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Review Article

Lateral Response Behavior of Symmetric High-Rise Buildings

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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 of minimum eccentricity. 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 subjected 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 approach is be demonstrated by several case study examples.
Keywords: high-rise, lateral response, period of vibration, vibration period, drift, minimum 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 methods are available to predict columns, shear walls, and footing loads under gravity loads. Experienced engineers judge any computer output as being right or wrong depending on these approximate approaches. Similar simplified methods are also available to estimate 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.

Design codes such as Uniform Building Code (UBC 1997), Egyptian Code of Practice (ECP201 20012), American Society of Civil Engineers (ASCE07-10 2010), International Building Code (IBC 2018), and other codes allow approximate and simplified methods for determining the vibration period for buildings. Newmark and Hall (1982) suggested a formula 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.

Quick Response Code

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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 formula for 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 for high-rise buildings. This paper presents a method for predicting the high-rise building response under lateral loads for small eccentricities (≤ 5%). 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 utilizes core walls with outriggers. The third structural system adopts tube-in-tube. The fourth structural system uses tube-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. For second and fourth structural 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) for fifty-six to sixty-four story buildings are considered in the configuration.

Figure 1 shows the structural systems used for shear wall case. The code used is (W10): the first letter indicates the type of systems (W for shear wall and T for tube-in-tube,), the second 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 the existence of outrigger (0 for no outrigger, and 1 for inclusion of outrigger). Figure 2 manifests the different shapes of shear wall with outrigger systems. In addition, Figure 3 presents the tube-in-tube structural systems. Figure 4 exhibits the shapes of tube-in-tube with outrigger systems.

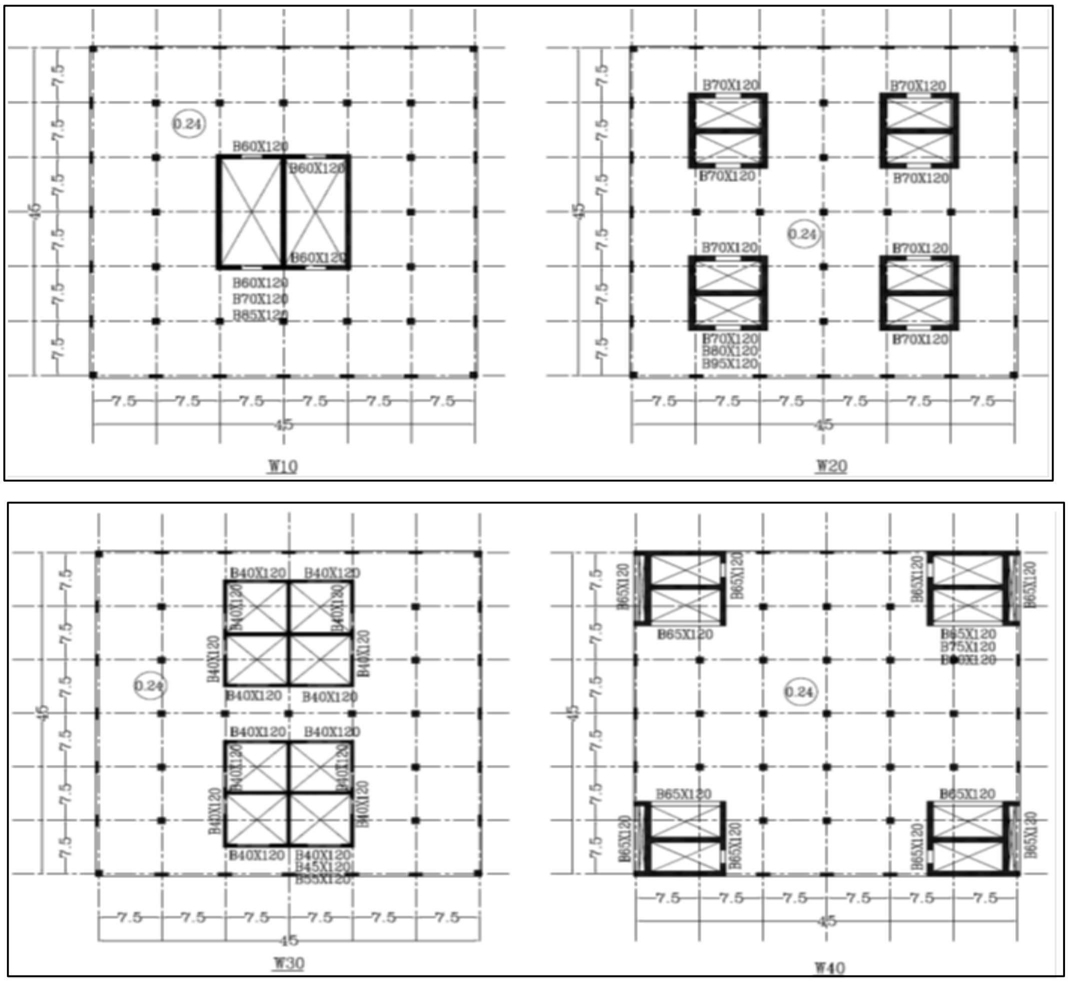

Fig. 1 Structural Systems used in Core (Shear Wall) Case.

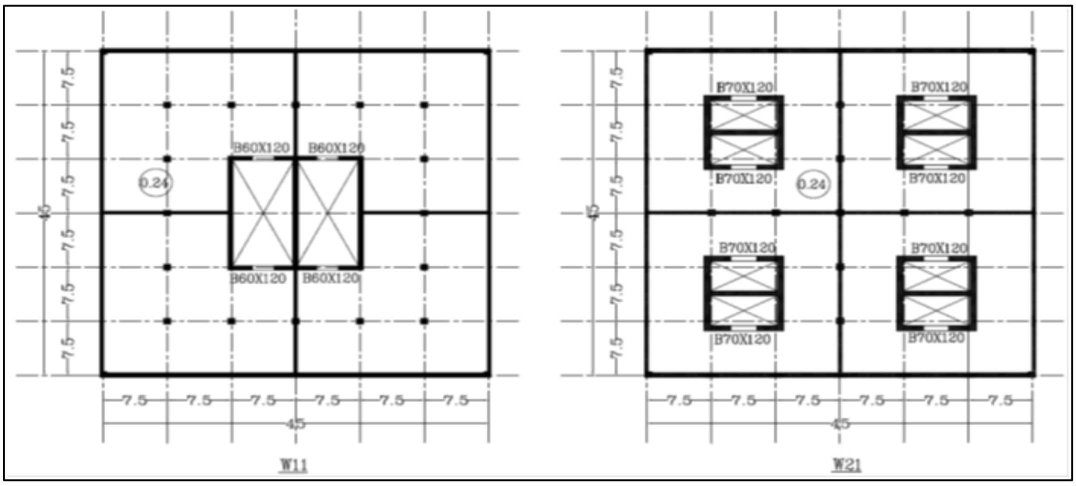

Fig. 2 Structural Systems used in Core (Shear Wall) with Outrigger.

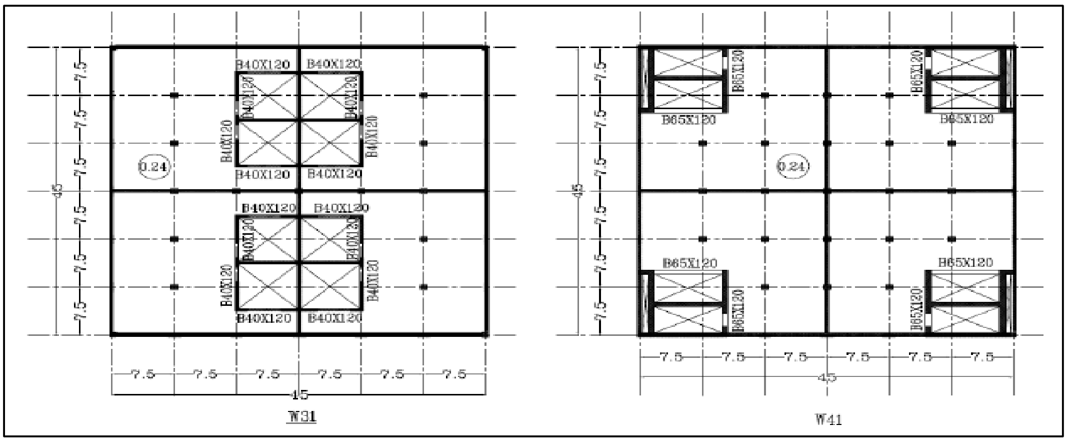

Fig. 2 (Cont.) Structural Systems used in Core (Shear Wall) with Outrigger.

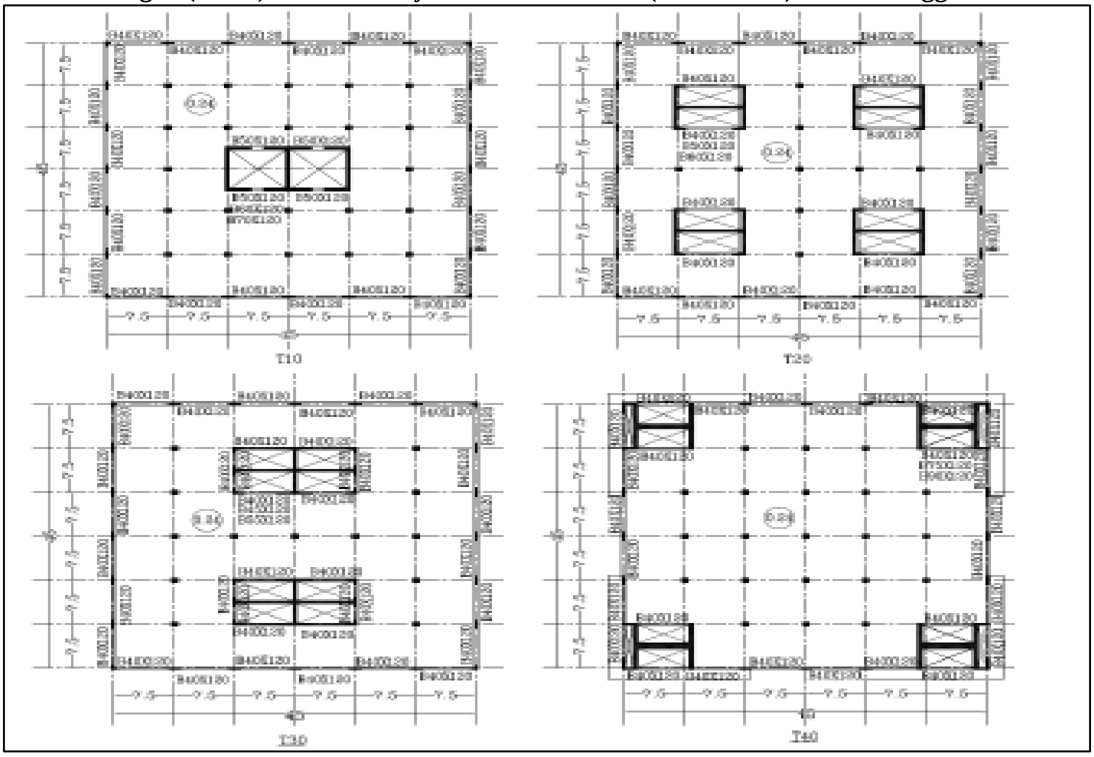

Fig. 3 Structural Systems used in Tube-in-Tube.

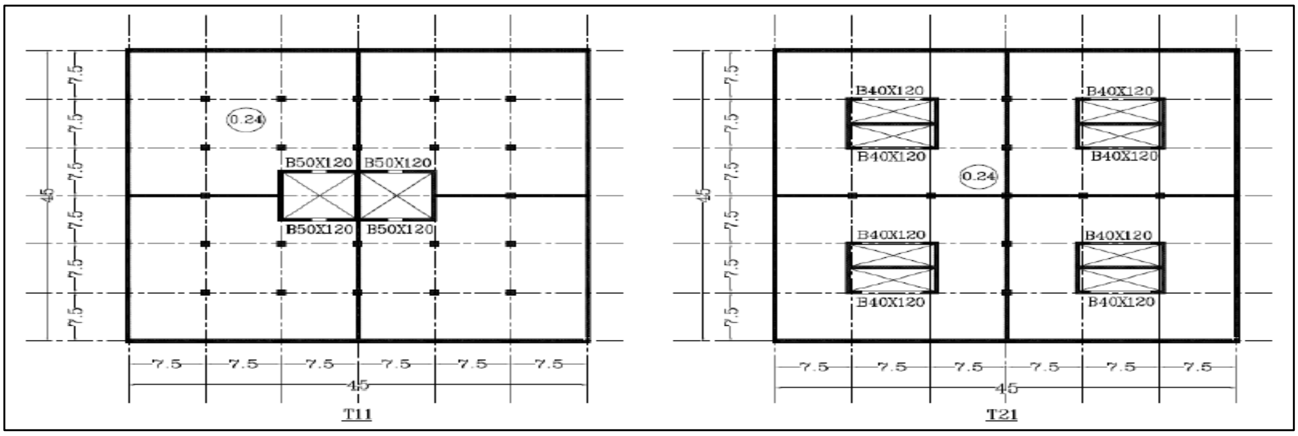

Fig. 4 Structural Systems used in Tube-in-Tube with Outrigger.

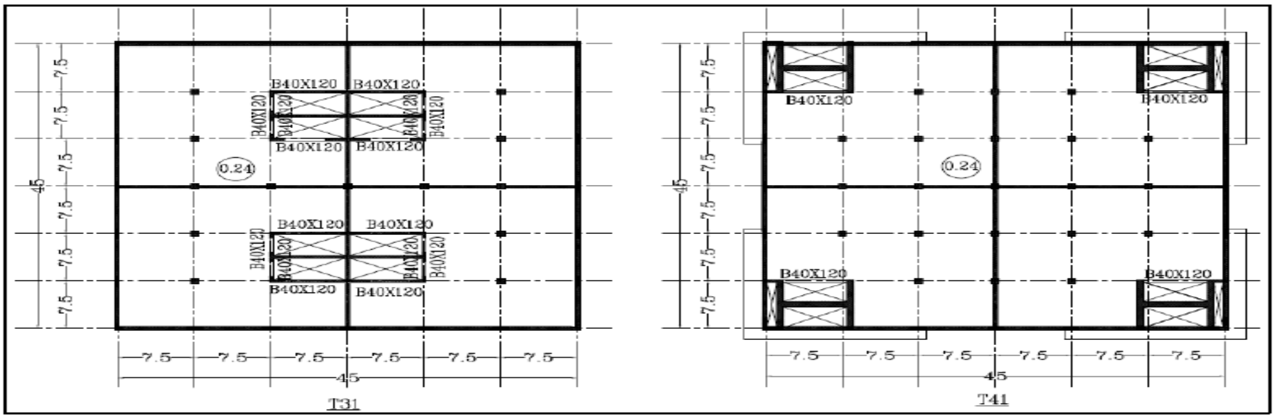

Fig. 4 (Cont.) Structural Systems used in Tube-in-Tube with Outrigger.

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 cores inertias are 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.

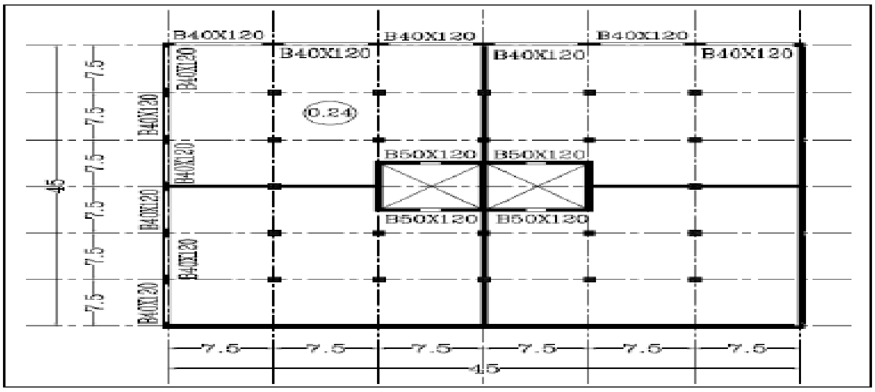

Fig. 5 Building Layout

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. If a 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.

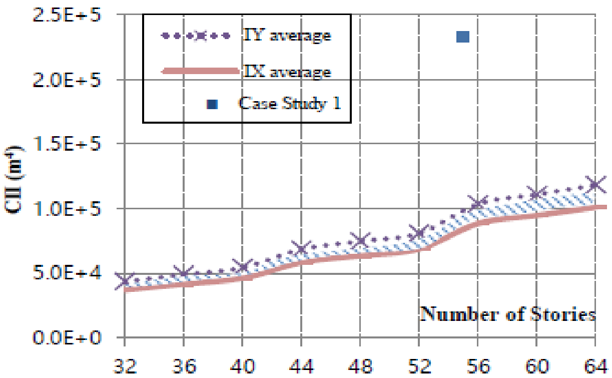

Fig. 6 Average Values CII for Shear Walls of Fig. 1.

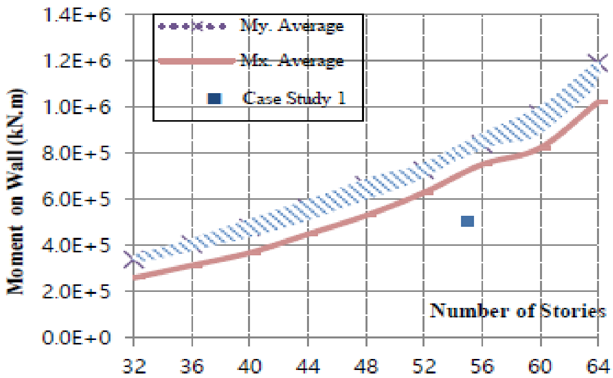

Fig. 7 Average Moments for Shear Walls of Fig. 1.

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

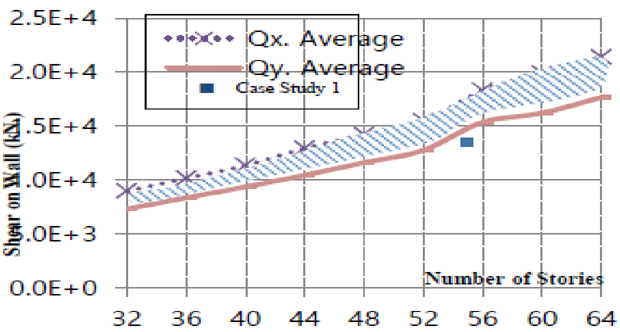

Fig. 8 Average Shear Forces for Shear Walls of Fig. 1.

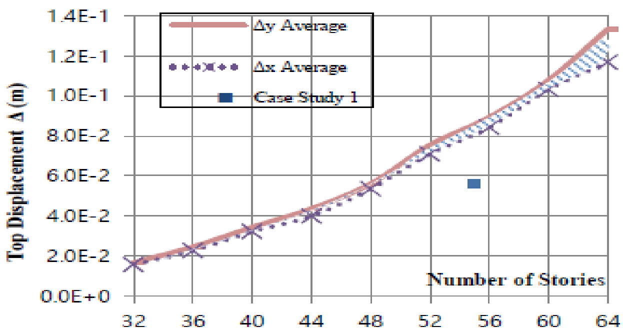

Fig. 9 Average Values of Top Displacements for Shear Walls of Fig. 1.

Inter-story drift and computed vibration period for shear wall cases are 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.

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

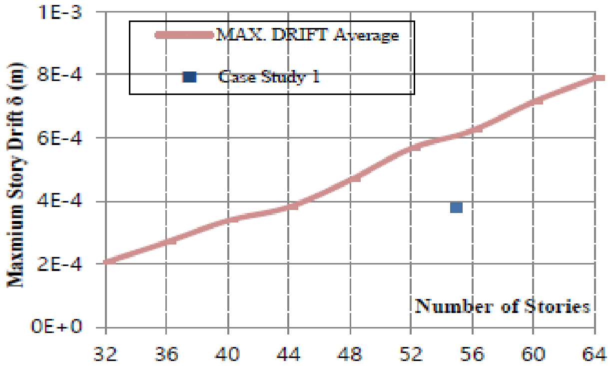

Fig. 10 Average Drifts Values for Shear Walls of Fig. 1.

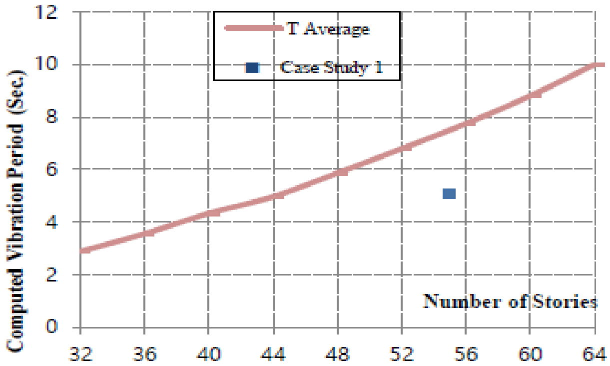

Fig. 11 Average Values for Vibration Periods for Shear Walls of Fig 1

$CII = 2309N\text{-}38474$ (3)
$M_{wall} \leq 432N^2+17397N+423328$ (4)
$Q_{wall} \leq 364N\text{-}4034$ (5)
$\Delta_{top} \leq 0.00006N2+0.0021N+0.0242$ (6)
$\delta_{drift} \leq 0.00002N\text{-}0.00040$ (7)
$T_c \leq 0.220N\text{-}4.47$ (8)

Where N is the number of stories

Case Study 1

Our case study is a building of total height 192.5 m (55 stories) designed and built in the Arabian Peninsula. The main system resisting the lateral loads is shear wall system (Fig. 12). The line of symmetry for this building is about y-axis. Therefore, the y-direction response is compared with the values obtained for shear wall case (*CII*, moment, shear, displacement, drift, and computed vibration period) as shown in previous 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 Study 1 (N = 55)

Response	*CII* (m^4)	M_{wall} (kN.m)	Q_{wall} (kN)	Δ_{top} (m)	δ_{drift} (m)	T_c(Sec.)
Referenced Values (this work)	88520	772186	15989	0.09	0.0007	7.64
Case Study 1	233428	505577	13500	0.056	0.0004	5.07
Checks	EQ.(3) √	EQ.(4) √	EQ.(5)√	EQ.(6) √	EQ.(7)√	EQ.(8)√

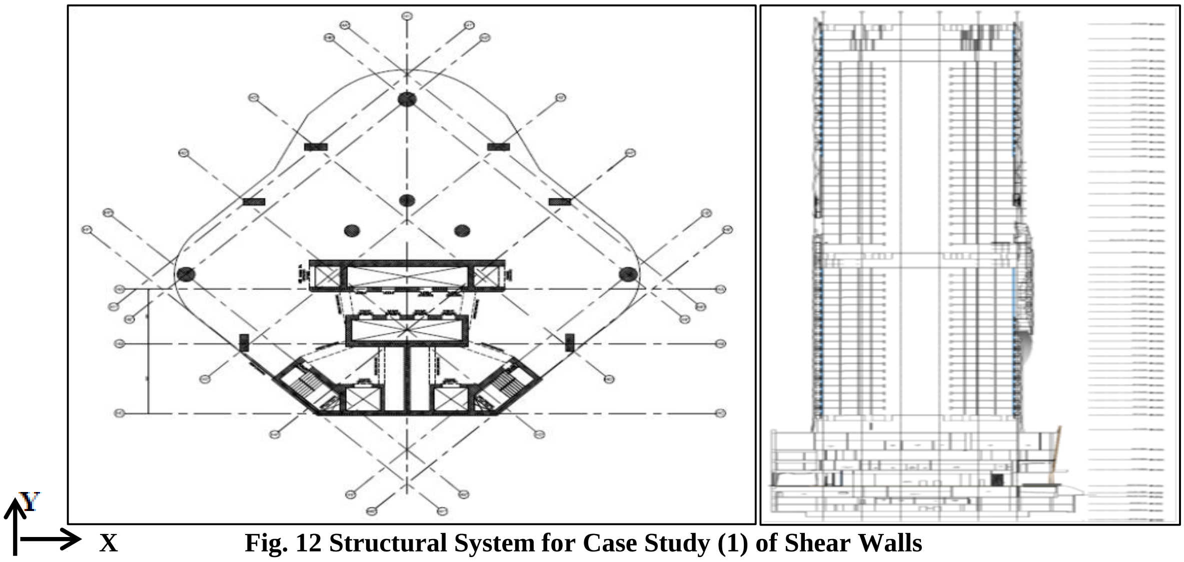

Fig. 12 Structural System for Case Study (1) of Shear Walls

4. Shear Walls with 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). Figure 13 presents the 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.

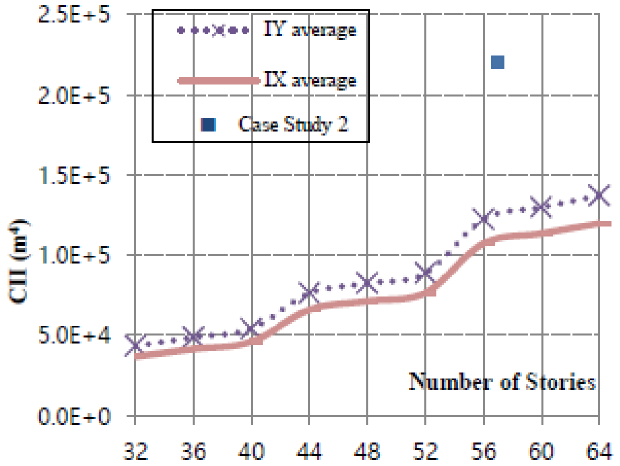

Fig. 13 Average Values for CII for Shear Walls of Fig. 2.

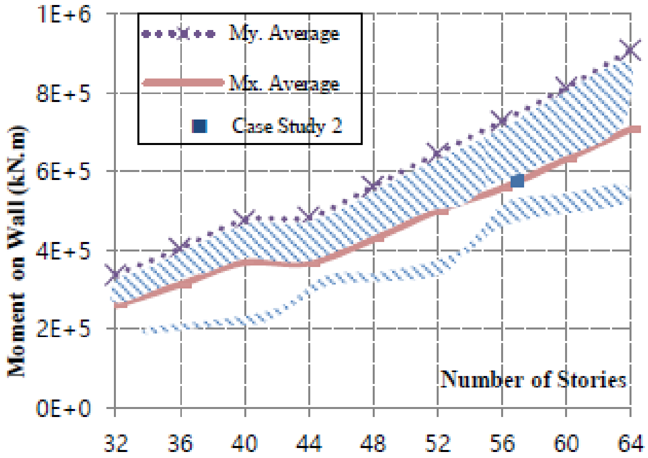

Fig. 14 Average Values for Moments for Shear Walls of Fig. 2.

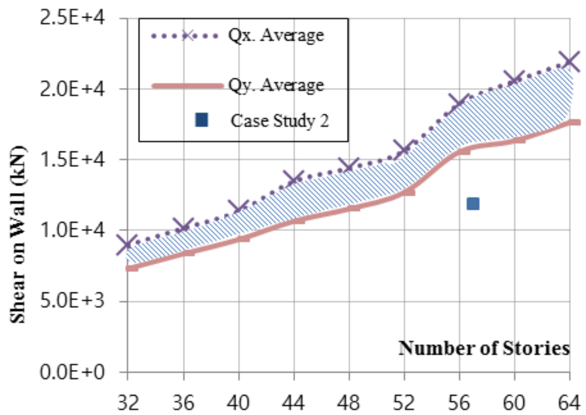

Fig. 15 Average Values for Shear forces for Shear Walls of Fig. 2.

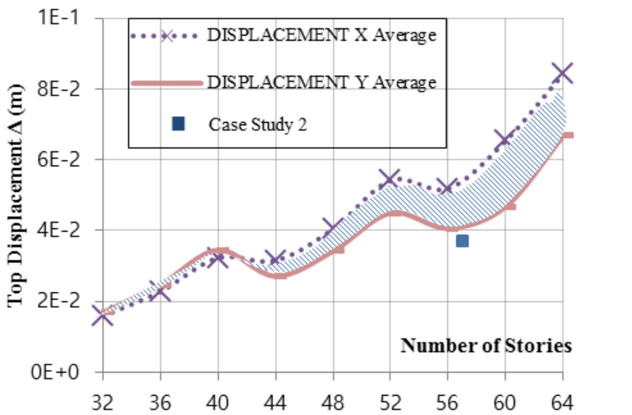

Fig. 16 Average Values for Top Displacements for Shear Walls of Fig. 2

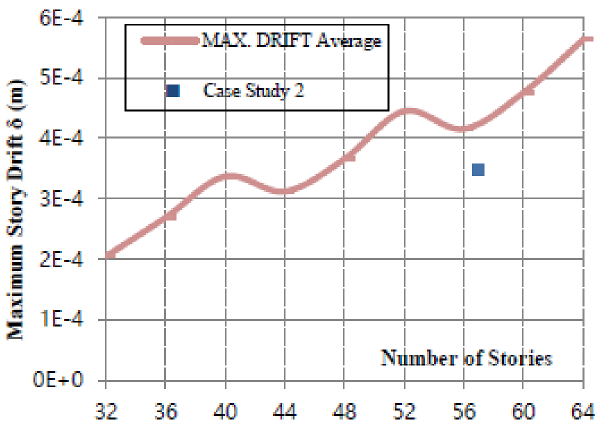

Fig. 17 Average Values for Drifts for Shear Walls of Fig. 2.

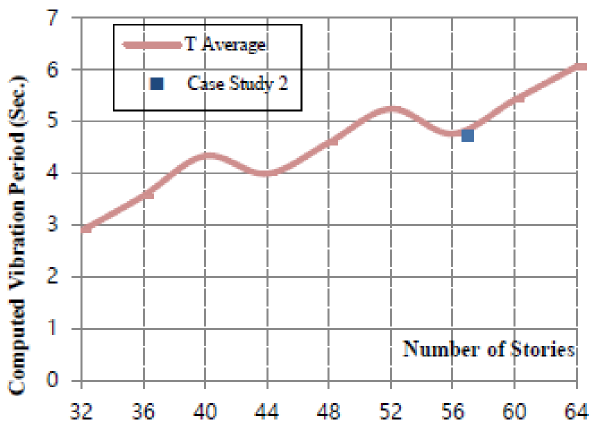

Fig. 18 Average Values for Vibration Periods for Shear Walls of Fig. 2.

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

$$CII = 3018N\text{-}63570 \quad (9)$$
$$M_{wall} \leq 213N^2\text{-}4997.0N\text{+}252953 \quad (10)$$
$$Q_{wall} \leq 375N\text{-}4378 \quad (11)$$
$$\Delta_{top} \leq 0.000025N^2\text{-}0.0011N\text{+}0.0253 \quad (12)$$
$$\delta_{drift} \leq 0.00001N\text{-}0.00009 \quad (13)$$
$$T_c \leq 0.04H^{0.92} \quad (14)$$

Where *N* is the number of stories.

Case Study 2

Figure 19 shows the structural system of building in which its height is 199.5 m (57 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 nineteen and thirty eight floors. The line of symmetry is about y-axis. Therefore, the y-direction results are compared with average results mentioned previously in Figs. 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 = 57)

Response	*CII* (m^4)	M_{wall} (kN.m)	Q_{wall} (kN)	Δ_{top} (m)	δ_{drift} (m)	T_c (Sec.)
Referenced Values (this work)	108439	661143	16975	0.0466	0.00048	5.29
Case Study 2	219548	576849	11806	0.037	0.00044	4.69
Checks	EQ.(9) √	EQ.(10) √	EQ.(11) √	EQ.(12) √	EQ.(13) √	EQ.(14) √

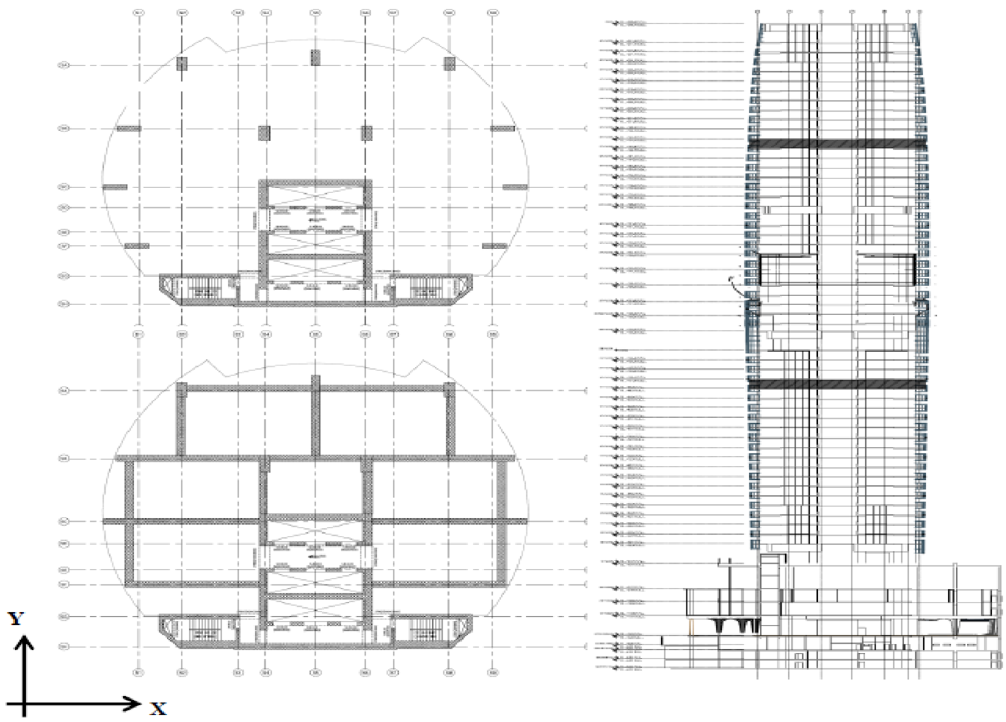

Fig. 19 Structural System for Case Study (2) of Shear Wall with Outriggers

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 25 show the average values for all models of Fig. 3 for *CII*, moments on walls, shear forces on shear walls, displacements, drifts of the building, and vibration periods, respectively.

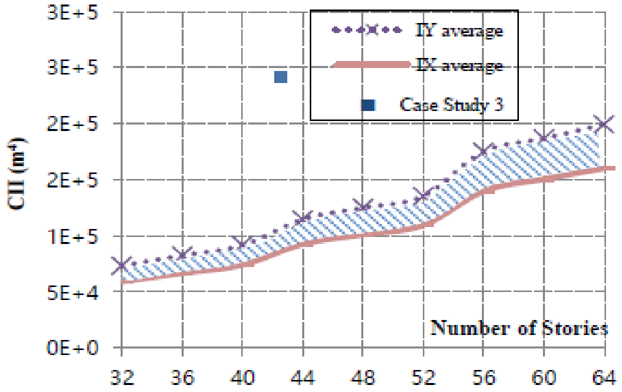

Fig. 20 Average Values for CII for Tube-in-Tube of Fig. 3.

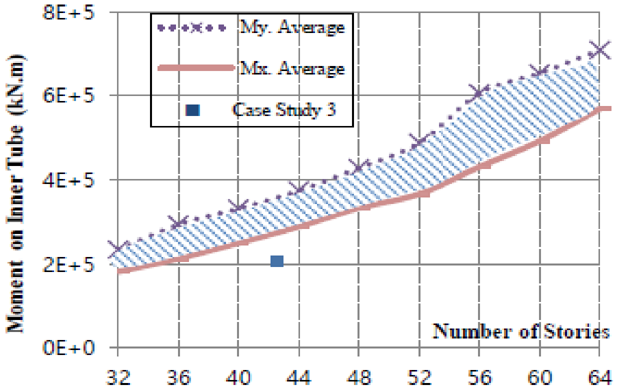

Fig. 21 Average Values for Moments for Tube-in-Tube of Fig. 3.

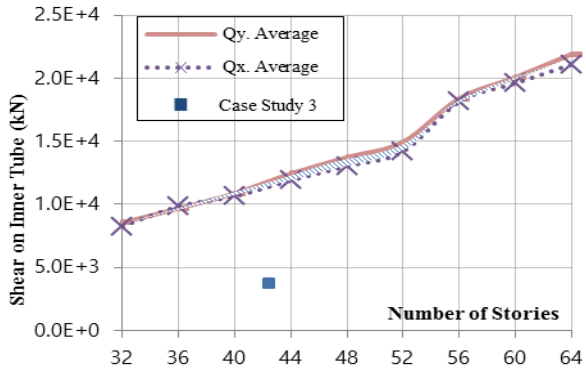

Fig. 22 Average Values of Shear Forces for Tube-Tube of Fig. 3.

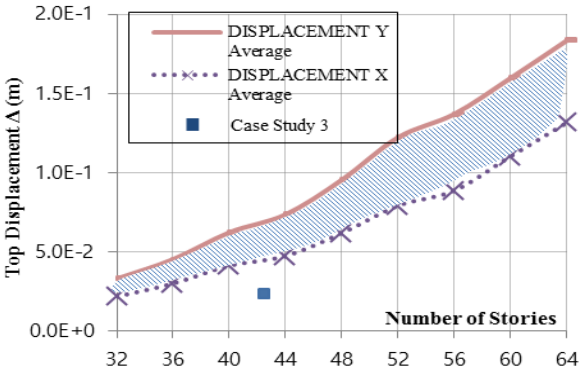

Fig. 23 Average Values of Top Displacements in-For Tube-in-Tube of Fig. 3.

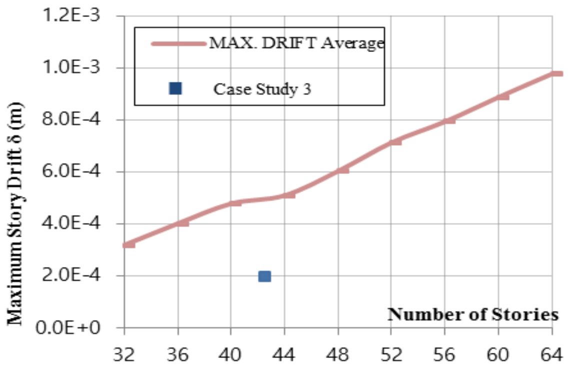

Fig. 24 Average Values of Top Drifts for Tube-Tube of Fig. 3.

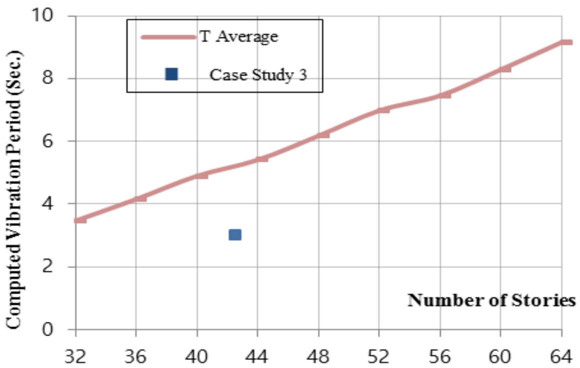

Fig. 25 Average Values of Vibration Periods in-for Tube-in-Tube of Fig. 3.

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

$CII = 3769N-62106$ (15)
$M_{inner\ tube} \leq 169N^2-2748.0N+126571$ (16)
$Q_{inner\ tube} \leq 417N-5706$ (17)
$\Delta_{top} \leq 0.00005N^2-0.00008N+0.0019$ (18)
$\delta_{drift} \leq 0.00002N-0.000040$ (19)
$T_c \leq 0.174N-2.14$ (20)

Where N is the number of stories

Case Study 3

Figure 26 manifests structural system of case study tower where the total height of the building is 149 m (43 stories) designed and built in the Gulf Area. Main system used to resist the lateral loads –for this case– is tube-in-tube. The line of symmetry is about y-axis. Therefore, the y-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.

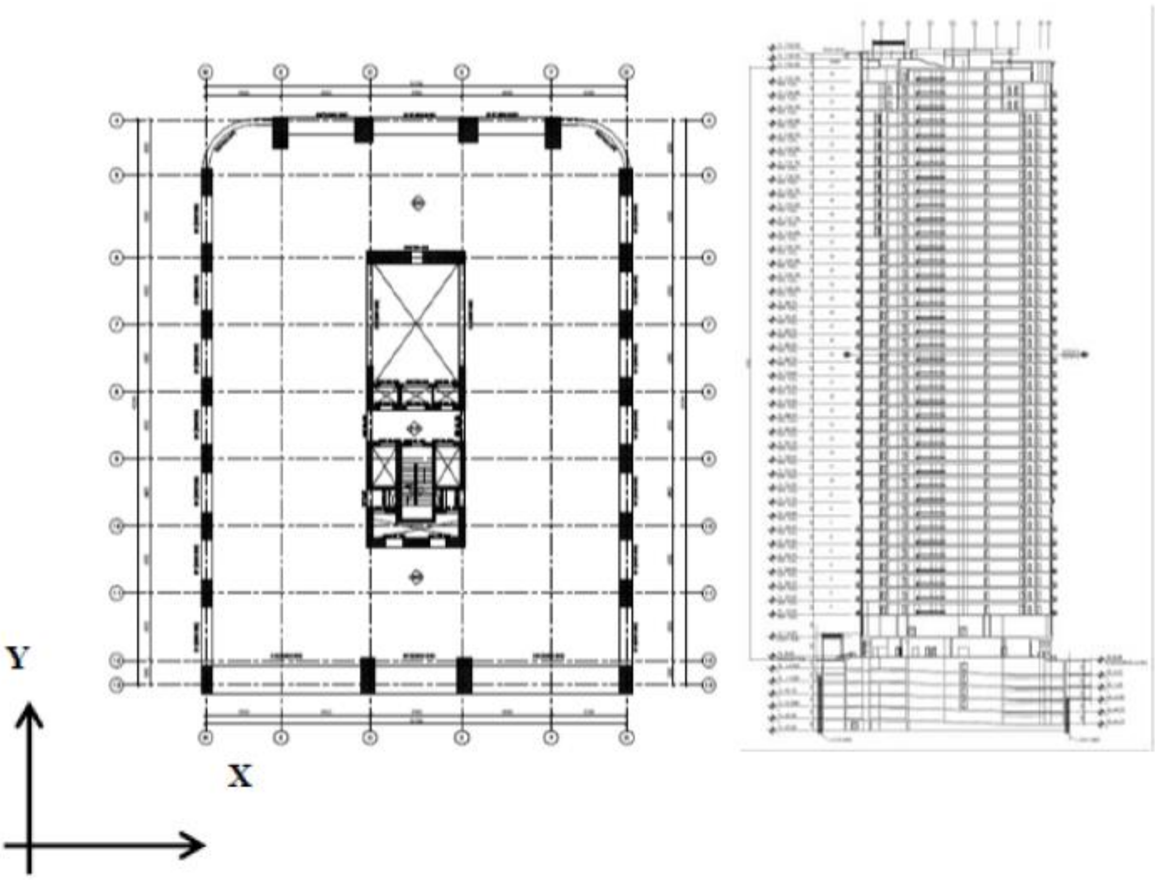

Fig. 26 Structural System for Case Study (3) of Tube-in-Tube Case

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)	99950	320992	12210	0.06	0.00046	5.35
Case Study 3	241898	208141	3682	0.023	0.0002	2.99
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. One outrigger 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, and 32 illustrate the average values for all models of Fig. 4 for *CII*: moments on walls, shear forces on shear walls, displacements, drifts of the building and vibration periods respectively. 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.

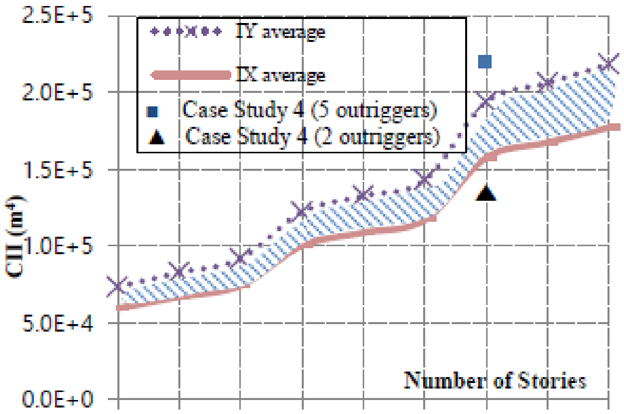

Fig. 27 Average Values of CII for Tube-in-Tube of Fig. 4.

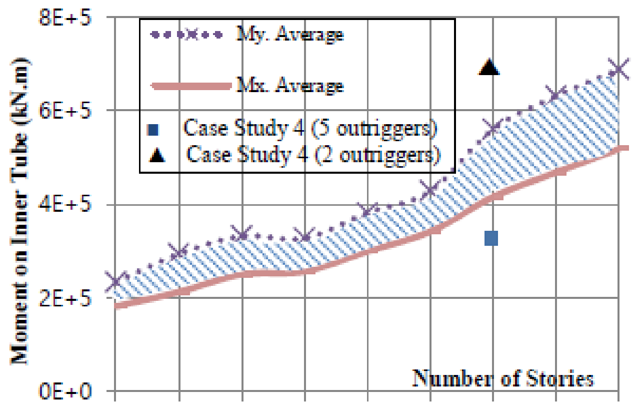

Fig. 28 Average Values of Moments for Tube-in-Tube of Fig. 4.

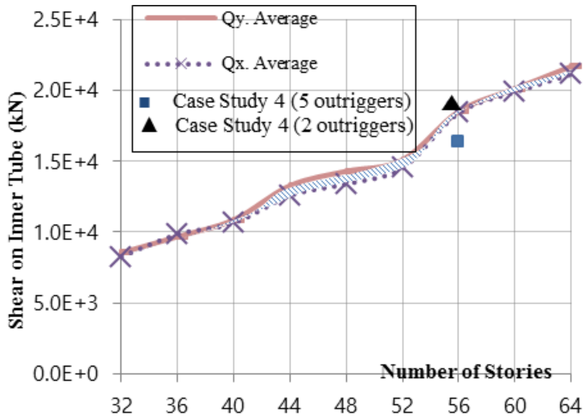

Fig. 29 Average Values of Shear Forces on Inner Tube for in-Tube of Fig. 4.

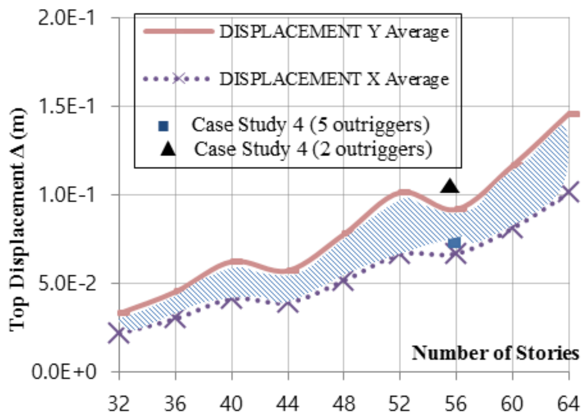

Fig. 30 Average Values for Top Displacements Tube-for Tube-in-Tube of Fig. 4.

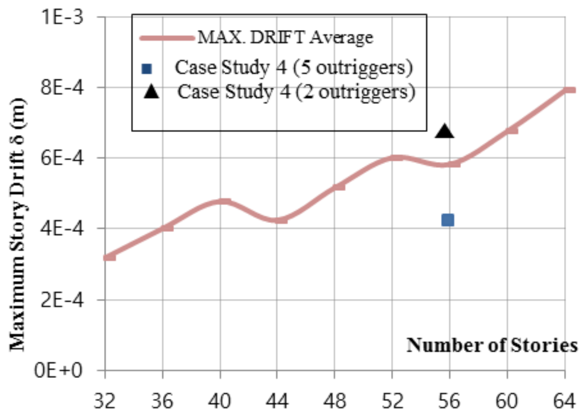

Fig. 31 Average Values for Maximum Drifts for Fig. 4.

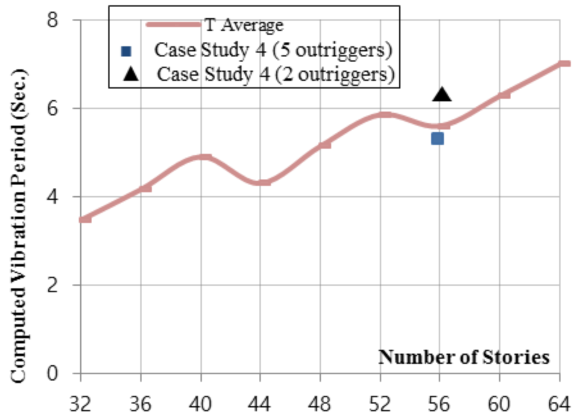

Fig. 32 Average Values for Vibration Tube-in-Tube of Period for Tube-in-Tube of Fig. 4.

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

$CII = 4441N-85941$ (21)
$M_{inner\ tube} \leq 225N^2-12188N+348080$ (22)
$Q_{inner\ tube} \leq 417N-5510$ (23)
$\Delta_{top} \leq 0.00004N^2-0.0012N+0.0248$ (24)
$\delta_{drift} \leq 0.00001N-0.00009$ (25)
$T_c \leq 0.16H^{0.89}$ (26)

Where N is the number of stories

Case Study 4

Figure 33 shows the structural system of application tower. The height of the building is 196 m (56 stories). The main system of the building is tube-in-tube with outrigger. The line of symmetry is about y-axis. Therefore, the y-direction result is compared with the average values as shown in previous figures. One case represents the usage of outriggers in five stories (labeled by ■) and the other represents the case where only two stories were fortified with outriggers (labeled by ▲). Figure 27 shows that *CII* value for application building (labeled by ■) is above the shaded area; hence, response values are within acceptable limits. Application building labeled by ▲ has a *CII* below the shaded area; hence, response values are not within acceptable limits as shown in Figs. 28-32 and Table 4.

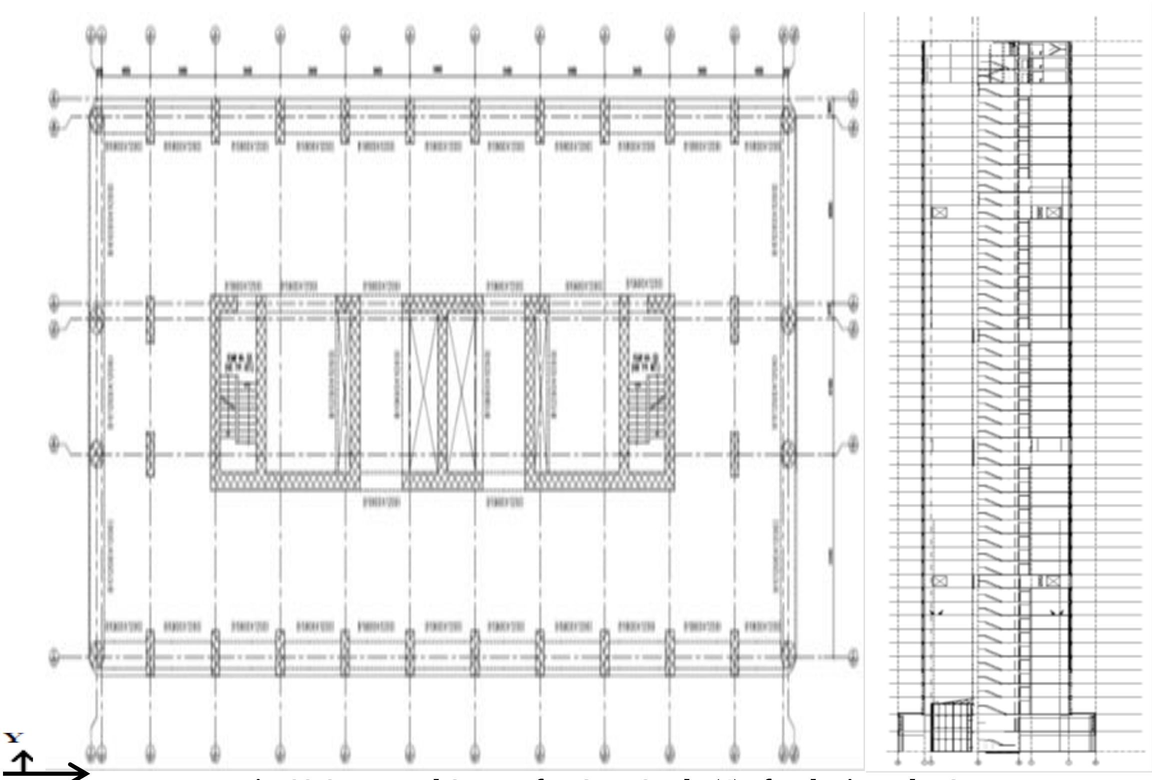

Fig. 33 Structural System for Case Study (4) of Tube-in-Tube Case

Table 4: Case Study 4 (N = 56)

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)	162772	372344	17814	0.085	0.00047	5.45
Case Study 4 (5 outriggers)	220000	326525	16331	0.073	0.00042	5.29
Checks	EQ.(21) √	EQ.(22) √	EQ.(23) √	EQ.(24) √	EQ.(25) √	EQ.(26) √
Case Study 4 (2 outriggers)	138177	606614	18035	0.102	0.00068	6.34
Checks	EQ.(21) x	EQ.(22) x	EQ.(23) x	EQ.(24) x	EQ.(25) x	EQ.(26) x

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 line 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 60–65% as compared to values of tube-in-tube structural systems.

Figures 35, 36, 37, 38, and 39 present the moments, shear forces, top displacements, drifts, and computed vibration periods, respectively. Figure 35 shows that the outrigger cases result in smaller moments on the shear walls (almost 75% of values for higher stories). This effect is almost negligible for tube-in-tube systems.

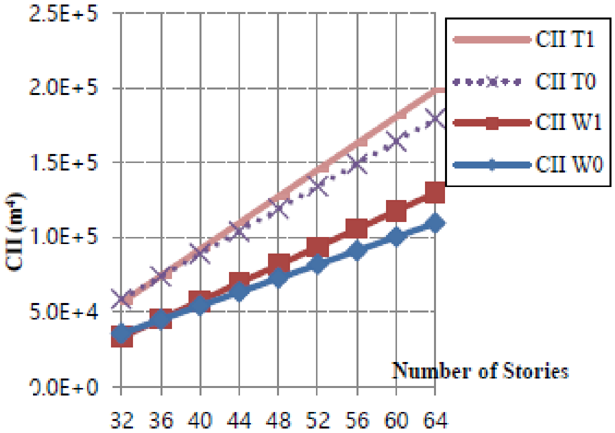

Fig. 34 CII averages for all 4 systems.

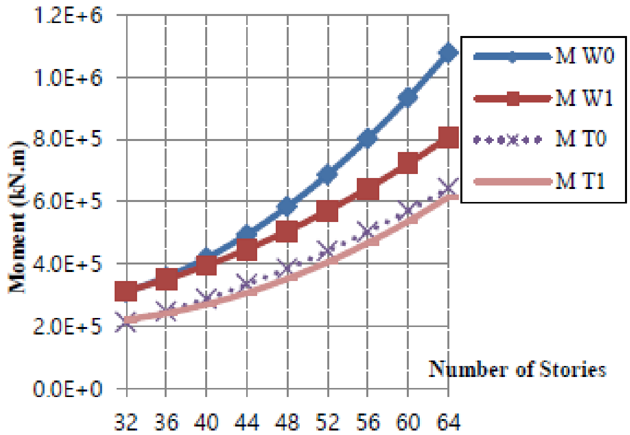

Fig. 35 Comparing Moment averages for all 4 systems.

Figure 36 highlights that adding outriggers does not affect the shearing forces exerted on shear walls. Shear force values are almost equal for different 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 45% of values for higher stories) than the tube-in-tube systems.

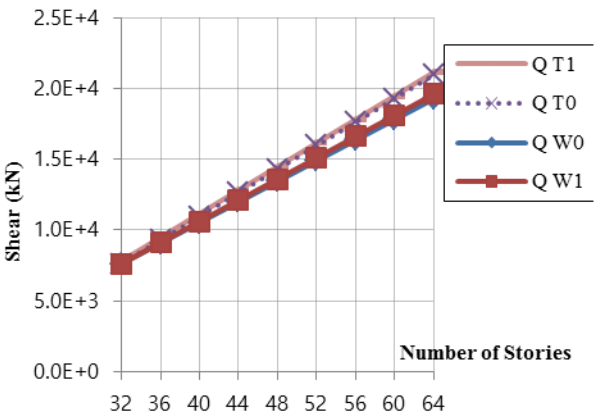

Fig. 36 Comparing Shear Force averages for systems.

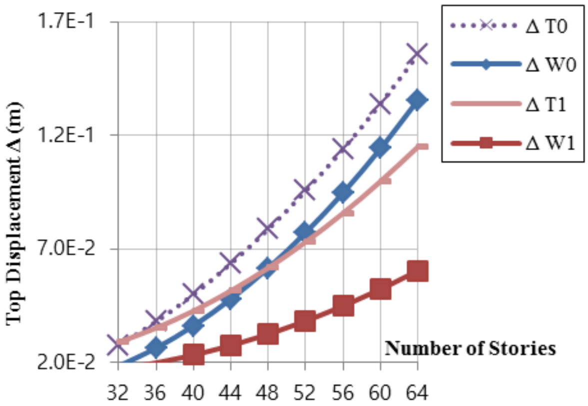

Fig. 37 Comparing Top Displacement averages all 4 for all 4 systems.

Figure 38 highlights that the type of system used does not affect the drift value for the building, since drift values are relative between stories, while adding outriggers reduces the drift significantly (almost 65% of values for higher stories). Finally, Fig. 39 shows the effect of adding outriggers on reducing the period. This reduction amount to 60–70% for shear wall systems and 75–80 % for tube-in-tube systems, of values for higher stories.

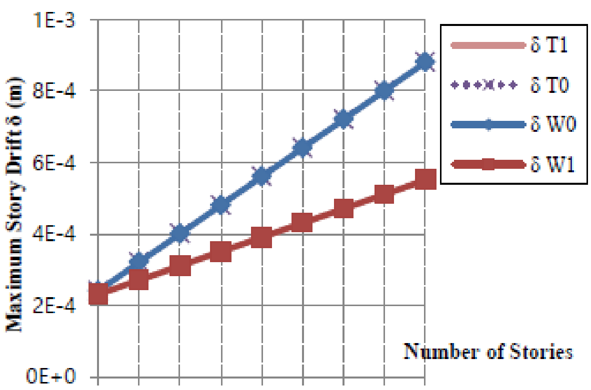

Fig. 38 Comparing Maximum Drift averages system.

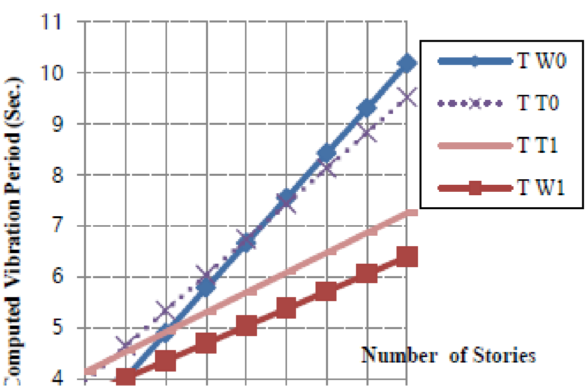

Fig. 39 Comparing Vibration Period averages for all 4 for all 4 systems..

Table 5 summarizes the equations presented in Fig. 34-39.

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

***CII* average**		
Shear Wall System	W0	*2309N-38474*
Shear Wall System with Outrigger (s)	W1	*3018N-63570*
Tube-in-Tube	T0	*3769N-62106*
Tube-in-Tube with Outrigger (s)	T1	*4441N-85941*
$M_{wall/inner\ tube}$ average		
Shear Wall System	W0	$432N^2+17397N+423328$
Shear Wall System with Outrigger (s)	W1	$213N^2-4997.0N+252953$
Tube-in-Tube	T0	$169N^2-2748.0N+126571$
Tube-in-Tube with Outrigger (s)	T1	$225N^2-12188N+348080$
$Q_{wall/inner\ tube}$ average		
Shear Wall System	W0	*364N-4034*
Shear Wall System with Outrigger (s)	W1	*375N-4378*
Tube-in-Tube	T0	*417N-5706*
Tube-in-Tube with Outrigger (s)	T1	*417N-5510*
Δ_{top} average		
Shear Wall System	W0	$0.00006N^2+0.0021N+0.0242$
Shear Wall System with Outrigger (s)	W1	$0.000025N^2-0.0011N+0.0253$
Tube-in-Tube	T0	$0.00005N^2-0.00008N+0.0019$
Tube-in-Tube with Outrigger (s)	T1	$0.00004N^2-0.0012N+0.0248$
δ_{drift} average		
Shear Wall System	W0	*0.00002N-0.00040*
Shear Wall System with Outrigger (s)	W1	*0.00001N-0.00009*
Tube-in-Tube	T0	*0.00002N-0.000040*
Tube-in-Tube with Outrigger (s)	T1	*0.00001N-0.00009*
T_c average		
Shear Wall System	W0	*0.220N-4.47*
Shear Wall System with Outrigger (s)	W1	$0.04H^{0.92}$
Tube-in-Tube	T0	*0.174N-2.14*
Tube-in-Tube with Outrigger (s)	T1	$0.16H^{0.89}$

Figure 40 shows a comparison between vibration period results obtained in this research and ponding values published in literature and renowned codes. The results show good correlation.

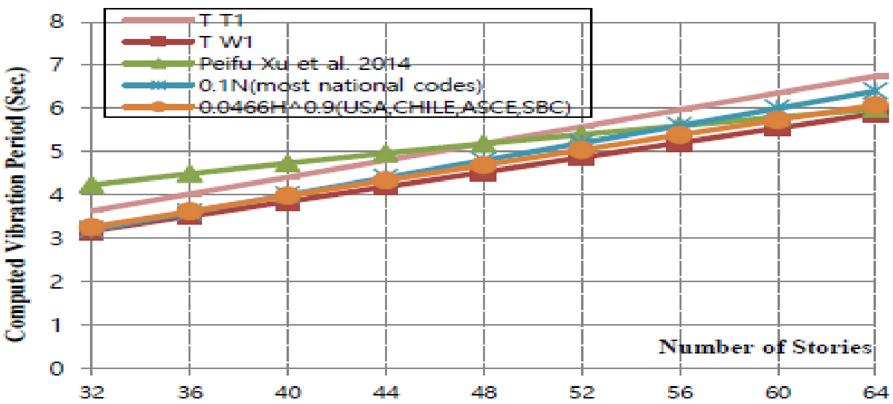

Fig. 40 Comparing Vibration Period Results with Literature and Renowned Codes

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.

The paper presents approximate approaches for predicting the high-rise building response under different loads for small eccentricity cases. 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 paper presents 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 architecture 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.

REFERENCES

1. Adeli, H. (1985), "Approximate formulae for period of vibration of building systems", *Journal of Civil Engineering for Practicing and Design Engineers*, **4**(1).
2. Algan, B. (1982), "Drift and damage considerations in earthquake-resistant design of reinforced concrete buildings", Ph.D. Thesis, University of Illinois at Urbana-Champaign.
3. Alguhane, M., Fayed, N., Hussin, A., & Ismail, M. (2016). "Simplified equations for estimating the period of vibration of KSA existing building", *Journal of Multidisciplinary Engineering Science and Technology*, **3**(3).
4. ASCE07-10 (2010). "Minimum Design Loads for Buildings and Other Structures", American Society of Civil Engineers, Reston, USA.
5. Bozdogan, K., & Ozturk, D. (2010). "An approximate method for lateral stability analysis of wall-frame buildings including shear deformations of walls", *Sadhana*, **35**(3), 241–253.
6. Brownjohn, J. M. W., Pan, T. C., & Deng, X. Y. (2000). "Correlating dynamic characteristics from field measurements and numerical analysis of high-rise building", *earthquake engineering and structural dynamics*, 29, 523-543.
7. Egyptian Code of Practice ECP201. (2012). "Egyptian Code for Loads Calculation in Structures and Buildings", Ministry of Building Construction, Research Center for Housing, Building and Physical Planning, Cairo, Egypt.
8. Hoedajanto, D. (1983). "A model to simulate lateral-force response of reinforced concrete structures with cylindrical and box sections", Ph.D. Thesis, University of Illinois at Urbana-Champaign.
9. Hoenderkamp, J. C. D., & Snijder, H. (2000). "Approximate analysis of high-rise frames with flexible connection", *The Structural Design of Tall buildings*, **9**, 233-248.
10. International Building Code IBC. (2018). "International Building Code 2018" International Code Council (INC), Club Hills.
11. Kamal, O., & Hamdy, O. (2003). "A simplified approach for approximate analysis against lateral loads", Tenth International Colloquium on Structural and Geotechnical Engineering, Ain Shams University, Egypt.
12. Meftah, S., Tounsi, A., & El Abbas, A. (2007). "A simplified approach for seismic calculation of a tall building braced by shear walls and thin-walled open section structures", *Engineering Structures*, **29**, 2576–2585.
13. Newmark, N. M., & Hall. W. J. (1982). "Earthquake Spectra and design", Earthquake Engineering Research Institute, Berkeley, California.
14. Panagiotis, G., & Mehdi, N. (2019). "Artificial bee colony-based neural network for the prediction of the fundamental period of infilled frame structures", *Neural Computing and Applications*.
15. Pavan, K., &Dhakal, P. (2016). "Prediction of fundamental period of regular frame buildings", *Bulletin of the New Zealand Society for Earthquake Engineering*, **49(**2).
16. Peifu, Xu., Congzhen, Xiao., & Jianhui, Li. (2014). "Research on Relationship between Natural Vibration Periods and Structural Heights for High-rise Buildings and Its Reference Range in China", *International Journal of High-Rise Buildings*, **3**(1), 49–64.
17. Rahgozar, A., Reza Ahmadi, B., & Sharifi, Y. (2010). "A simple mathematical model for approximate analysis of tall buildings", *Applied Mathematical Modelling*, **34,** 2437–2451.
18. SBC; "Saudi Building Code for Loads and Forces Requirements", General Secretariat of the Saudi Building Code National Committee, KSA.
19. Tarjan, G., & Kollar, P. (2004). "Approximate analysis of building structures with identical stories subjected to earthquakes", *International Journal of Solids and Structures*, **41**, 1411–1433.
20. Uniform Building Code UBC. (1997). "Uniform Building Code 1997", International Conference of Building Officials (ICBO), Denver, Whittier.