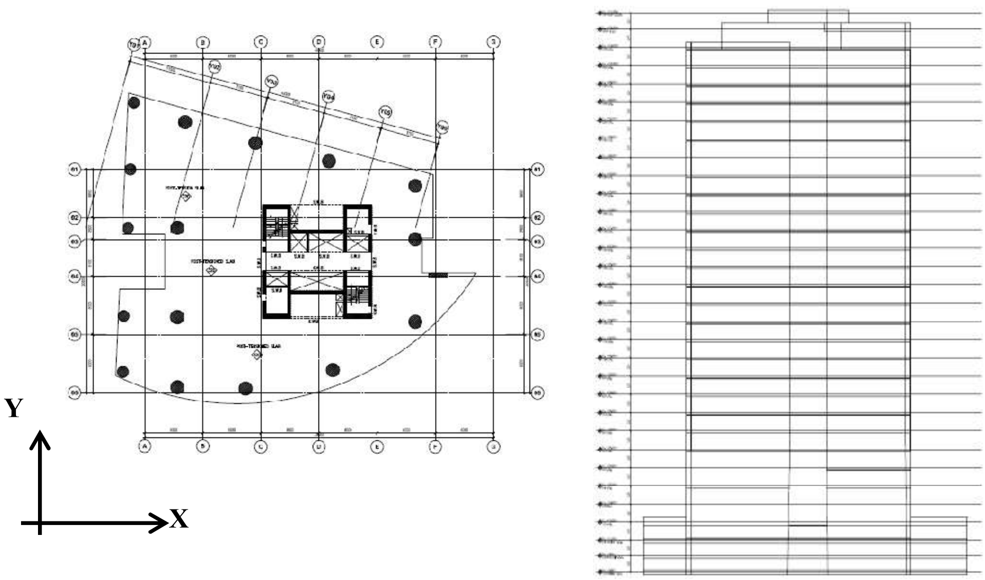


Fig. 12Structural System for Case Study (1)ofShear Walls.

4. Shear Wallswith Outriggers

The main structural system used to resist lateral load –for this case–is shear walls fortified with outriggers. The shape and locations of outrigger are explained in previous discussion (in the proposed model section).Figure13 presentsthe average values for *CII*for all models for shear walls of Fig. 2 and the calculated nominated shaded area.The effect of each outrigger on *CII* values for stories exceeding 40 and 52 are apparent on graph. Figure14 shows the average values for moments in each direction on walls.Figures 15, 16, and 17 expound the average shear forces on shear walls with outriggers, average top displacements, and average values for drifts,respectively. Figure 18 manifests average values for computed vibration periods. The effect of adding one outrigger (or two) on decreasing the displacements, drifts, and periods is apparent.

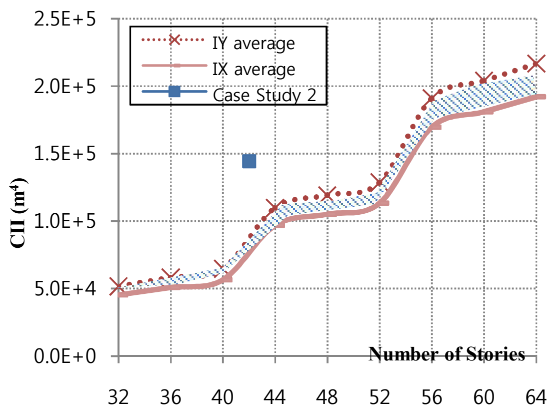


Fig. 13Average Values for CII for Shear Walls of Fig.2.

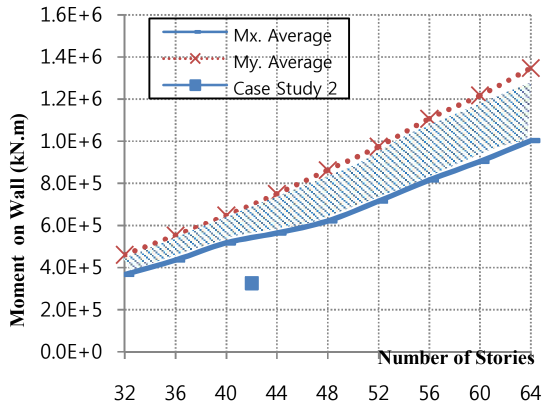


Fig. 14Average Values for Moments for Shear Walls of Fig.2.

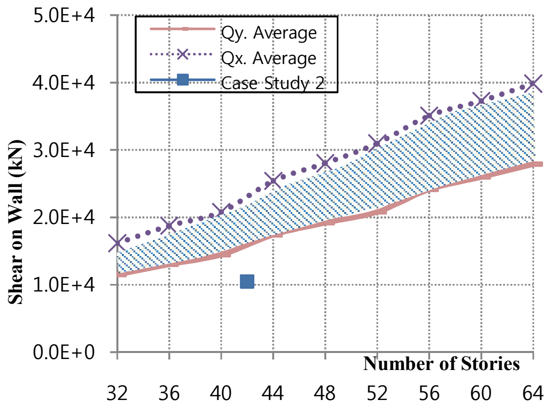


Fig. 15Average Values for Shear forces for Shear Walls of Fig.2.

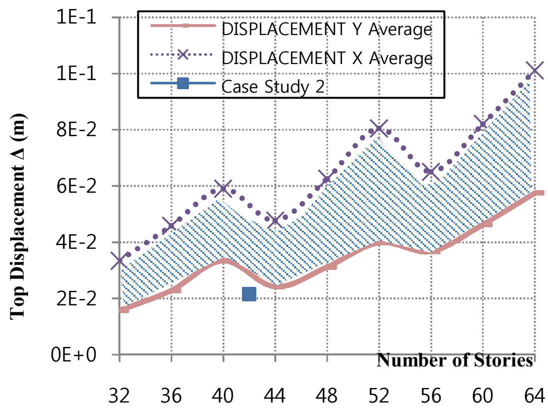


Fig. 16 Average Values for Top Displacements Walls for Shear Walls of Fig.2

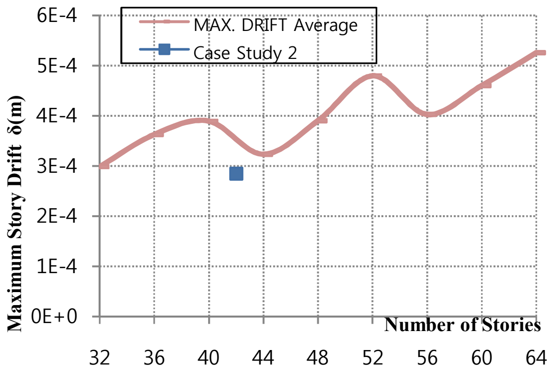


Fig. 17Average Values for Driftsfor Shear Walls of Fig.2.

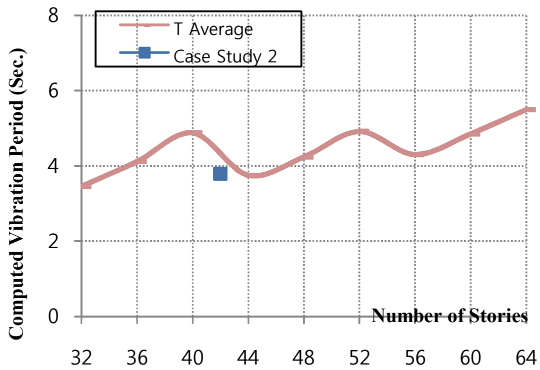


Fig. 18Average Values for Vibration Periodsfor Shear Walls of Fig.2.

For the shear wall with outriggers case, the average values for the previous charts can be represented as idealized equations in the following:

$$CII=5455N-140651 \quad (9)$$

$$M_{wall}\leq 179N^2+6486N+25981 \quad (10)$$

$$Q_{wall}\leq 649N-7472 \quad (11)$$

$$\Delta_{top}\leq 0.00002N^2-0.0002N+0.018 \quad (12)$$

$$\delta_{drift}\leq 0.000005N+0.0002 \quad (13)$$

$$T_c\leq 0.45H^{0.45} \quad (14)$$

where N is the number of stories.

Case Study 2

Figure 19 shows the structural system of building in which its height is 147 m (42 stories) designed and built in U.A.E. The main system used to resist the lateral loads is shear wall with outriggers. The outrigger for this building are located at fifteen and thirty floors.The buildinghas 9.97% eccentricityinx-axis.Therefore, the y-direction resultsare compared with average results mentioned previouslyinFigs. 13, 14, 15, 16, 17 and 18(labeled by ■).

Figure 13 shows the inertia of building in y-direction. Apparently, it is greater than the *CII* limit for shear wall with outrigger reference curves. Consequently, the lateral response components of the building are within acceptable limits, as shown in the previous Figs. 14-18 and the following Table 2.

Table 2: Case Study 2 (N = 42)

Response	*CII* (m^4)	M_{wall} (kN.m)	Q_{wall} (kN)	Δ_{top} (m)	δ_{drift} (m)	T_c (Sec.)
Referenced Values (this work)	83059	614149	19786	0.045	0.00038	2.42
Case Study 2	144407	324735	10464	0.0215	0.0003	3.8
Checks	EQ.(9) √	EQ.(10) √	EQ.(11) √	EQ.(12) √	EQ.(13) √	EQ.(14) √

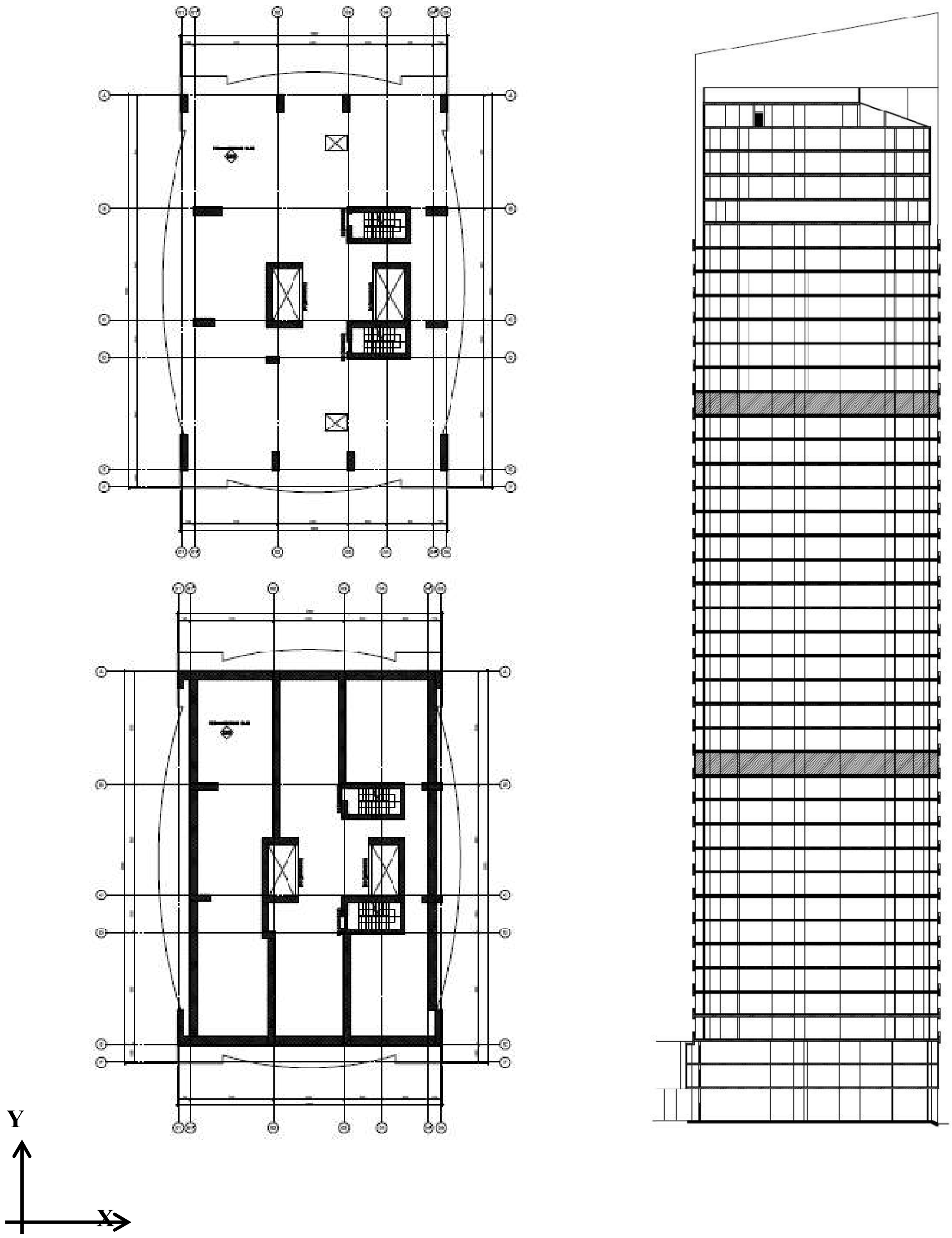


Fig. 19Structural System for Case Study (2)of Shear Wall with Outriggers.

5. Tube-in-Tube

In this case, the results will take same sequence as mentioned before. The structural system used to resist lateral loads is shear wall fortified with frames in outer perimeter (tube-in-tube).Figures 20, 21, 22, 23, 24, and 25show the average valuesfor all models of Fig. 3 for *CII*,moments on walls, shear forceson shear walls,displacements,drifts of the building,and vibration periods,respectively.

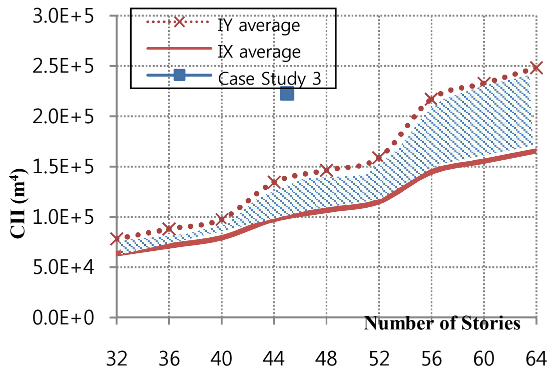


Fig. 20 Average Values for CII for Tube-in-Tube of Fig.3.

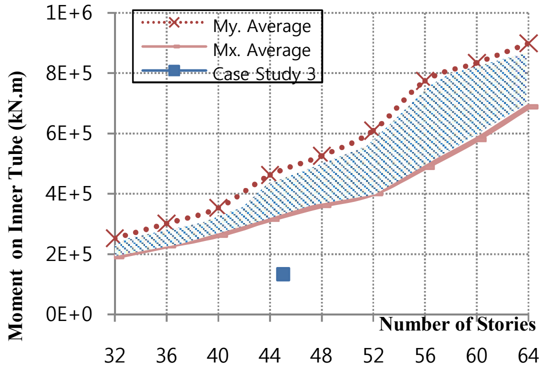


Fig. 21 Average Values for Moments for Tube-in-Tube of Fig.3.

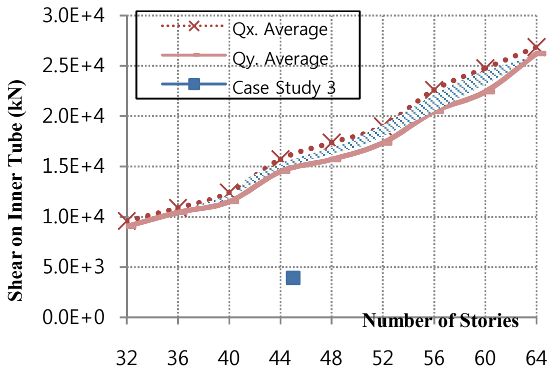


Fig. 22 Average Values of Shear Forces for Tube-in-Tube of Fig.3

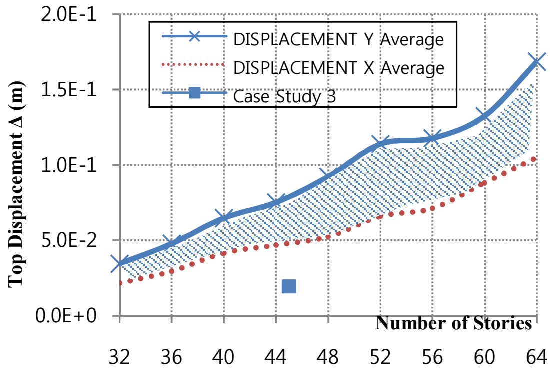


Fig. 23Average Values of Top Displacements for Tube-in-Tube of Fig.3.

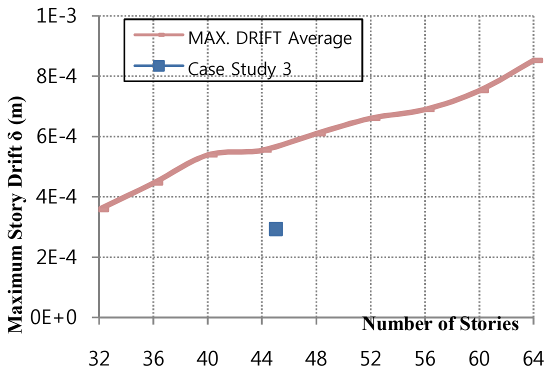


Fig. 24 Average Values of Top Drifts for Tube-in-Tube of Fig.3.

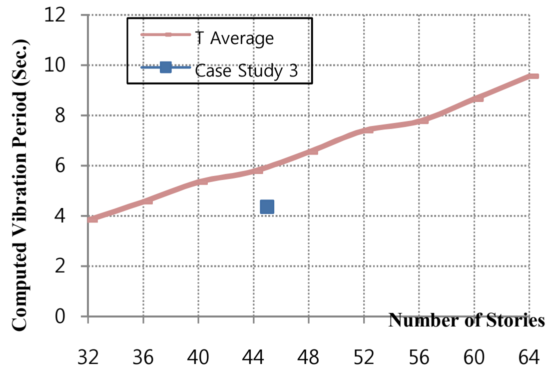


Fig. 25 Average Values of Vibration Periods for Tube-in-Tube of Fig.3

For the tube-in-tube case, the average values of previous charts are presented as idealized equations in the following:

$$CII=4556N-85456 \quad (15)$$

$$M_{inner\ tube} \leq 248N^2-5526N+256255 \quad (16)$$

$$Q_{inner\ tube} \leq 541N-8956 \quad (17)$$

$$\Delta_{top} \leq 0.00003N^2+0.00015N-0.0073 \quad (18)$$

$$\delta_{drift} \leq 0.00001N+0.00018 \quad (19)$$

$$T_c \leq 0.173N-1.73 \quad (20)$$

where N is the number of stories.

Case Study 3

Figure 26manifestsstructural system ofcase study tower where the total height of the building is 157.5 m (45 stories)designed and built in the Gulf Area. Main system used to resist the lateral loads –for this case– is tube-in-tube.The building has 9.64% eccentricity in y-axis. Therefore, the x-direction result is compared with average results mentioned previously (labeled by ■). From Figure 20, the *CII* of the application tower is apparently greater than limits of tube-in-tube case reference curves. Consequently, the lateral response components of the building are within acceptable limits, as shown in the previous Figs. 21-25 and the following Table 3.

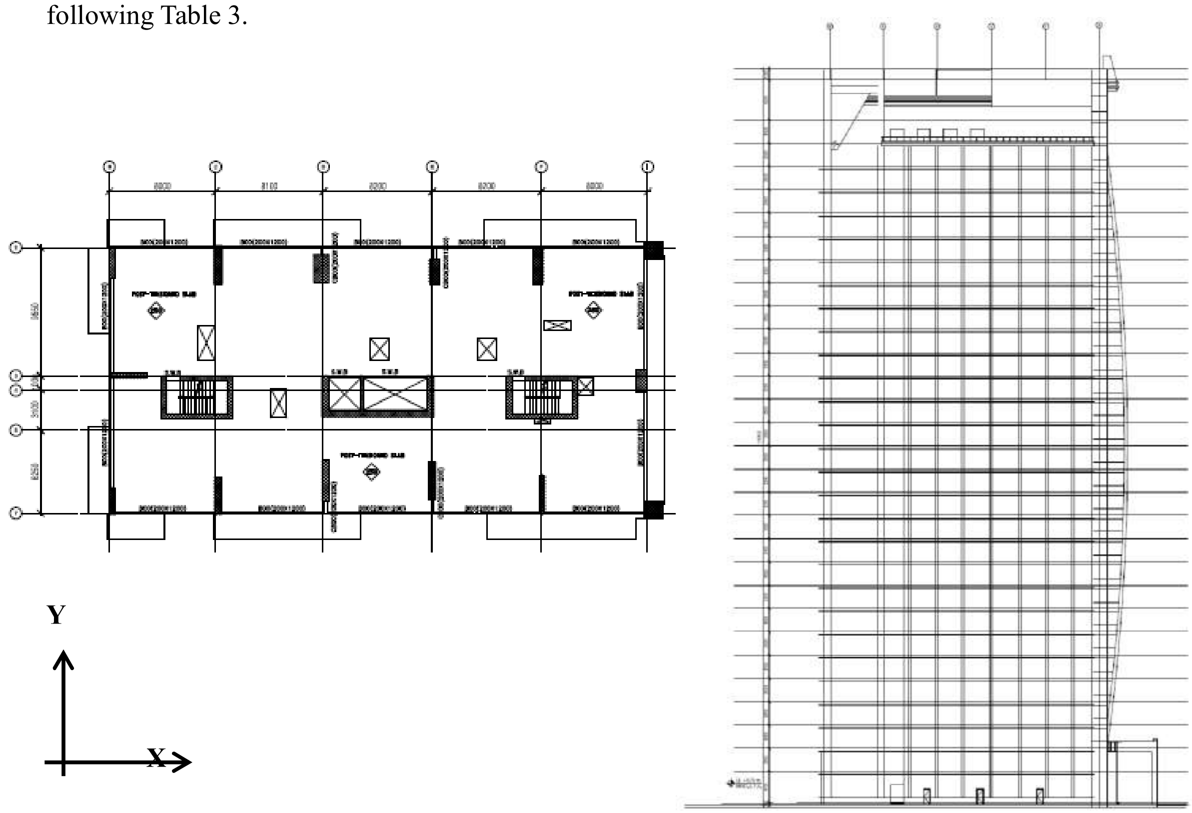


Fig. 26Structural System for Case Study (3)ofTube-in-Tube Case.

Table 3: Case Study 3 (N = 43)

Response	*CII* (m^4)	$M_{inner\ tube}$ (kN.m)	$Q_{inner\ tube}$ (kN)	Δ_{top} (m)	Δ_{drift} (m	T_c(Sec.)
Predicted Values (this work)	110452	478384	14325	0.055	0.00037	5.73
Case Study 3	222587	133834.4	3918	0.0196	0.000293	4.35
Checks	EQ.(15) √	EQ.(16) √	EQ.(17) √	EQ.(18) √	EQ.(19) √	EQ.(20) √

6. Tube-in-Tube with Outriggers

The structural system used to resist lateral loads in this case is tube-in-tube fortified with outriggers. Oneoutrigger is used at mid-height for buildings with forty-four to fifty-two stories. Two outriggers are placed at one-third and two-third for buildings with fifty-six to sixty-four stories. Figures 27, 28, 29, 30, 31, and32illustrate the average values for all models of Fig. 4 for *CII*:moments on walls, shear forceson shear walls,displacements, drifts of the buildingand vibration periodsrespectively. The effect of each outrigger on*CII* values for stories exceeding forty and fifty-two are apparent.

The figures represent average values in each direction for tube-in-tube with outriggers structural systems. The effect of adding one outrigger (or two) on decreasing the displacement, drift, and periods is apparent. If building response value falls higher than the upper limits, the building is considered over-designed for this response value. Otherwise, it is under-designed.

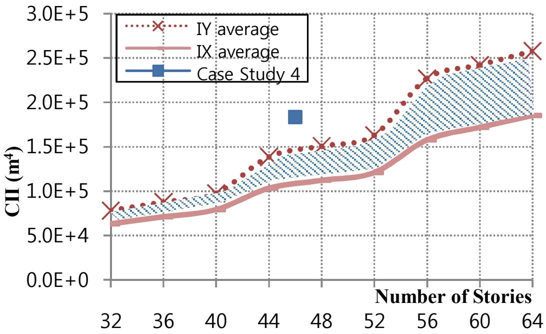


Fig. 27Average Values of CII for Tube-.in-Tube of Fig.4

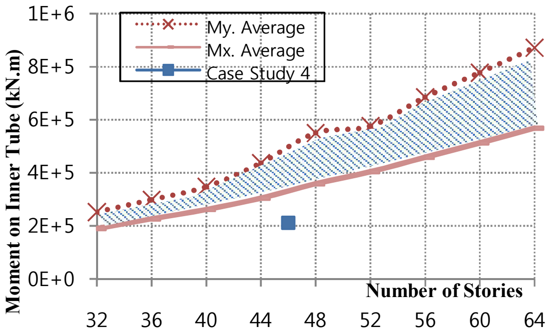


Fig. 28Average Values of Moments for Tube-in-Tube .of Fig.4

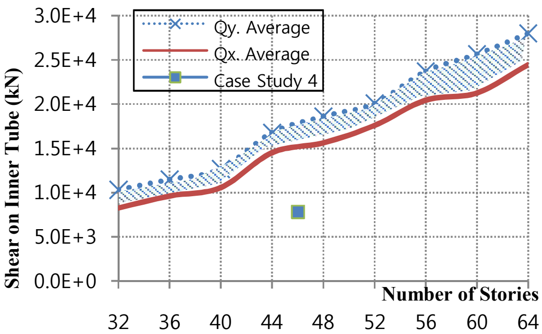


Fig. 29Average Values of Shear Forces for Tube-in-Tube of Fig.4.

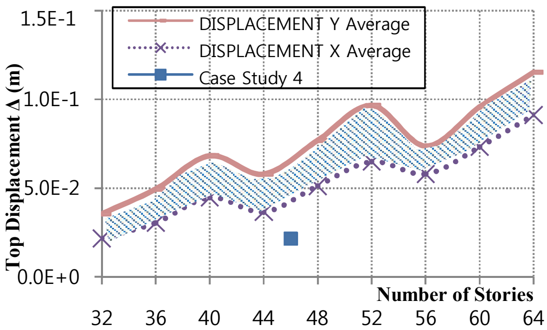
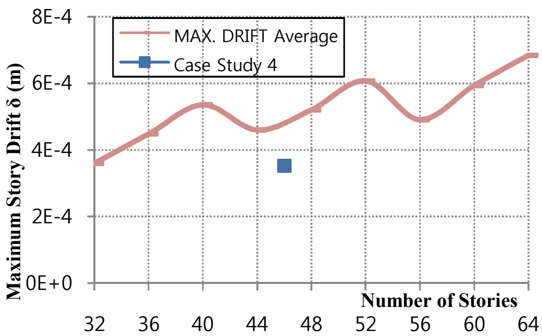


Fig. 30Average Values for Top Displacements for Tube-in-Tube of Fig.4.



- Fig. 31Average Values for Maximum Drifts for Tube-in Tube of Fig.4.

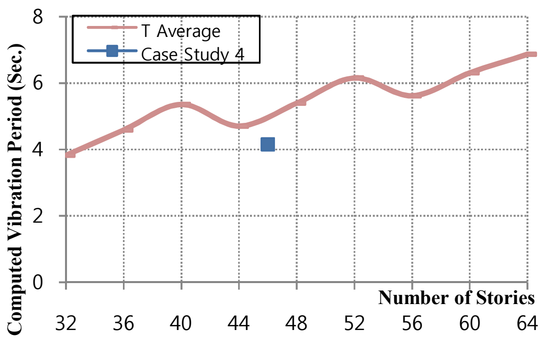


Fig. 32 Average Values for Vibration Period for Tube-in-Tube of Fig.4.

For the tube-in-tube systemwith outrigger,the average values of previous charts are presented as equations in the following:

$$CII=5060N-103610 \tag{21}$$

$$M_{inner\ tube} \leq 134N^2+2939N-15398 \tag{22}$$

$$Q_{inner\ tube} \leq 543N-8893 \tag{23}$$

$$\Delta_{top} \leq 0.000008N^2+0.0012N-0.015 \tag{24}$$

$$\delta_{drift} \leq 0.000008N+0.0001 \tag{25}$$

$$T_c \leq 0.14H^{0.71} \tag{26}$$

where N is the number of stories.

Case Study 4

Figure 33showsthe structural system ofapplication tower. The height of the building is 161 m (46 stories). The main system of the building is tube-in-tube with outrigger. The outrigger for this building are located at eighteen and thirty two floors.Thebuilding has 9.50% eccentricityin y-axis.Therefore, the x-direction result is compared with the average valuesas shown in previous figures.Figure 27 shows that *CII* value for application building (labeled by ■) is above the shaded area; hence, response values are within acceptable limits, as shown in Figs. 28-32 and Table 4.

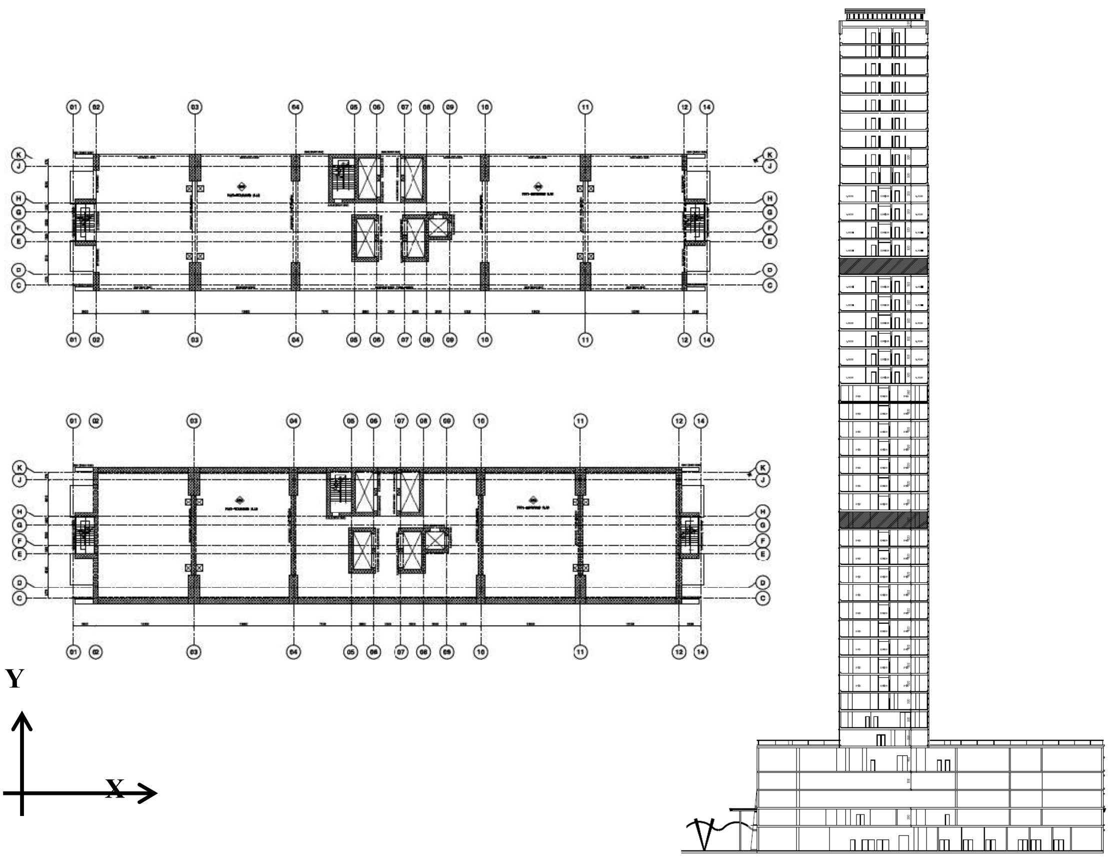


Fig. 33Structural System for Case Study (4)of Tube-in-TubeCase.

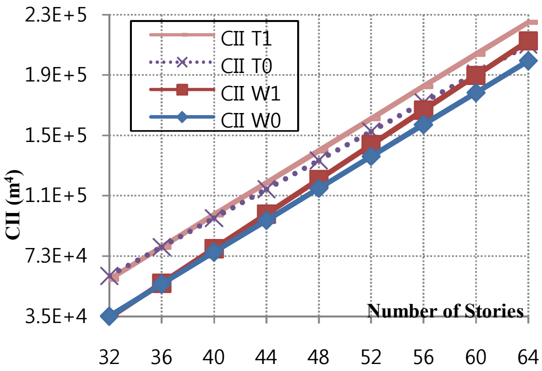
Table 4: Case Study 4 (N = 46)

Response	CII (m^4)	$M_{inner\ tube}$ (kN.m)	$Q_{inner\ tube}$ (KN)	Δ_{top} (m)	δ_{drift} (m)	T_c (Sec.)
Reference Values (this work)	222399	403369	16085	0.057	0.00052	5.27
Case Study 4	183467	211856.4	7826	0.0217	0.00035	4.15
Checks	EQ.(21) √	EQ.(22) √	EQ.(23) √	EQ.(24) √	EQ.(25) √	EQ.(26) √

7. Comparison between Different Structural Systems

In this section,a cross comparison between the previous four structural systems (shear wall (W0), shear wall with outrigger (W1), tube-in-tube (T0), and tube-in-tube with outrigger (T1) is conducted.The following figures represent the averages of best fit curve for each system. Figure 34 expound the *CII*values for all structural systems adopted in this research.*CII*values for building with shear wall structural systems range from 60% for lower buildings up to 95%for higher ones as compared to values of tube-in-tube structural systems.The effect of adding one outrigger from forty-four to fifty-two or twooutriggers from fifty-six to sixty-four is apparent.

Figures35, 36, 37, 38, and 39present the moments, shear forces, top displacements, drifts, and computed vibration periods, respectively. Variation of results for first three heights (thirty-two, thirty-six, and forty stories) for cases of "with or without outriggers" for shear-walls-only and tube-in-tube systems are due to best-curve fitting.Figure 35 shows that the outrigger cases result in smaller moments on the shear walls (almost 80% of values for higher stories). This effect is almost 90%of values for higher stories for tube-in-tube systems.Moments on shear walls for tube-in-tube systems range from 50% to 60% as compared to corresponding values for shear-walls-only systems.



.Fig. 34 CII averages for all 4 systems

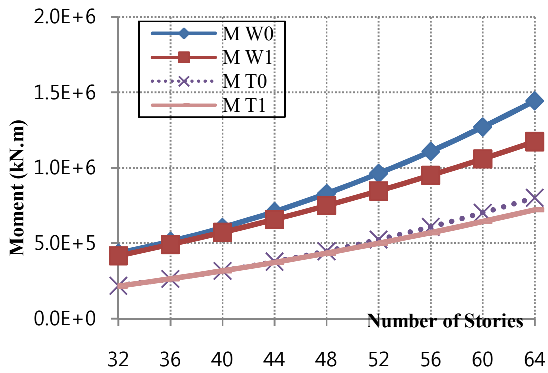
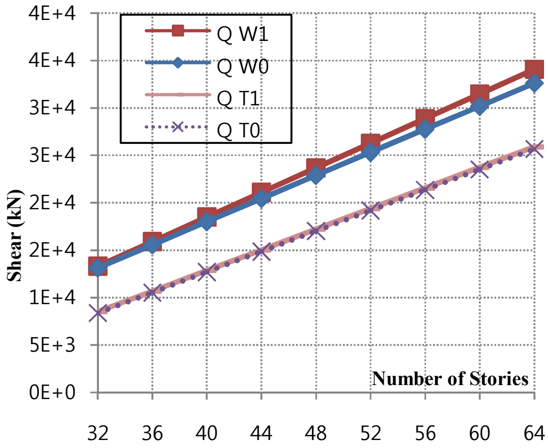


Fig. 35Comparing Moment averages for all 4 systems.

Figure 36 highlights that adding outriggers does not affect the shearing forces exerted on shear walls. Shear force values are almost equal for the same system.However, shear forces on shear walls for tube-in-tube systems range from 65% to 80% as compared to corresponding values for shear-walls-only systems. Figure 37 shows the effect of presence of outriggers in reducing the overall top displacement. This effect is much significant for the shear wall systems (almost 70% of values for higher stories versus 75% for the tube-in-tube systems).



.Fig. 36 Comparing Shear Force averages for all 4 systems.

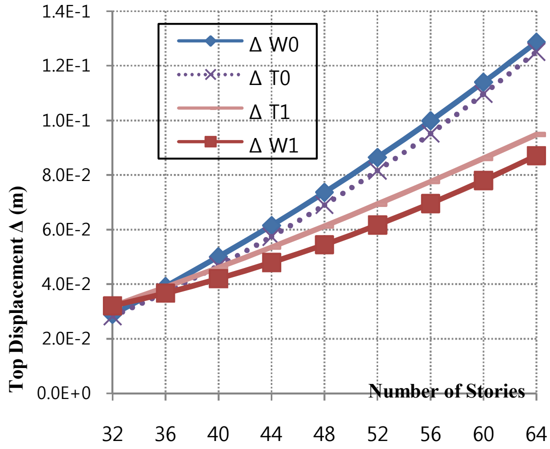


Fig. 37Comparing Top Displacement averages for all 4 systems

Figure 38 shows the effect of presence of outriggers in reducing the drift. Finally, Fig. 39 shows the effect of adding outriggers on reducing the period. This reduction amount to 55–65% for shear wall systems and 70–80 % for tube-in-tube systems, of values for higher stories.

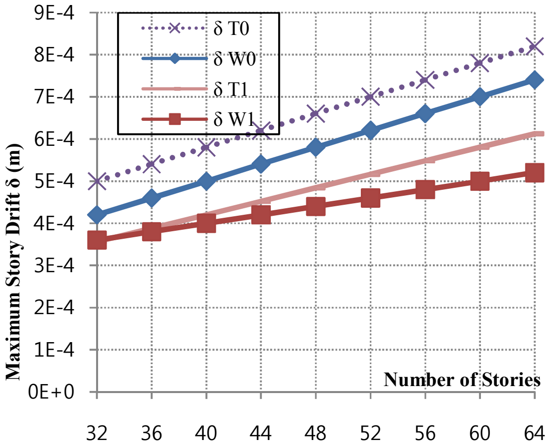


Fig. 38Comparing Maximum Drift averages for all 4 .systems.

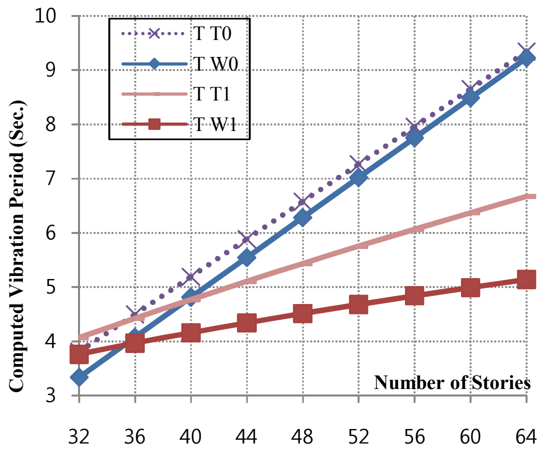


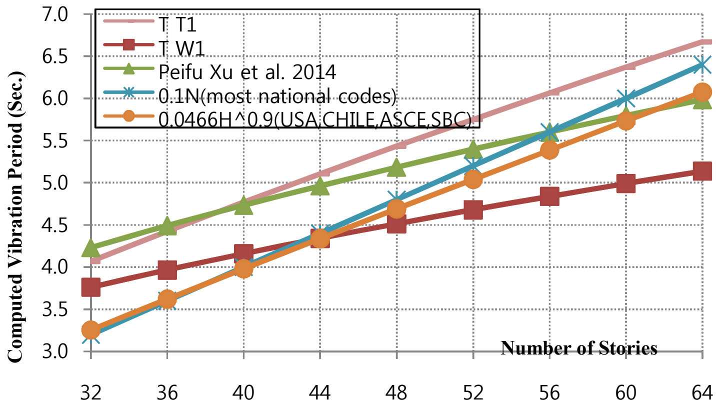
Fig. 39 Comparing Vibration Period averages for all 4 systems

Table 5summarizesthe equations presented in Fig. 34-39.

Table 5: Cross-Comparison of Response Parameters for Different Structural Systems

CII average		
Shear Wall System	W0	*5030N-125928*
Shear Wall System with Outrigger(s)	W1	*5455N-140651*
Tube-in-Tube	T0	*4556N-85456*
Tube-in-Tube with Outrigger(s)	T1	*5060N-103610*
$M_{wall/inner\ tube}$ average		
Shear Wall System	W0	$427N^2-9449N+299826$
Shear Wall System with Outrigger(s)	W1	$179N^2+6486N+25981$
Tube-in-Tube	T0	$248N^2-5526N+256255$
Tube-in-Tube with Outrigger(s)	T1	$134N^2+2939N-15398$
$Q_{wall/inner\ tube}$ average		
Shear Wall System	W0	*609N-6364*
Shear Wall System with Outrigger(s)	W1	*649N-7472*
Tube-in-Tube	T0	*541N-8956*
Tube-in-Tube with Outrigger(s)	T1	*543N-8893*
Δ_{top}average		
Shear Wall System	W0	$0.00002N^2+0.0012N-0.03$
Shear Wall System with Outrigger(s)	W1	$0.00002N^2-0.0002N+0.018$
Tube-in-Tube	T0	$0.00003N^2+0.00015N-0.0073$
Tube-in-Tube with Outrigger(s)	T1	$0.000008N^2+0.0012N-0.015$
δ_{drift}average		
Shear Wall System	W0	*0.00001N-0.00010*
Shear Wall System with Outrigger(s)	W1	*0.000005N+0.0002*
Tube-in-Tube	T0	*0.00001N+0.00018*
Tube-in-Tube with Outrigger(s)	T1	*0.000008N+0.0001*
T_c average		
Shear Wall System	W0	*0.184N-2.55*
Shear Wall System with Outrigger(s)	W1	$0.45H^{0.45}$
Tube-in-Tube	T0	*0.173N-1.73*
Tube-in-Tube with Outrigger(s)	T1	$0.14H^{0.71}$

Figure 40 shows a comparison between vibration period results obtained in this research and corresponding values published in literature and renowned codes. The results show that the approximate created formulae for tube-in-tube with outriggers system and shear wall with outriggers system form acceptable boundary range for several formulae cited in literature.



.Fig. 40 Comparing Vibration Period Results with Literature and Renowned Codes

9. Conclusions

There are approximate renowned reliable methods to predict response of building under gravity loads. However, there is no such method for predicting response due to lateral loads, especially for complex and hybrid lateral resisting load systems. Therefore, judgment of the response values for such cases becomes a harder task.

Thepaper presents approximate approaches for predicting the high-rise building response under different loads for medium eccentricity cases (≥ 5%, and ≤ 10%). Different distributions of columns, shear walls, and outriggers are considered. Plan layouts with different aspect ratios are studied ($2.5 < \frac{H}{B} < 5$), where H is the total height of the building, and B is the width of the building. The study comprises nine towers (thirty-two, thirty-six, forty, forty-four, forty-eight, fifty-two, fifty-six, sixty, and sixty-four) floors. Four structural systems are considered: shear walls only, shear walls with outriggers, tube-in-tube only, and tube-in-tube with outriggers systems.

A numerical simulation procedure for *CII* index has been proposed in this study. For each structural system, charts and equations has been developed for different response parameters such as moments, shear forces, displacements, drifts, and vibration periods for a variety of story heights. Such charts and equations had been tested successfully for several existing case studies buildings.

This paperpresents a quick guide approach for predicting the results of the building response parameters during the preliminary study phase.This enables the structural engineer to direct the architect in choosing suitable systems with suitable dimensions during the preliminary phase of the design of the project and provides him (the structural engineer) with a tool to judge the output results once the final results are available.

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