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# Modeling of shear-wall dominant symmetrical flat-plate reinforced concrete buildings

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## Abstract

Flat-slab building structures exhibit significant higher flexibility compared with traditional frame structures, and shear walls (SWs) are vital to limit deformation demands under earthquake excitations. The objective of this study is to identify an appropriate finite element (FE) model of SW dominant flat-plate reinforced concrete (R/C) buildings, which can be used to study its dynamic behavior. Three-dimensional models are generated and analyzed to check the adequacy of different empirical formulas to estimate structural period of vibration via analyzing the dynamic response of low- and medium-height R/C buildings with different cross-sectional plans and different SW positions and thicknesses. The numerical results clarify that modeling of R/C buildings using block (solid) elements for columns, SWs, and slab provides the most appropriate representation of R/C buildings since it gives accurate results of fundamental periods and consequently reliable seismic forces. Also, modeling of R/C buildings by FE programs using shell elements for both columns and SWs provides acceptable results of fundamental periods (the error does not exceed 10%). However, modeling of R/C buildings using frame elements for columns and/or SWs overestimates the fundamental periods of R/C buildings. Empirical formulas often overestimate or underestimate fundamental periods of R/C buildings. Some equations provide misleading values of fundamental period for both intact and cracked R/C buildings. However, others can be used to estimate approximately the fundamental periods of flat-plate R/C buildings. The effect of different SW positions is also discussed.

**Keywords:** Finite element programs, flat plate, shear wall, FE modeling and reinforced concrete buildings

## Introduction

Flat-slab building structure is widely used due to the many advantages it possesses over conventional moment-resisting frames. It provides lower building heights, unobstructed space, architectural flexibility, easier formwork, and shorter construction time. However, it suffers low transverse stiffness due to lack of deep beams and/or shear walls (SWs). This may lead to potential damage even when subjected to earthquakes with moderate intensity. The brittle punching failure due to transfer of shear forces and unbalanced moments between slabs and columns may cause serious problems. Flat-slab systems are also susceptible to significant reduction in stiffness resulting from the cracking that occurs from construction loads, service gravity, and lateral loads. Therefore, it is recommended that in regions with high seismic hazard, flat-slab construction should only be used as the vertical load-carrying system in structures braced with frames or SWs responsible for the lateral capacity of the structure (Erberik and Elnashai 2004).

Indeed, significant social and economic impacts of recent earthquakes affecting urban areas have motivated many researchers to devote their efforts to estimate and mitigate the risks associated with these potential losses (e.g., Crowley et al. 2005; Moharram et al. 2008). Sindel (1996) concluded that ductile moment-resisting frames may not escape nonstructural damage. He recommended the use of ductile SWs in almost all reinforced concrete (R/C) buildings not only to provide adequate structural safety, but also to protect against nonstructural damage. Sezen et al. (2003) found that buildings constructed using SWs as the primary lateral load-resisting system performed quite well in the 1999 Kocaeli, Turkey earthquake, and for the most part, buildings with SWs survived with limited or no damage. Ayala and Charleson (2002) and Sonuvar et al. (2004) have shown that the most effective and economic method of increasing the stiffness and lateral load strength of existing buildings is

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adding new elements such as a SW to the existing building system. Coelho et al. (2004) found that R/C flat-slab building structures exhibit significant higher flexibility compared with traditional frame structures and recommended using SWs to limit deformation demands under earthquake excitations.

Indeed, modeling of columns and shear walls is very important for researchers and designer engineers since appropriate modeling leads to accurate results. The objective of this study is to identify an appropriate finite element (FE) model of SW dominant symmetrical flat-plate R/C buildings, which can be used in the study of its dynamic behavior. Three different finite element programs were used in the analysis, namely Marc and Mentat (MSC Software 2010), ETABS version 9.5 (CSI 2008), and SAP2000 version 14 (CSI 2009). Six-storey and ten-storey R/C buildings are considered in the analyses to represent low- and medium-height buildings, respectively. Also, a one-storey R/C building is used for the convergence analysis. Both square and rectangular in-plane geometries of slab are used for each building height with different SW thicknesses and positions. Three-dimensional finite element models are generated and investigated using different finite elements to analyze the dynamic response of the buildings. The objectives of this investigation can be summarized as follows:

1. Check the accuracy of different finite element analysis modeling of R/C buildings using different FE programs which may be useful for researchers and designer engineers.
2. Check the adequacy of different empirical formulas to estimate structural period of vibration.
3. Analyze the dynamic response of low- and medium-height R/C buildings with different cross-sectional plans and different SW positions and thicknesses.

## Methods

### Empirical formulas of fundamental period

The period of vibration $T$ is an important parameter in the force-based design of structures as this parameter defines the spectral acceleration and consequently the base shear force to which the building should be designed. For the usual range of structural periods, higher periods of vibration lead to underestimation of seismic design forces and vice versa. Thus, it is recommended not to overestimate the structural period of vibration.

The Egyptian code of loads (ECL) (HBRC 2008) provides a simple formula for computing the fundamental period of buildings with heights up to 60 m. It depends only on the building height and is expressed as follows:

$$T = C_t H^{3/4}, \tag{1}$$

where $C_t$ is a coefficient = 0.05 (for buildings other than moment-resisting frames and with shear walls) and $H$ is the building height in meters. ECL (HBRC 2008) recommends that the period computed from a rational analysis should not exceed 1.2 times the value obtained from Equation 1. It is worth to mention that ICC [International Code Council] 1997, 2003 specifies an identical equation to Equation 1. As an alternative for buildings with concrete or masonry SWs, ICC [International Code Council] (1997) provides the following formula to compute $C_t$ which depends on the properties of the SWs as follows:

$$C_t = \frac{0.075}{(A_c)^{1/2}}, \tag{2a}$$

where

$$A_c = \sum\nolimits_{i=1}^{NW} A_i\left[0.2 + (L_i/H)^2\right], \tag{2b}$$

where $A_i$ is the horizontal area (in square meters), $L_i$ is the dimension in the direction under consideration (in meters) of the $i$th SW in the first floor of the structure, and NW is the total number of SWs. The value of $(L_i/H)$ in Equation 2b should not exceed 0.9. It should be noted that Equation 2a,b is identical to those reported in the Eurocode 8 (CEN 1998) and ECL (HBRC 2003), except that Equation 2b took the following form:

$$A_c = \sum\nolimits_{i=1}^{NW} A_i\left[0.2 + (L_i/H)\right]^2 \tag{3}$$

Crowley and Pinho (2010) state that Equation 3 has an error and that Equation 2b is the original one; the difference may be due to an editing error, and the error should be rectified. Goel and Chopra (1998) calibrated the Dunkerley's equation (Inman 1996) using the measured periods of vibration of SW buildings and obtained the formula in Equation 4 which has been included in ASCE (2006) as follows:

$$T = \frac{0.0063}{\sqrt{C_w}} H, \tag{4a}$$

where the equivalent shear area is as follows:

$$C_w = \frac{100}{A_B} \sum_{i=1}^{NW} \left(\frac{H}{H_i}\right)^2 \frac{A_i}{\left[1 + 0.83\left(\frac{H_i}{L_i}\right)^2\right]}, \tag{4b}$$

where $A_B$ is the building plan area, $H$ is the building height in meters, $A_i$,$H_i$, and $L_i$ are the area in square meters and height and length in meters in the direction under consideration of the $i$th SW, and NW is the number of SWs. They also recommended that the period computed from a rational analysis should not exceed 1.4 times the value obtained from Equation 4. The lower limit of fundamental period represents the value measured under ambient vibration for the intact building with no cracks. However, the upper limit represents that obtained from strong motion records of the cracked building (Morales 2000).

Morales (2000) found that Equation 4 provided improved results as compared with any of the code-suggested expressions, e.g., the Canadian code NBCC [National Building Code of Canada] (1996) or the American code, ICC [International Code Council] (1997). Michel et al. (2010) suggested that for French existing buildings, the fundamental period is proportional to building height or floor number. However, for design, they recommended relationships based on the wall lengths by Goel and Chopra (1998). Crowley and Pinho (2010) suggested updating Equation 3 in the Eurocode 8 (CEN 1998) by the equation proposed by Goel and Chopra (1998). It is worth to mention that Equation 4 is valid for SW with different heights and takes into account shape factor and shear modulus, as well as both flexural and shear deformations. However, Equations 1, 2, and 4 are used in the fundamental period evaluation in this study.

## Finite element analysis

Three-dimensional finite element models using three different finite element programs are used in the analyses; these are Marc and Mentat (MSC Software 2010), ETABS version 9.5 (CSI 2008), and SAP2000 version 14 (CSI 2009) programs. In the Marc and Mentat package, elements 7 and 21 are used. Element 7 is an eight-node solid element, while element 21 is a 20-node solid element: each node of these two elements has three global translational degrees of freedom. In ETABS and SAP2000, the R/C slabs are modeled as thick shell elements, and three cases are considered for modeling columns and SWs (column-SW), namely (1) beam-beam, (2) beam-shell/wall, and (3) shell/wall-shell/wall, where ‘beam’ and ‘shell/wall’ refer to the type of elements used to model the columns and SWs, respectively. The thicknesses of SWs are considered to be 0.4, 0.35, or 0.30 m.

In the present study, it is assumed that all materials are elastic for the intact buildings. Smeared cracks are assumed for cracked elements as recommended by many codes, and the coefficients of stiffness for cracked elements are as follows: 0.7 for columns, 0.5 for SWs, and 0.25 for flat slab of the intact elements.

### *Description of R/C buildings*

Figures 1 and 2 show two typical floor plans of the studied symmetrical cross-sectional buildings. The center line dimensions of the first building are 36 × 36 m from 5 × 5 bays, and each bay is 7.2 m. However, the dimensions of the second building are 36 × 21.6 m from 5 × 3 bays, and each bay is 7.2 m. The building floors have been designed according to the Egyptian code of practice for R/C design and construction (HBRC 2007) as R/C flat slabs and cast in C30 concrete, which is typical for this type of construction in Egypt. The cross sections of the columns and SWs are kept constant throughout the height of the building in multi-storey buildings. Table 1 shows the dimensions of columns for different building heights. The thickness of the flat slab is fixed to be 0.24 m, and each floor has a middle opening of 7.2 × 7.2 m. The floors have been designed to carry an imposed load of 2.0 kN/m$^2$. The clear height of the ground floor is 4.4 m, but the clear height of the repeated floors is 2.8 m. The overall heights of the R/C buildings are 32, 19.84, and 4.64 m for ten-, six- and one-storey buildings, respectively.

Six-storey and ten-storey R/C buildings are considered in this study to represent low- and medium-height symmetrical buildings, respectively. Both square and rectangular in-plan geometries of slab are used for each building height with different SW thicknesses and positions. The reason for choosing low- and medium-height buildings is twofold. Because of the inherent flexibility of flat-slab buildings, it may not be possible to satisfy the drift demands in high-rise construction. On the other hand, low- and medium-height buildings are common in the Middle East region.

### *Convergence of vibration period results*

The accuracy of the finite element method (FEM) can be checked via comparing the FEM results with analytical solutions (analytical methods) and/or via checking the convergence of the numerical solution using different meshes. The package Marc and Mentat software (MSC Software 2010) is used in the present analysis. To check the convergence of FEM results, two element types are used in the analysis: elements 7 and 21. Element 7 is an eight-node solid arbitrary hexahedral element with each node having three global translational degrees of freedom. On the other hand, element 21 is a 20-node solid arbitrary hexahedral element with each node having three global translational degrees of freedom. Both elements can be used for all constitutive relations, but in general, we need more of the lower-order elements (element 7) than the higher-order elements such as element 21. Indeed, element type 21 can give an accurate representation of the strain fields in elastic analyses even with only one element through the thickness (MSC Software 2010).

Due to a huge number of elements used in multi-storey buildings, only the one-storey building is used in the convergence study for the two plans in Figures 1 and 2. The material properties for concrete are density, ($\rho$ = 2,500 kg/m$^3$), compressive strength (30 MPa),

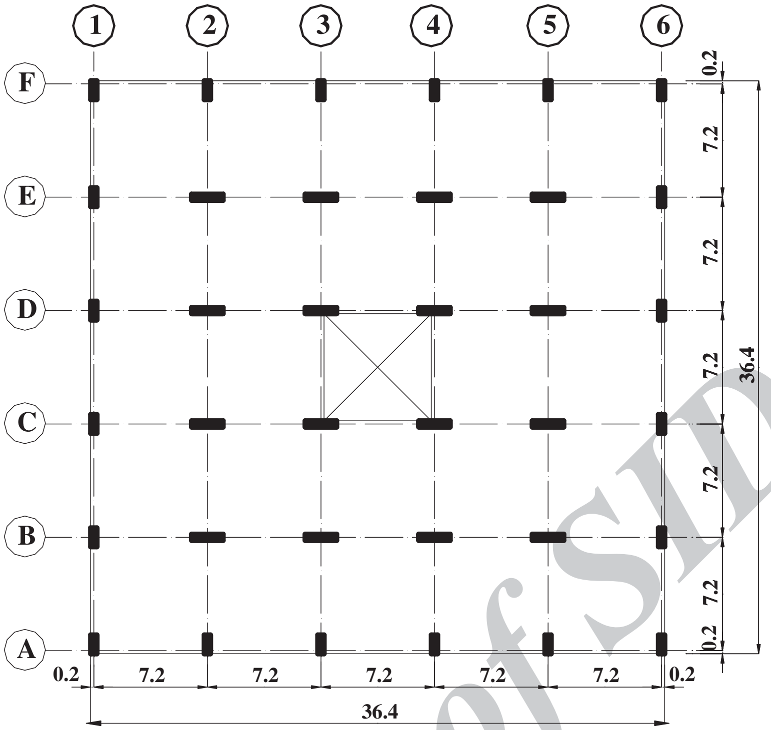


**Figure 1** Plan of square cross-sectional flat-plate building (in meters).

Young's modulus ($E = 24$ GPa), and Poisson's ratio ($\nu = 0.2$). The reference model consists of 16,776 solid elements of type 21 and 99,144 nodes for the square cross-sectional (SCS) building, and 9,960 elements and 59,652 nodes for the rectangular cross-sectional (RCS) building. The size of elements for columns is $0.4 \times 0.4 \times 0.2$ m and for slab is $0.4 \times 0.4 \times 0.12$ m. Four independent convergence studies have been carried out on the mesh sizes for concrete columns and slabs of solid element type 7. The first mesh consists of 8,388 elements and 18,000 nodes for the SCS building, and 4,980 elements and 10,848 nodes for the RCS building. The size of elements for columns is $0.4 \times 0.4 \times 0.4$ m and for slab is $0.4 \times 0.4 \times 0.24$ m. The second mesh consists of 8,784 elements and 19,584 nodes for the SCS building, and 5,244 elements and 11,904 nodes for the RCS building. The size of elements for columns is $0.4 \times 0.4 \times 0.2$ m and for slab is $0.4 \times 0.4 \times 0.24$ m. The third mesh consists of 16,776 elements and 27,792 nodes for the SCS building, and 9,960 elements and 16,800

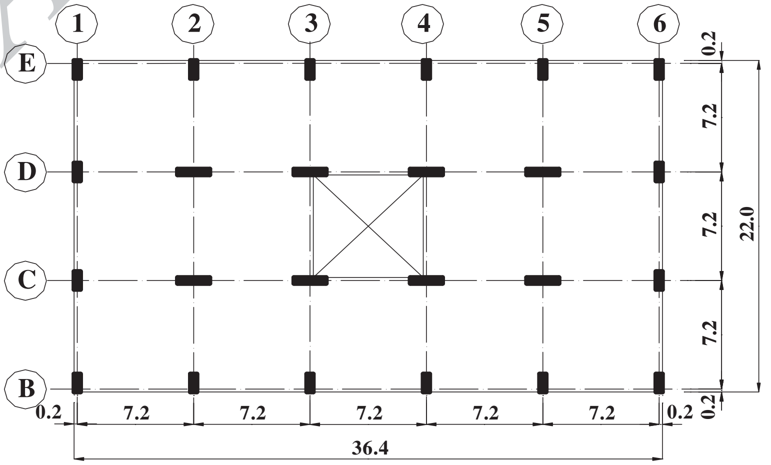


**Figure 2** Plan of rectangular cross-sectional (RCS) flat-plate building (in meters).

**Table 1 Dimensions of columns for flat-plate R/C buildings**

| Number of floors | Interior columns | Exterior columns |
|---|---|---|
| One storey | 0.4 × 0.4 m | 0.4 × 0.4 m |
| Six storeys | 0.4 × 1.2 m | 0.4 × 0.8 m |
| Ten storeys | 0.4 × 2.0 m | 0.4 × 1.2 m |

nodes for the RCS building. The size of elements for columns is 0.4 × 0.4 × 0.2 m and for slab is 0.4 × 0.4 × 0.12 m. The finest mesh consists of 67,104 elements and 104,328 nodes for the SCS building, and 39,840 elements and 62,424 nodes for the RCS building. The size of elements for columns is 0.2 × 0.2 × 0.2 m and for slab is 0.2 × 0.2 × 0.12 m.

Even though the finite element analysis provides a detailed picture of the modal analysis, only the periods of the first five mode shapes are presented for brevity. Figures 3 and 4 plot the percentage error of building periods related to the reference case with element type 21 for SCS and RCS buildings, respectively. It is shown that the finer the mesh, the more accurate the results. Thus, for the fourth mesh, the percentage error is less than 0.2% of the reference case for both of the two buildings. Also, the percentage error for the first mesh (coarse one) and the reference one is less than 1%. Therefore, finite element analysis based on the first mesh seems to be satisfactory for numerical investigation in predicting the elastic behavior of symmetrical cross section of flat-plate buildings. Thus, the mesh where the size of elements for columns is 0.4 × 0.4 × 0.4 m and for slab is 0.4 × 0.4 × 0.24 m using element type 7, which is reliable as it provides a numerical solution with relative error less than 1%, will be used in this study as a reference to check the accuracy of the other two programs, ETABS and SAP2000.

### R/C shear walls

Six scenarios of SW positions are considered in this study. Each scenario contains four typical SWs which have fixed thickness through the height of the building and are arranged symmetrically in cross-sectional plan. The length of each SW is 7.2 m for the ten-storey building and 4.0 m for the six-storey one. Three thicknesses of SWs are considered: 0.4, 0.35, and 0.30 m. Figure 5 plots the different SW positions. It is important to mention that the six types of SW positions are considered for the SCS building, while only the first five types of SW positions are considered for the RCS building.

## Results and discussion

### Evaluation of vibration periods for different SW positions

Three-dimensional models are analyzed using Marc and Mentat, and ETABS programs. As mentioned in the 'Convergence of vibration period results' subsection, results of the Marc and Mentat program where the size of brick elements are 0.4 × 0.4 × 0.4 m and 0.4 × 0.4 × 0.24 m for columns and slabs, respectively, are used as reference for comparison with other programs and different empirical formulas of vibration periods (Equations 1, 2, and 4). As mentioned above, the clear height of the ground floor is 4.4 m, and the clear height of the repeated floors is 2.8 m. The overall height of R/C buildings are 32 and 19.84 m for ten- and six-storey buildings, respectively. In the SAP2000 and ETABS programs, the R/C slabs are modeled as thick shell elements at the centerline of the slab thickness, and three cases are considered for modeling column-SW, namely (1) beam-beam, (2)

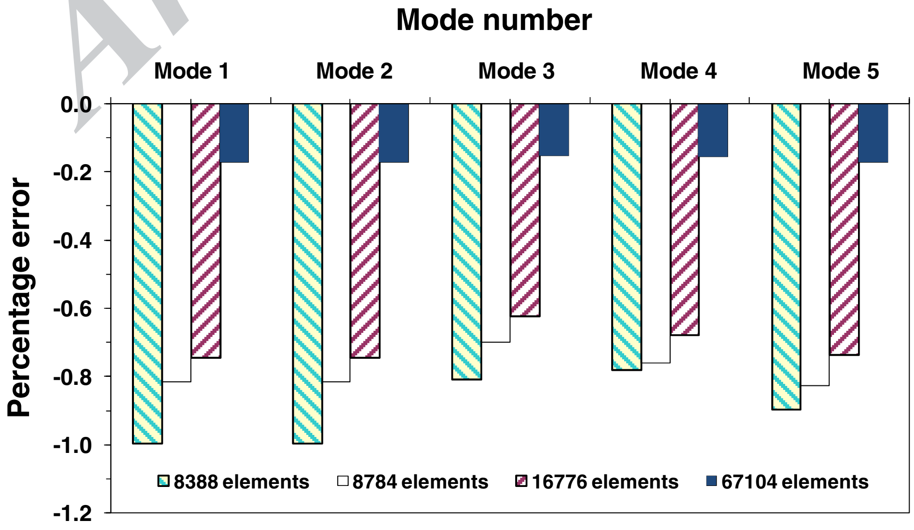


**Figure 3** Percentage error of vibration periods for different FE meshes of the SCS building.

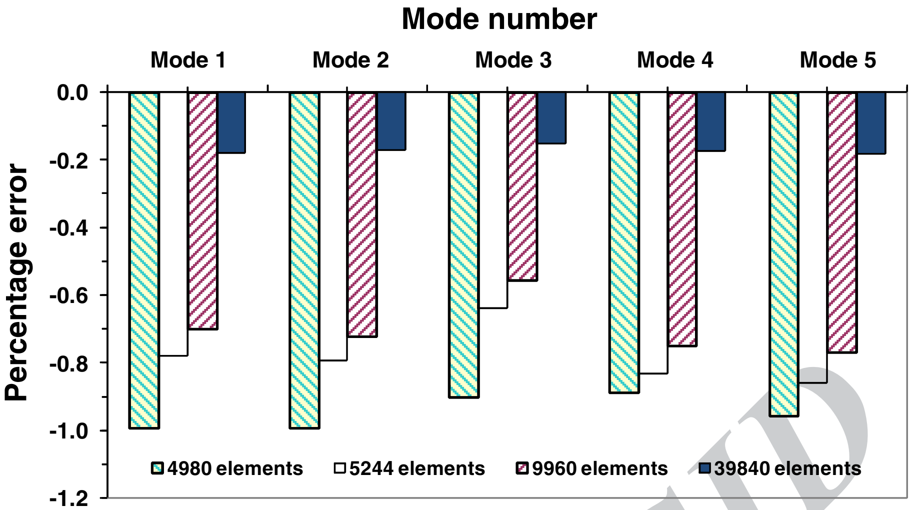


**Figure 4** Percentage error of vibration periods for different FE meshes of the RCS building.

beam-shell/wall, and (3) shell/wall-shell/wall; where beam and shell/wall refer to the type of elements used to model the columns and SWs, respectively. The thickness of each SW is considered to be 0.4 m. The first ten vibration periods of each model for each type of SW position are estimated, and the results are analyzed. For brevity, only the first three periods of each intact model for each type of SW position are listed in the following study. Figure 6 shows different FE models and views of ten-storey flat-plate R/C buildings.

### Intact ten-storey SCS building

Table 2 lists the percentage error of period of vibration for the intact ten-storey SCS building. The results show that for type-1 of SW position where the SWs are near the center of the building, the fundamental mode is torsional, but the second and third modes are flexural in the $y$ and $x$ directions, respectively. Also, modeling of R/C buildings using beam elements for both columns and SWs highly overestimates the fundamental period of the intact R/C building for both SAP2000 and ETABS programs (>140% of those obtained using block elements by the Marc and Mentat program). Indeed, this is mainly due to the fact that in type-1, the four SWs form a box section and that beam elements represent individual elements and not a box section. On the other hand, modeling of R/C buildings using beam elements for columns but thick shell elements for SWs greatly decreases the percentage error and provides acceptable results of vibration periods (<9% for fundamental periods). Furthermore, modeling of R/C buildings using thick shell elements for both columns and SWs

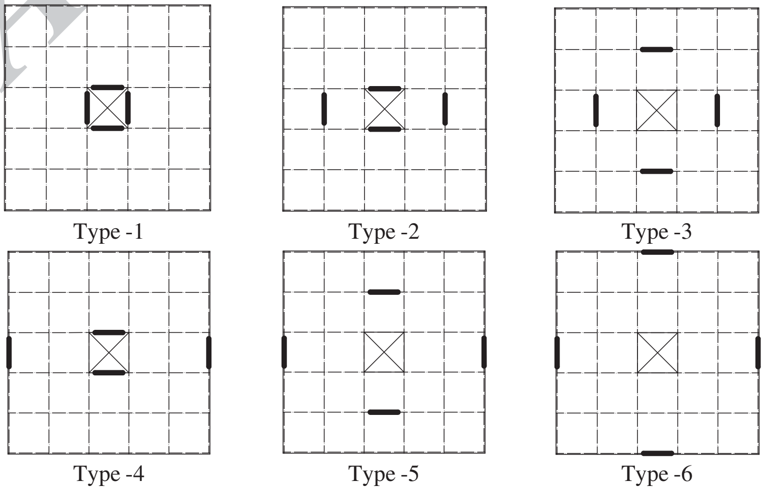
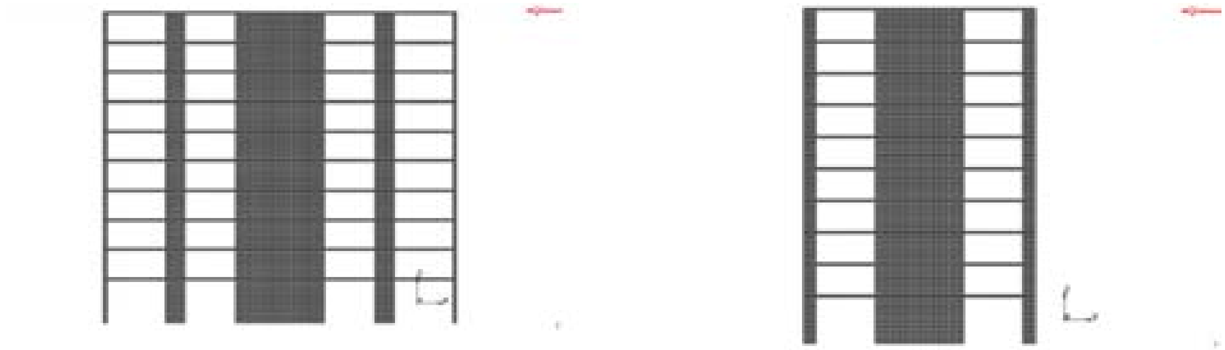
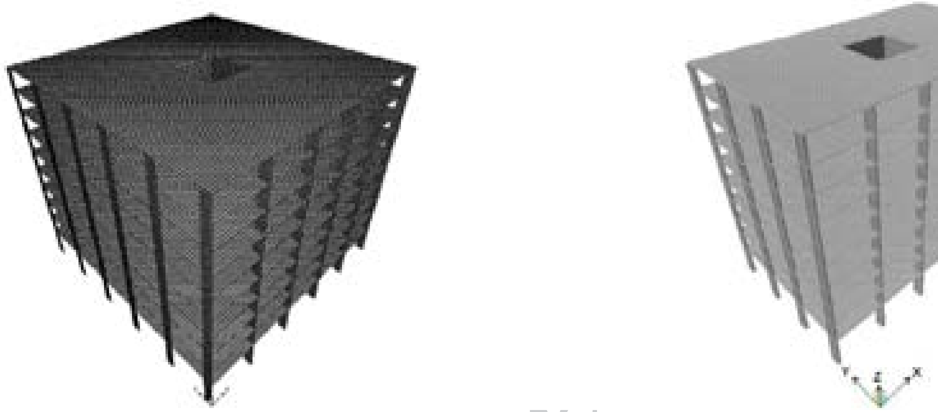


**Figure 5** Different types of SW positions.



(a) Elevation of SCS building by MARC/Mentat (2010).

(b) Side view of RCS building by MARC/Mentat (2010).



(c) Isometric view of SCS building by SAP2000 (2009).

(d) Isometric view of RCS building by ETABS (2008).

**Figure 6 Different FE models of 10-storey R/C buildings.**

provides more accurate results of fundamental periods since the percentage error is very small. In general, the ETABS program always provides more accurate results of fundamental periods of R/C buildings than those obtained by the SAP2000 program. Also, it is shown that Equation 1 underestimates the fundamental period of the intact R/C building. Equation 2 overestimates the fundamental period of the intact R/C building, and Equation 4 highly overestimates the fundamental period of the intact R/C building of type-1 (five times higher than that of Equation 2).

For type-2 of SW position where the distance between the walls is increased from 7.2 to 21.6 m in the $x$ direction but still 7.2 m in the $y$ direction, the results show that the fundamental mode is still torsional and that the second and third modes are still flexural in the $y$ and $x$ directions, respectively. Also, modeling of R/C buildings using beam elements for both columns and SWs highly overestimates the fundamental periods of R/C buildings for both SAP2000 and ETABS programs (>40% of those obtained using block elements). On the other hand, modeling of R/C buildings using beam elements for columns but thick shell elements for SWs leads to less percentage error of vibration periods, but percentage errors are still high (≈30% for fundamental period). Furthermore, modeling of R/C buildings using thick shell elements for both columns and SWs enhances considerably the results of vibration periods and provides more accurate results of fundamental periods since the percentage error is very small. Again, the ETABS program provides more accurate results of fundamental periods of R/C buildings than those obtained by the SAP2000 program. Also, it is shown that Equation 2 underestimates the fundamental period of the intact R/C building, but still, the results are acceptable. Equation 1 highly underestimates the fundamental period of the intact of R/C building ($\approx -30\%$ for fundamental period). On the contrary, Equation 4 highly overestimates the fundamental period of the intact R/C building of type-2 ($\approx +30\%$ for fundamental period).

For type-3 of SW position where the distance between the walls is 21.6 m in both the $x$ and $y$ directions, the results show that the fundamental mode is changed from torsional to flexural mode in the $y$ direction due to the increase in torsional stiffness of the building. Also, modeling of R/C buildings using beam elements for both

**Table 2 Percentage error of vibration periods for the intact ten-storey SCS building**

| SW position | Column model | SW model | Mode shape | SAP2000 | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|---|---|
| Type-1 | Beam | Beam | (1) Tors | 145.49 | 142.81 | −8.18 | 14.63 | 72.14 |
| | | | (2) Fl(*y*) | 83.00 | 82.54 | - | - | - |
| | | | (3) Fl(*x*) | 85.07 | 84.67 | - | - | - |
| | Beam | Shell/wall | (1) Tors | 8.65 | 3.87 | −8.18 | 14.63 | 72.14 |
| | | | (2) Fl(*y*) | 8.09 | 5.30 | - | - | - |
| | | | (3) Fl(*x*) | 11.56 | 8.79 | - | - | - |
| | Shell/wall | Shell/wall | (1) Tors | 2.02 | −4.04 | −8.18 | 14.63 | 72.14 |
| | | | (2) Fl(*y*) | 2.53 | −1.04 | - | - | - |
| | | | (3) Fl(*x*) | 2.45 | −1.79 | - | - | - |
| Type-2 | Beam | Beam | (1) Tors | 41.76 | 40.79 | −31.03 | −13.89 | 29.32 |
| | | | (2) Fl(*y*) | 35.73 | 35.58 | - | - | - |
| | | | (3) Fl(*x*) | 37.99 | 37.69 | - | - | - |
| | Beam | Shell/wall | (1) Tors | 30.73 | 28.28 | −31.03 | −13.89 | 29.32 |
| | | | (2) Fl(*y*) | 21.04 | 18.51 | - | - | - |
| | | | (3) Fl(*x*) | 23.89 | 20.86 | - | - | - |
| | Shell/wall | Shell/wall | (1) Tors | 8.22 | 3.00 | −31.03 | −13.89 | 29.32 |
| | | | (2) Fl(*y*) | 9.15 | 4.96 | - | - | - |
| | | | (3) Fl(*x*) | 8.76 | 3.73 | - | - | - |
| Type-3 | Beam | Beam | (1) Fl(*y*) | 36.77 | 36.61 | −24.95 | −6.31 | 40.70 |
| | | | (2) Tors | 39.80 | 39.66 | - | - | - |
| | | | (3) Fl(*x*) | 36.98 | 36.30 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 20.92 | 18.50 | −24.95 | −6.31 | 40.70 |
| | | | (2) Tors | 24.06 | 21.59 | - | - | - |
| | | | (3) Fl(*x*) | 23.91 | 21.50 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 9.07 | 4.78 | −24.95 | −6.31 | 40.70 |
| | | | (2) Tors | 8.36 | 3.94 | - | - | - |
| | | | (3) Fl(*x*) | 8.35 | 3.77 | - | - | - |
| Type-4 | Beam | Beam | (1) Fl(*y*) | 30.79 | 30.44 | −28.14 | −10.29 | 34.72 |
| | | | (2) Fl(*x*) | 40.48 | 40.18 | - | - | - |
| | | | (3) Tors | 30.58 | 29.82 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 22.10 | 20.04 | −28.14 | −10.29 | 34.72 |
| | | | (2) Fl(*x*) | 29.37 | 26.67 | - | - | - |
| | | | (3) Tors | 23.16 | 21.09 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 8.88 | 5.09 | −28.14 | −10.29 | 34.72 |
| | | | (2) Fl(*x*) | 8.41 | 2.62 | - | - | - |
| | | | (3) Tors | 8.17 | 4.10 | - | - | - |
| Type-5 | Beam | Beam | (1) Fl(*y*) | 31.81 | 31.45 | −27.70 | −9.73 | 35.56 |
| | | | (2) Fl(*x*) | 41.58 | 41.44 | - | - | - |
| | | | (3) Tors | 29.00 | 28.41 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 21.83 | 19.82 | −27.70 | −9.73 | 35.56 |
| | | | (2) Fl(*x*) | 27.40 | 25.11 | - | - | - |
| | | | (3) Tors | 19.71 | 17.48 | - | - | - |

**Table 2 Percentage error of vibration periods for the intact ten-storey SCS building** *(Continued)*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 8.86 | 5.00 | −27.70 | −9.73 | 35.56 |
| | | | (2) Fl(*x*) | 8.09 | 2.84 | - | - | - |
| | | | (3) Tors | 8.23 | 4.58 | - | - | - |
| Type-6 | Beam | Beam | (1) Fl(*y*) | 30.15 | 29.82 | −28.63 | −10.89 | 33.81 |
| | | | (2) Fl(*x*) | 37.96 | 37.72 | - | - | - |
| | | | (3) Tors | 25.26 | 24.73 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 22.06 | 20.10 | −28.63 | −10.89 | 33.81 |
| | | | (2) Fl(*x*) | 30.17 | 28.38 | - | - | - |
| | | | (3) Tors | 17.54 | 15.39 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 9.09 | 5.62 | −28.63 | −10.89 | 33.81 |
| | | | (2) Fl(*x*) | 7.82 | 2.37 | - | - | - |
| | | | (3) Tors | 8.18 | 4.72 | - | - | - |

columns and SWs highly overestimates the fundamental period of the intact R/C building for both the SAP2000 and ETABS programs. On the other hand, modeling of R/C buildings using beam elements for columns but thick shell elements for SWs leads to a decrease in the percentage error of vibration periods, but percentage errors are still high ($\approx +20\%$ for fundamental period). Furthermore, modeling of R/C buildings using thick shell elements for both columns and SWs enhances considerably the results of vibration periods and provides more accurate results of fundamental periods since the percentage error is very small. Again, the ETABS program provides more accurate results of fundamental periods of R/C buildings than those obtained by the SAP program. Also, it is shown that Equation 2 underestimates the fundamental period of the intact R/C building, but still, the results are acceptable ($\approx -7\%$). Equation 1 highly underestimates the fundamental period of the intact R/C building (four times that obtained using Equation 2). On the contrary, Equation 4 highly overestimates the fundamental period of the intact R/C building of type-3 ($\approx +40\%$ for fundamental period).

For types-4, -5, and -6 of SW positions where at least one pair of the parallel SWs is on the perimeter of the building, the results show that the fundamental mode is flexural in the $y$ direction. Indeed, the results are approximately similar to those obtained for type-3 of SW position. Thus, modeling of R/C buildings using thick shell elements for both columns and SWs enhances considerably the results of vibration periods and provides relatively accurate results of fundamental periods since the percentage error is very small. Also, the ETABS program provides more accurate results of fundamental periods of R/C buildings than those obtained by the SAP2000 program. Furthermore, it is shown that Equation 2 underestimates the fundamental periods of R/C buildings, but still, the results are acceptable. Equations 1 and 4 provide fundamental period of the intact R/C buildings that are highly underestimated or highly overestimated, respectively.

It is well known that each empirical equation provides fixed period of vibration for all shear wall positions for the same building. In Table 2, it is shown that the percentage error of vibration period using empirical formulas has a maximum value for type-1 and decreases greatly for the other types of SW positions. This implies that the vibration period of type-1 is the least among different SW positions. This is due to high flexural and torsional stiffnesses of SWs, forming a box or closed section in type-1. Also, it is easily seen that, except for type-1, the percentage errors of vibration periods obtained by the three empirical equations for other SW positions (types-2 to -6) do not change so much (e.g., from −13.89% to −6.31% for Equation 2). This implies that different SW positions have a small influence on the fundamental periods of R/C buildings when the SWs are arranged near the perimeter of the building.

### *Intact ten-storey RCS building*

Table 3 lists the percentage error of period of vibration for the intact ten-storey RCS building. The results show that for type-1 of SW position where the SWs are near the center of the building, the fundamental mode is flexural in the $y$ direction, but the third mode is torsional. Also, modeling of R/C buildings using beam elements for both columns and SWs highly overestimates the fundamental periods of R/C buildings for both the SAP2000 and ETABS programs (>190% of those obtained using block elements by the Marc and Mentat program). Indeed, this is mainly due to the fact that in type-1, the four SWs form a box section and beam elements represent individual elements and not a box section. On the other hand, modeling of R/C buildings using beam

**Table 3 Percentage error of vibration periods for the intact ten-storey RCS building**

| SW position | Column model | SW model | Mode shape | SAP2000 | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|---|---|
| Type-1 | Beam | Beam | (1) Fl(*y*) | 196.76 | 191.46 | 23.90 | 54.68 | 79.93 |
| | | | (2) Fl(*x*) | 90.27 | 89.85 | - | - | - |
| | | | (3) Tors | 92.55 | 92.17 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 6.38 | 3.38 | 23.90 | 54.68 | 79.93 |
| | | | (2) Fl(*x*) | 6.95 | 4.03 | - | - | - |
| | | | (3) Tors | 3.85 | −1.13 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 1.56 | −2.07 | 23.90 | 54.68 | 79.93 |
| | | | (2) Fl(*x*) | 1.59 | −1.92 | - | - | - |
| | | | (3) Tors | 0.88 | −5.05 | - | - | - |
| Type-2 | Beam | Beam | (1) Fl(*x*) | 33.84 | 32.80 | −15.99 | 4.88 | 22.00 |
| | | | (2) Tors | 32.53 | 32.25 | - | - | - |
| | | | (3) Fl(*y*) | 34.83 | 34.71 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*x*) | 19.84 | 17.21 | −15.99 | 4.88 | 22.00 |
| | | | (2) Tors | 16.11 | 12.73 | - | - | - |
| | | | (3) Fl(*y*) | 18.73 | 15.97 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*x*) | 6.00 | 0.96 | −15.99 | 4.88 | 22.00 |
| | | | (2) Tors | 3.89 | 0.92 | - | - | - |
| | | | (3) Fl(*y*) | 3.84 | 0.91 | - | - | - |
| Type-3 | Beam | Beam | (1) Fl(*x*) | 29.55 | 29.43 | −15.53 | 5.46 | 22.68 |
| | | | (2) Fl(*y*) | 33.31 | 33.04 | - | - | - |
| | | | (3) Tors | 28.94 | 28.15 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*x*) | 17.87 | 15.78 | −15.53 | 5.46 | 22.68 |
| | | | (2) Fl(*y*) | 18.59 | 16.04 | - | - | - |
| | | | (3) Tors | 17.61 | 15.33 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*x*) | 5.49 | 0.94 | −15.53 | 5.46 | 22.68 |
| | | | (2) Fl(*y*) | 4.45 | 0.91 | - | - | - |
| | | | (3) Tors | 4.32 | 0.79 | - | - | - |
| Type-4 | Beam | Beam | (1) Fl(*y*) | 27.97 | 27.63 | −16.39 | 4.38 | 21.42 |
| | | | (2) Fl(*x*) | 35.02 | 34.75 | - | - | - |
| | | | (3) Tors | 23.73 | 23.05 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 18.50 | 16.28 | −16.39 | 4.38 | 21.42 |
| | | | (2) Fl(*x*) | 22.19 | 19.15 | - | - | - |
| | | | (3) Tors | 15.75 | 13.68 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 4.82 | 0.95 | −16.39 | 4.38 | 21.42 |
| | | | (2) Fl(*x*) | 4.00 | 0.93 | - | - | - |
| | | | (3) Tors | 5.22 | 0.70 | - | - | - |
| Type-5 | Beam | Beam | (1) Fl(*y*) | 27.27 | 26.92 | −17.20 | 3.37 | 20.24 |
| | | | (2) Fl(*x*) | 32.06 | 31.81 | - | - | - |
| | | | (3) Tors | 22.24 | 21.66 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 18.43 | 16.32 | −17.20 | 3.37 | 20.24 |
| | | | (2) Fl(*x*) | 23.09 | 21.13 | - | - | - |
| | | | (3) Tors | 14.40 | 12.29 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 5.48 | 0.96 | −17.20 | 3.37 | 20.24 |
| | | | (2) Fl(*x*) | 3.79 | 0.94 | - | - | - |
| | | | (3) Tors | 5.30 | 0.63 | - | - | - |

elements for columns but thick shell elements for SWs greatly decreases the percentage error and gives acceptable results of vibration periods (<7%). Furthermore, modeling of R/C buildings using thick shell elements for both columns and SWs provides more accurate results of fundamental periods since the percentage error is very small (≈2% for fundamental period). In general, the ETABS program always provides more accurate results of fundamental periods of R/C buildings than those obtained by the SAP2000 program. Also, it is shown that Equations 1, 2, and 4 overestimate the fundamental period of the intact R/C building by 23.9%, 54.7%, and 79.9%, respectively.

For types-2, -3, -4, and -5, the results are approximately similar, and the fundamental mode is flexural in the $x$ or $y$ direction. Table 3 shows that modeling of R/C buildings using beam elements for both columns and SWs highly overestimates the fundamental period of the intact R/C building for both the SAP2000 and ETABS programs (≈ + 30% of those obtained using block elements). On the other hand, modeling of R/C buildings using beam elements for columns but thick shell elements for SWs leads to less percentage errors of vibration periods, but percentage errors are still high (≈ + 20% for fundamental period). Furthermore, modeling of R/C buildings using thick shell elements for both columns and SWs enhances considerably the results of vibration periods and provides more accurate results of fundamental periods since the percentage error is very small. Again, the ETABS program provides more accurate results of fundamental periods of R/C buildings than those obtained by the SAP2000 program. Also, it is shown that Equation 2 overestimates the fundamental period of the intact R/C building, but still, the results are acceptable (≈ + 5%). Equation 1 highly underestimates the fundamental period of the intact R/C building (≈ – 15% for fundamental period). On the contrary, Equation 4 highly overestimates the fundamental period of the intact R/C building (≈ + 20% for fundamental period).

Similar to the observations found in Table 2, it is inferred that the vibration period of type-1 is the least among the different SW positions due to high flexural and torsional stiffnesses of SWs, forming a box or closed section in type-1. Also, it is easily seen that, except for type-1, different SW positions have a small influence on the fundamental periods of R/C buildings when the SWs are arranged near the perimeter of the building.

#### *Intact six-storey SCS building*

Table 4 lists the percentage error of period of vibration for the intact six-storey SCS building. The results show that for type-1 of SW position where the SWs are near the center of the building, the fundamental mode is torsional, but the second and third modes are flexural in the $y$ and $x$ directions, respectively. Also, modeling of R/C buildings using beam elements for both columns and SWs overestimates the fundamental periods of R/C buildings for both the SAP2000 and ETABS programs (> + 35% of those obtained using block elements by the Marc and Mentat program). On the other hand, modeling of R/C buildings using beam elements for columns but thick shell elements for SWs leads to less percentage error of vibration periods, but the percentage error is still high (> + 30% for fundamental period). Furthermore, modeling of R/C buildings using thick shell elements for both columns and SWs greatly enhances the results and provides more accurate results of fundamental periods since the percentage error is very small. In general, the ETABS program always provides more accurate results of fundamental periods of R/C buildings than those obtained by the SAP2000 program. Also, it is shown that Equations 1 and 2 underestimate the fundamental period by 48.6% and 12.14%, respectively. However, Equation 4 overestimates the fundamental period by 27.31%.

For type-2, the fundamental mode is still torsional, but the second and third modes are flexural in the $y$ and $x$ directions, respectively. It is shown that the results of the ETABS and SAP2000 programs for type-2 are approximately similar to those obtained for type-1. Also, the ETABS program always provides more accurate results of fundamental periods of R/C buildings than those obtained by the SAP2000 program. Also, it is shown that Equation 1 underestimates the fundamental period by 39.88%. However, Equations 2 and 4 overestimate the fundamental period by 2.76% and 48.9%, respectively.

For types-3, -4, -5, and -6, the results are approximately similar, and the fundamental mode is changed to flexural mode in the $y$ direction instead of torsional mode in types-1 and -2. Table 4 shows that modeling of R/C buildings using thick shell elements for both columns and SWs enhances considerably the results of vibration periods and provides more accurate results of fundamental periods since the percentage error is very small. Again, the ETABS program gives more accurate results of fundamental periods of R/C buildings than those obtained by the SAP2000 program. Also, it is shown that Equation 2 overestimates the fundamental periods of R/C buildings, but still, the results are acceptable (≈ + 5%). Equation 1 highly underestimates the fundamental period of the intact R/C building (≈ – 40% for fundamental period). On the contrary, Equation 4 highly overestimates the fundamental period of the intact R/C building (≈ + 50% for fundamental period).

From Table 4, it is seen that the percentage error using empirical formulas is minimum for type-1 of the SW position. Thus, it is inferred that the vibration period of type-1 is the greatest among different SW positions due to small flexural and torsional stiffnesses of SWs with a

**Table 4 Percentage error of vibration periods for the intact six-storey SCS building**

| SW position | Column model | SW model | Mode shape | SAP2000 | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|---|---|
| Type-1 | Beam | Beam | (1) Tors | 36.41 | 35.40 | −48.60 | −12.14 | 27.31 |
| | | | (2) Fl(*y*) | 28.80 | 28.38 | - | - | - |
| | | | (3) Fl(*x*) | 32.19 | 31.80 | - | - | - |
| | Beam | Shell/wall | (1) Tors | 33.51 | 31.88 | −48.60 | −12.14 | 27.31 |
| | | | (2) Fl(*y*) | 18.55 | 15.52 | - | - | - |
| | | | (3) Fl(*x*) | 22.15 | 19.24 | - | - | - |
| | Shell/wall | Shell/wall | (1) Tors | 7.43 | −0.61 | −48.60 | −12.14 | 27.31 |
| | | | (2) Fl(*y*) | 6.75 | 1.01 | - | - | - |
| | | | (3) Fl(*x*) | 5.97 | −1.18 | - | - | - |
| Type-2 | Beam | Beam | (1) Tors | 33.87 | 33.01 | −39.88 | 2.76 | 48.90 |
| | | | (2) Fl(*y*) | 26.38 | 26.18 | - | - | - |
| | | | (3) Fl(*x*) | 56.69 | 56.24 | - | - | - |
| | Beam | Shell/wall | (1) Tors | 26.71 | 24.17 | −39.88 | 2.76 | 48.90 |
| | | | (2) Fl(*y*) | 16.99 | 14.54 | - | - | - |
| | | | (3) Fl(*x*) | 33.72 | 28.95 | - | - | - |
| | Shell/wall | Shell/wall | (1) Tors | 6.11 | −1.97 | −39.88 | 2.76 | 48.90 |
| | | | (2) Fl(*y*) | 5.55 | 0.44 | - | - | - |
| | | | (3) Fl(*x*) | 8.51 | −11.10 | - | - | - |
| Type-3 | Beam | Beam | (1) Fl(*y*) | 27.89 | 27.69 | −38.79 | 4.62 | 51.59 |
| | | | (2) Fl(*x*) | 29.53 | 29.34 | - | - | - |
| | | | (3) Tors | 27.99 | 27.34 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 16.04 | 13.47 | −38.79 | 4.62 | 51.59 |
| | | | (2) Fl(*x*) | 17.69 | 15.08 | - | - | - |
| | | | (3) Tors | 19.20 | 16.62 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 5.35 | 0.28 | −38.79 | 4.62 | 51.59 |
| | | | (2) Fl(*x*) | 4.94 | −0.26 | - | - | - |
| | | | (3) Tors | 4.91 | −0.58 | - | - | - |
| Type-4 | Beam | Beam | (1) Fl(*y*) | 22.97 | 22.52 | −39.66 | 3.15 | 49.46 |
| | | | (2) Tors | 33.56 | 33.19 | - | - | - |
| | | | (3) Fl(*x*) | 46.52 | 45.58 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 17.66 | 15.68 | −39.66 | 3.15 | 49.46 |
| | | | (2) Tors | 18.90 | 16.59 | - | - | - |
| | | | (3) Fl(*x*) | 35.69 | 31.11 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 5.49 | 1.26 | −39.66 | 3.15 | 49.46 |
| | | | (2) Tors | 4.59 | −1.51 | - | - | - |
| | | | (3) Fl(*x*) | 8.38 | −11.67 | - | - | - |
| Type-5 | Beam | Beam | (1) Fl(*y*) | 24.42 | 23.99 | −40.22 | 2.18 | 48.05 |
| | | | (2) Fl(*x*) | 30.62 | 30.43 | - | - | - |
| | | | (3) Tors | 21.40 | 20.78 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 16.59 | 14.48 | −40.22 | 2.18 | 48.05 |
| | | | (2) Fl(*x*) | 20.21 | 17.83 | - | - | - |
| | | | (3) Tors | 14.10 | 11.72 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 5.29 | 0.78 | −40.22 | 2.18 | 48.05 |
| | | | (2) Fl(*x*) | 4.87 | −1.24 | - | - | - |
| | | | (3) Tors | 3.72 | −0.40 | - | - | - |

**Table 4 Percentage error of vibration periods for the intact six-storey SCS building** *(Continued)*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Type-6 | Beam | Beam | (1) Fl(*y*) | 23.13 | 22.70 | −40.62 | 1.49 | 47.06 |
| | | | (2) Fl(*x*) | 29.13 | 28.78 | - | - | - |
| | | | (3) Tors | 18.16 | 17.60 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 16.92 | 14.90 | −40.62 | 1.49 | 47.06 |
| | | | (2) Fl(*x*) | 23.23 | 21.43 | - | - | - |
| | | | (3) Tors | 11.84 | 9.64 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 5.65 | 1.78 | −40.62 | 1.49 | 47.06 |
| | | | (2) Fl(*x*) | 5.14 | −2.00 | - | - | - |
| | | | (3) Tors | 3.18 | −0.90 | - | - | - |

small distance between parallel SWs in type-1. Also, it is easily seen that, except for type-1, the percentage errors of vibration periods obtained by the three empirical equations for other SW positions (types-2 to -6) do not change so much (e.g., from +47.06% to +51.59% for Equation 4). This implies that different SW positions have a small influence on the fundamental periods of R/C buildings when the SWs are arranged near the perimeter of the building.

### *Intact six-storey RCS building*

Table 5 lists the percentage error of period of vibration for the intact six-storey RCS building. The results are seen to be approximately similar to those obtained in Table 4 but with less percentage of error. Thus, Table 5 confirms the conclusions which have been drawn of the intact six-storey SCS R/C building.

## Effect of SW positions on storey displacement

To investigate the effect of SW positions on displacement of R/C buildings, the maximum horizontal displacements of R/C buildings with different heights and different cross-sectional plans are estimated for all SW positions using the ETABS program. The model used for each building is the cracked R/C building with a 0.4-m SW thickness. The maximum horizontal displacements are plotted for each storey in global $x$ and $y$ directions. The recommended values of coefficients by ECL (HBRC 2008) and many other codes are as follows: 0.25 for slabs, 0.7 for columns, and 0.5 for SWs.

### *Ten-storey R/C building*

Figure 7a,b plots the maximum horizontal displacements of the cracked ten-storey SCS building with different SW positions in the $x$ and $y$ directions, respectively. It is shown that type-1 provides minimum horizontal displacement in both the $x$ and $y$ directions. This is due to the fact that the SWs in type-1 constitute a box section, which has very high flexural and torsional stiffnesses. Also, it is shown that the SW position of type-6 provides minimum horizontal displacement among the non-combined SWs (types-2 to -6). Furthermore, SW position type-2 provides maximum horizontal displacement in the $y$ direction. This is attributed to the small distance in the $y$ direction between SWs. Thus, as the distance between parallel SWs increases, both flexural and torsional stiffnesses of the building increase, and consequently, the corresponding horizontal displacements decrease.

Figure 8a,b plots the maximum horizontal displacements of the cracked RCS ten-storey building with different SW positions in the $x$ and $y$ directions, respectively. Again, it is shown that type-1 provides minimum horizontal displacement in both the $x$ and $y$ directions. This is due to the high flexural and torsional stiffnesses of SWs, forming a box section. Also, it is shown that SW position type-5 provides a minimum horizontal displacement among non-combined SWs (types-2 to -5). Again, as the distance between parallel SWs increases, both flexural and torsional stiffnesses of the building increase, and consequently, the corresponding horizontal displacements decrease. Thus, it is easily seen that positioning of SWs on the perimeter of the R/C building is the most appropriate position for minimum horizontal displacement.

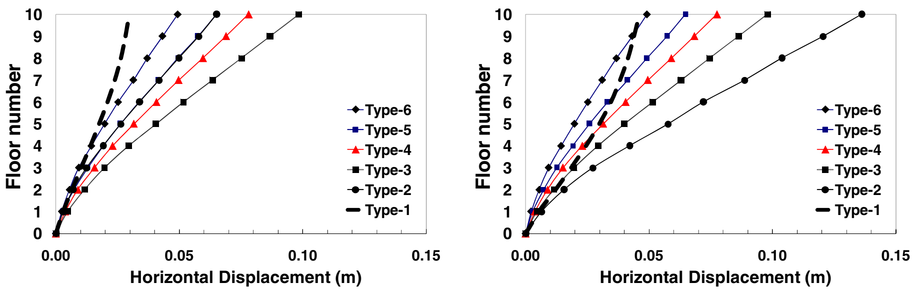
### *Six-storey R/C building*

Figure 9a,b plots the maximum horizontal displacements of the cracked six-storey SCS building with different SW positions in the $x$ and $y$ directions, respectively. It is shown that SW position type-6 provides minimum horizontal displacement among all the other SW types. However, SW position type-1 provides maximum horizontal displacement in both the $x$ and $y$ directions. This is attributed to the small distance between parallel SWs. Thus, as the distance between parallel SWs increases, both flexural and torsional stiffnesses of the building increase, and consequently, the corresponding horizontal displacements decrease.

Figure 10a,b plots the maximum horizontal displacements of the cracked six-storey RCS building with different SW positions in the $x$ and $y$ directions, respectively.

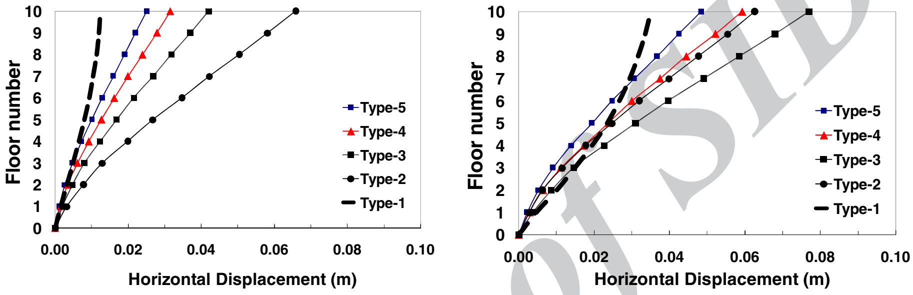
**Table 5 Percentage error of vibration periods for the intact six-storey RCS building**

| SW position | Column model | SW model | Mode shape | SAP2000 | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|---|---|
| Type-1 | Beam | Beam | (1) Tors | 43.48 | 41.56 | −41.77 | −0.47 | 11.71 |
| | | | (2) Fl(*y*) | 25.46 | 25.15 | - | - | - |
| | | | (3) Fl(*x*) | 34.86 | 34.51 | - | - | - |
| | Beam | Shell/wall | (1) Tors | 37.06 | 34.35 | −41.77 | −0.47 | 11.71 |
| | | | (2) Fl(*y*) | 12.81 | 9.59 | - | - | - |
| | | | (3) Fl(*x*) | 21.37 | 17.93 | - | - | - |
| | Shell/wall | Shell/wall | (1) Tors | 13.76 | 6.31 | −41.77 | −0.47 | 11.71 |
| | | | (2) Fl(*y*) | 3.27 | −2.48 | - | - | - |
| | | | (3) Fl(*x*) | 10.20 | 4.79 | - | - | - |
| Type-2 | Beam | Beam | (1) Fl(*y*) | 26.56 | 25.50 | −31.40 | 17.26 | 31.61 |
| | | | (2) Tors | 30.40 | 30.23 | - | - | - |
| | | | (3) Fl(*x*) | 67.18 | 66.75 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 15.51 | 12.56 | −31.40 | 17.26 | 31.61 |
| | | | (2) Tors | 18.32 | 15.58 | - | - | - |
| | | | (3) Fl(*x*) | 35.62 | 29.92 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 1.13 | −3.75 | −31.40 | 17.26 | 31.61 |
| | | | (2) Tors | 7.78 | −0.64 | - | - | - |
| | | | (3) Fl(*x*) | 11.68 | −9.90 | - | - | - |
| Type-3 | Beam | Beam | (1) Fl(*y*) | 23.56 | 23.41 | −32.10 | 16.06 | 30.26 |
| | | | (2) Fl(*x*) | 26.03 | 25.72 | - | - | - |
| | | | (3) Tors | 22.33 | 21.50 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 13.88 | 11.76 | −32.10 | 16.06 | 30.26 |
| | | | (2) Fl(*x*) | 13.23 | 10.55 | - | - | - |
| | | | (3) Tors | 13.14 | 10.50 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 5.19 | 1.97 | −32.10 | 16.06 | 30.26 |
| | | | (2) Fl(*x*) | 4.63 | −0.01 | - | - | - |
| | | | (3) Tors | 3.86 | −0.96 | - | - | - |
| Type-4 | Beam | Beam | (1) Fl(*y*) | 17.46 | 17.06 | −33.75 | 13.25 | 27.11 |
| | | | (2) Tors | 51.87 | 51.50 | - | - | - |
| | | | (3) Fl(*x*) | 32.11 | 31.23 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 11.19 | 9.19 | −33.75 | 13.25 | 27.11 |
| | | | (2) Tors | 26.04 | 21.03 | - | - | - |
| | | | (3) Fl(*x*) | 23.40 | 20.68 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | 1.27 | −2.58 | −33.75 | 13.25 | 27.11 |
| | | | (2) Tors | 4.48 | −0.42 | - | - | - |
| | | | (3) Fl(*x*) | 11.22 | −10.81 | - | - | - |
| Type-5 | Beam | Beam | (1) Fl(*y*) | 18.77 | 18.37 | −34.40 | 12.13 | 25.85 |
| | | | (2) Fl(*x*) | 27.82 | 27.53 | - | - | - |
| | | | (3) Tors | 14.75 | 14.12 | - | - | - |
| | Beam | Shell/wall | (1) Fl(*y*) | 11.20 | 9.14 | −34.40 | 12.13 | 25.85 |
| | | | (2) Fl(*x*) | 20.05 | 18.07 | - | - | - |
| | | | (3) Tors | 7.65 | 5.35 | - | - | - |
| | Shell/wall | Shell/wall | (1) Fl(*y*) | −0.65 | 0.80 | −34.40 | 12.13 | 25.85 |
| | | | (2) Fl(*x*) | 1.65 | 0.77 | - | - | - |
| | | | (3) Tors | −0.70 | 0.55 | - | - | - |



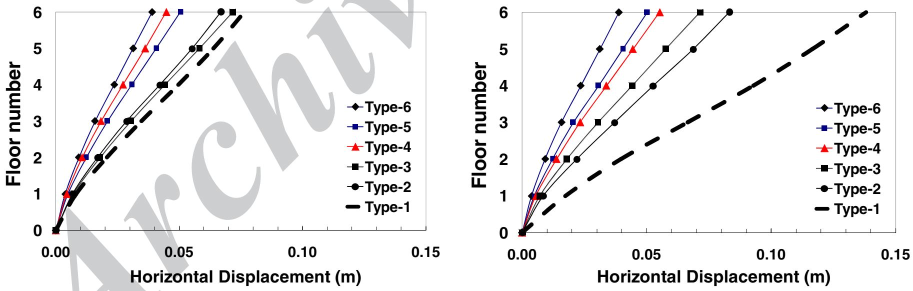
(a) (b)

**Figure 7** Maximum horizontal displacements of the SCS ten-storey R/C building: (a) *x* direction, (b) *y* direction.



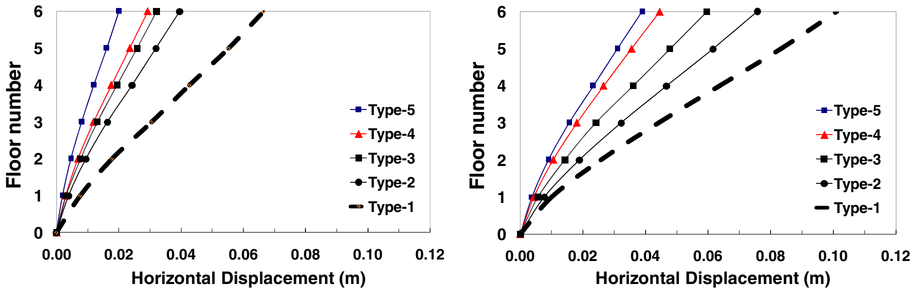
(a) (b)

**Figure 8** Maximum horizontal displacements of the RCS ten-storey R/C building: (a) *x* direction, (b) *y* direction.



(a) (b)

**Figure 9** Maximum horizontal displacements of the SCS six-storey R/C building: (a) *x* direction, (b) *y* direction.



(a) (b)

**Figure 10** Maximum horizontal displacements of the RCS six-storey R/C building: (a) *x* direction, (b) *y* direction.

Again, it is shown that type-5 provides minimum horizontal displacement among all the other SW positions. However, SW position type-1 provides maximum horizontal displacement in both the *x* and *y* directions. This is attributed to the small distance between parallel SWs. Again, as the distance between parallel SWs increases, both flexural and torsional stiffnesses of the building increase, and consequently, the corresponding horizontal displacements decrease. Thus, it is easily seen that positioning of SWs on the perimeter of R/C building (type-5) is the most appropriate position for minimum horizontal displacement.

### Effect of SW thickness on vibration periods

To take into account the effect of SW thickness, three different SW thicknesses are considered: 0.40, 0.35, and 0.30 m. Since types-6 and -5 of SW positions are seen to be the most suitable for SCS and RCS R/C buildings, respectively, type-6 is used in the analysis of the SCS R/C building and type-5 is used for the RCS R/C building. Columns and SWs are modeled as thick shell elements because this modeling provides more accurate results of the period of vibration than other modeling as concluded from the above analysis. In this section, the analysis includes both intact and cracked R/C buildings. The recommended values of coefficients by ECL (HBRC 2008) and many other codes are as follows: 0.25 for slabs, 0.7 for columns, and 0.5 for SWs. For brevity, only the first three periods of vibration of each model for each SW thickness are listed in the following study.

#### *Ten-storey R/C building*

Table 6 lists the periods of vibration for the intact ten-storey SCS building with different SW thicknesses for type-6 of SW position. Table 7 lists the periods of vibration for the cracked ten-storey SCS building with different SW thicknesses for type-6 of SW position. In Tables 6 and 7, the results of the ETABS program show that increasing the SW thickness leads to a small increase in fundamental period for the intact R/C building and considerable increment in fundamental period of the cracked R/C building. Also, it is shown that Equation 1 does not take the thickness of SWs into consideration and provides one value for fundamental period of vibration for different SW thicknesses. However, Equations 2 and 4 provide different values of fundamental periods of vibration for different SW thicknesses. Also, it is easily seen that Equations 1 and 2 underestimate the

**Table 6 Periods of vibration for the intact ten-storey SCS building (in seconds)**

| SW position | SW thickness (m) | Mode shape | ETABS | Equation 1 | Equation2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | (1) Fl(*y*) | 0.996 | 0.673 | 0.840 | 1.261 |
| | | (2) Fl(*x*) | 0.859 | - | - | - |
| | | (3) Tors | 0.683 | - | - | - |
| | 0.35 | (1) Fl(*y*) | 1.025 | 0.673 | 0.898 | 1.348 |
| | | (2) Fl(*x*) | 0.877 | - | - | - |
| | | (3) Tors | 0.707 | - | - | - |
| | 0.30 | (1) Fl(*y*) | 1.059 | 0.673 | 0.970 | 1.456 |
| | | (2) Fl(*x*) | 0.898 | - | - | - |
| | | (3) Tors | 0.735 | - | - | - |

**Table 7 Periods of vibration for the cracked ten-storey SCS building (in seconds)**

| SW position | SW thickness (m) | Mode shape | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | (1) Fl(*y*) | 1.244 | 0.673 | 0.840 | 1.261 |
| | | (2) Fl(*x*) | 1.125 | - | - | - |
| | | (3) Tors | 0.794 | - | - | - |
| | 0.35 | (1) Fl(*y*) | 1.301 | 0.673 | 0.898 | 1.348 |
| | | (2) Fl(*x*) | 1.166 | - | - | - |
| | | (3) Tors | 0.834 | - | - | - |
| | 0.30 | (1) Fl(*y*) | 1.368 | 0.673 | 0.970 | 1.456 |
| | | (2) Fl(*x*) | 1.213 | - | - | - |
| | | (3) Tors | 0.882 | - | - | - |

fundamental period, but Equation 4 overestimates it for different SW thicknesses. Furthermore, Equation 1 provides misleading values of fundamental period for both intact and cracked R/C buildings. Equation 2 gives a conservative value of fundamental period of vibration for the intact flat-plate R/C buildings. However, Equation 4 is the best one among the three equations to estimate approximately the fundamental period of vibration for the cracked flat-plate R/C buildings. Using cracked buildings increases the fundamental period greatly, by 25% for 0.4 -m SW thickness and by 30% for a 0.3-m SW thickness more than those of the intact building.

Table 8 lists the periods of vibration for the intact ten-storey RCS building with different SW thicknesses for type-5 of SW position. Table 9 lists the periods of vibration for the cracked ten-storey RCS building with different SW thicknesses for type-5 of SW position. Indeed, Tables 8 and 9 confirm the results found in Tables 6 and 7 for the SCS R/C building. Again, Equation 4 is the best one among the three empirical equations to estimate approximately the fundamental periods of vibration for the cracked flat-plate R/C buildings. However, Equation 1 provides misleading values of fundamental period for both intact and cracked R/C buildings. Also, from Tables 6, 7, 8, and 9, it is shown

**Table 8 Periods of vibration for the intact ten-storey RCS building (in seconds)**

| SW position | SW thickness (m) | Mode shape | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-5 | 0.40 | (1) Fl(*y*) | 0.857 | 0.673 | 0.840 | 0.977 |
| | | (2) Fl(*x*) | 0.789 | - | - | - |
| | | (3) Tors | 0.583 | - | - | - |
| | 0.35 | (1) Fl(*y*) | 0.885 | 0.673 | 0.898 | 1.044 |
| | | (2) Fl(*x*) | 0.810 | - | - | - |
| | | (3) Tors | 0.605 | - | - | - |
| | 0.30 | (1) Fl(*y*) | 0.917 | 0.673 | 0.970 | 1.128 |
| | | (2) Fl(*x*) | 0.835 | - | - | - |
| | | (3) Tors | 0.630 | - | - | - |

**Table 9 Periods of vibration for the cracked ten-storey RCS building (in seconds)**

| SW position | SW thickness (m) | Mode shape | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-5 | 0.40 | (1) Fl(*y*) | 1.019 | 0.673 | 0.840 | 0.977 |
| | | (2) Fl(*x*) | 0.969 | - | - | - |
| | | (3) Tors | 0.654 | - | - | - |
| | 0.35 | (1) Fl(*y*) | 1.067 | 0.673 | 0.898 | 1.044 |
| | | (2) Fl(*x*) | 1.010 | - | - | - |
| | | (3) Tors | 0.687 | - | - | - |
| | 0.30 | (1) Fl(*y*) | 1.125 | 0.673 | 0.970 | 1.128 |
| | | (2) Fl(*x*) | 1.058 | - | - | - |
| | | (3) Tors | 0.726 | - | - | - |

**Table 10 Periods of vibration for the intact six-storey SCS building (in seconds)**

| SW position | SW thickness (m) | Mode shape | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | (1) Fl(*y*) | 0.806 | 0.470 | 0.803 | 1.164 |
| | | (2) Fl(*x*) | 0.696 | - | - | - |
| | | (3) Tors | 0.581 | - | - | - |
| | 0.35 | (1) Fl(*y*) | 0.826 | 0.470 | 0.859 | 1.245 |
| | | (2) Fl(*x*) | 0.709 | - | - | - |
| | | (3) Tors | 0.600 | - | - | - |
| | 0.30 | (1) Fl(*y*) | 0.850 | 0.470 | 0.928 | 1.344 |
| | | (2) Fl(*x*) | 0.724 | - | - | - |
| | | (3) Tors | 0.622 | - | - | - |

**Table 11 Periods of vibration for the cracked six-storey SCS building (in seconds)**

| SW position | SW thickness (m) | Mode shape | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | (1) Fl(*y*) | 1.064 | 0.470 | 0.803 | 1.164 |
| | | (2) Fl(*x*) | 0.959 | - | - | - |
| | | (3) Tors | 0.702 | - | - | - |
| | 0.35 | (1) Fl(*y*) | 1.108 | 0.470 | 0.859 | 1.245 |
| | | (2) Fl(*x*) | 0.991 | - | - | - |
| | | (3) Tors | 0.737 | - | - | - |
| | 0.30 | (1) Fl(*y*) | 1.158 | 0.470 | 0.928 | 1.344 |
| | | (2) Fl(*x*) | 1.026 | - | - | - |
| | | (3) Tors | 0.778 | - | - | - |

that only Equation 4 takes into account the area of the building in calculating the fundamental period of vibration.

### *Six-storey R/C building*

Table 10 lists the periods of vibration for the intact six-storey SCS building with different SW thicknesses for type-6 of SW position. Table 11 lists the periods of vibration for the cracked six-storey SCS building with different SW thicknesses for type-6 of SW position. Also, Table 12 lists the periods of vibration for the intact six-storey RCS building with different SW thicknesses for type-5 of SW position. Table 13 lists the periods of vibration for the cracked six-storey RCS building with different SW thicknesses for type-5 of SW position. Indeed, Tables 10, 11, 12, and 13 confirm the results found in the 'Ten-storey R/C building' subsection under 'Effect of SW thickness on vibration periods' section. Again, Equation 4 is the best one among the considered three equations to estimate approximately the fundamental periods of vibration for the cracked flat-plate R/C buildings. However, Equation 1 gives misleading values of fundamental period for both intact and cracked R/C buildings. Also, only Equation 4 takes into account the area of the building in calculating the fundamental period of vibration.

## Effect of SW thickness on base shear ratio

In the ECL (HBRC 2008), all buildings should be designed to resist the horizontal elastic response spectrum which is adopted depending on the location of the city. Two elastic response spectrums are presented by this code: the first suits all regions in Egypt, while the second suits coastal cities along the Mediterranean Sea and extends 40 km parallel to the shore. Figure 11 depicts the type 1 elastic response spectrum noting that the type 2 spectrum carries the same features as type 1 except for the governing period values ($T_B$, $T_C$, and $T_D$).

According to the ECL (HBRC 2008), the main analysis method for calculating seismic loads is the response spectrum using elastic structural model and design spectrum. The design spectrum is less than what can be obtained from the elastic response spectrum due to the expected nonlinear behavior of structures. Other alternatives for calculating the seismic loads are the simplified modal response spectrum (equivalent static load) method or time history analysis method. The

**Table 12 Periods of vibration for the intact six-storey RCS building (in seconds)**

| SW position | SW thickness (m) | Mode shape | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-5 | 0.40 | (1) Fl(*y*) | 0.712 | 0.470 | 0.803 | 0.902 |
| | | (2) Fl(*x*) | 0.656 | - | - | - |
| | | (3) Tors | 0.505 | - | - | - |
| | 0.35 | (1) Fl(*y*) | 0.734 | 0.470 | 0.859 | 0.964 |
| | | (2) Fl(*x*) | 0.673 | - | - | - |
| | | (3) Tors | 0.525 | - | - | - |
| | 0.30 | (1) Fl(*y*) | 0.759 | 0.470 | 0.928 | 1.041 |
| | | (2) Fl(*x*) | 0.693 | - | - | - |
| | | (3) Tors | 0.548 | - | - | - |

**Table 13 Periods of vibration for the cracked six-storey RCS building (in seconds)**

| SW position | SW thickness (m) | Mode shape | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-5 | 0.40 | (1) Fl(*y*) | 0.888 | 0.470 | 0.803 | 0.902 |
| | | (2) Fl(*x*) | 0.843 | - | - | - |
| | | (3) Tors | 0.579 | - | - | - |
| | 0.35 | (1) Fl(*y*) | 0.929 | 0.470 | 0.859 | 0.964 |
| | | (2) Fl(*x*) | 0.878 | - | - | - |
| | | (3) Tors | 0.610 | - | - | - |
| | 0.30 | (1) Fl(*y*) | 0.978 | 0.470 | 0.928 | 1.041 |
| | | (2) Fl(*x*) | 0.918 | - | - | - |
| | | (3) Tors | 0.646 | - | - | - |

ECL (HBRC 2008) limits the application of the simplified modal response spectrum (SMRS) method to buildings which are regular in both plan and elevation and having a fundamental period equal to or less than either 4 $T_C$ or 2 s. The basic base shear $F_b$ (at foundation level) according to the SMRS method can be obtained as follows:

$$F_b = \frac{S_d(T_i)\lambda W}{g}, \tag{5}$$

wherein $S_d$ is the design response spectrum, $T_i$ is the fundamental period of the building in the direction of analysis, $\lambda$ is a correction factor which is equal to 0.85 if $T_i \leq 2\ T_C$ and is equal to 1.0 if $T_i > 2\ T_C$, $W$ is the total considered weight of the structure (dead weight + fraction of live loads according to the building function), and $g$ is the gravity acceleration.

In this study, a comparison is carried out between the base shear ratio obtained by the ETABS program and those obtained using the SMRS method using vibration periods calculated by Equations 1, 2, and 4. Base shear ratio is defined as seismic base shear of the building ($F_b$) divided by its weight ($W$). The design response spectrum is used for all studied buildings. It is assumed that the R/C buildings are for dwellings and are located in cities with low seismicity ($a_g = 0.10$ g) on soil type D. The correction factor $\lambda$ is 1.0, and the total considered weight of the building = dead loads + 0.25 × live loads.

To take into account the effect of SW thickness, three different SW thicknesses are considered: 0.40, 0.35, and 0.30 m. Again, columns and SWs are modeled as thick shell elements because this modeling provides more accurate results of period of vibration than other modeling as concluded from the above analysis. Also, the analysis includes both intact and cracked R/C buildings. The recommended values of coefficients by ECL (HBRC 2008) and many other codes are as follows: 0.25 for slabs, 0.7 for columns, and 0.5 for SWs. For brevity, only the results of types-6 and -5 of SW positions which are found to be suitable for SCS and RCS R/C buildings, respectively, are tabulated.

### Ten-storey R/C building

Table 14 lists the base shear ratio for the intact ten-storey SCS building with different SW thicknesses for type-6 of SW position. Also, Table 15 lists the base shear

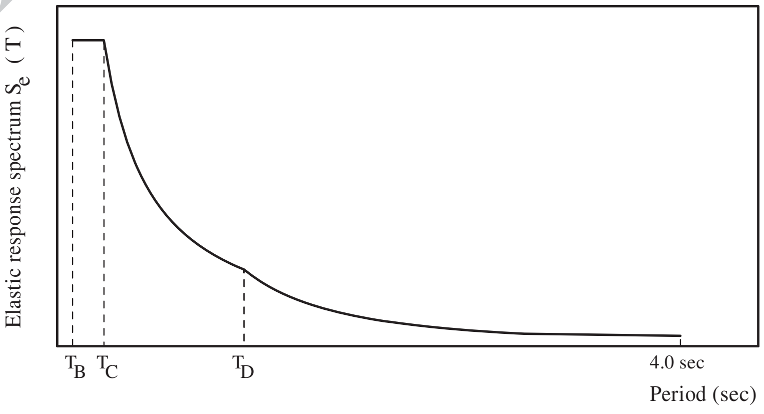


**Figure 11** Type 1 elastic response spectrum (HBRC 2008).

**Table 14 Base shear ratio for the intact ten-storey SCS building**

| SW position | SW thickness (m) | Direction | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | *x* | 0.0152 | 0.0279 | 0.0223 | 0.0149 |
| | | *y* | 0.0145 | 0.0279 | 0.0223 | 0.0149 |
| | 0.35 | *x* | 0.0145 | 0.0279 | 0.0209 | 0.0139 |
| | | *y* | 0.0136 | 0.0279 | 0.0209 | 0.0139 |
| | 0.30 | *x* | 0.0141 | 0.0279 | 0.0193 | 0.0129 |
| | | *y* | 0.0132 | 0.0279 | 0.0193 | 0.0129 |

**Table 15 Base shear ratio for the cracked ten-storey SCS building**

| SW position | SW thickness (m) | Direction | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | *x* | 0.0137 | 0.0279 | 0.0223 | 0.0149 |
| | | *y* | 0.0134 | 0.0279 | 0.0223 | 0.0149 |
| | 0.35 | *x* | 0.0133 | 0.0279 | 0.0209 | 0.0139 |
| | | *y* | 0.0127 | 0.0279 | 0.0209 | 0.0139 |
| | 0.30 | *x* | 0.0129 | 0.0279 | 0.0193 | 0.0129 |
| | | *y* | 0.0117 | 0.0279 | 0.0193 | 0.0129 |

ratio for the cracked ten-storey SCS building with different SW thicknesses for type-6 of SW position. In Tables 14 and 15, the results of the ETABS program show that decreasing SW thickness leads to a small decrease in the base shear ratio in both intact and cracked R/C buildings due to the decrease in building stiffness. Also, cracked buildings have less base shear ratios than intact buildings by approximately 10% for different SW thicknesses. Furthermore, it is shown that Equation 1 provides one value for base shear ratio for different SW thicknesses because it does not take the thickness of SWs into consideration. However, Equations 2 and 4 provide different values of base shear ratios for different SW thicknesses. Also, it is easily seen that Equations 1 and 2 highly overestimate the base shear ratios, but Equation 4 gives base shear ratios approximately similar to that obtained by the ETABS program for the intact building but overestimates it for the cracked building for different SW thicknesses. Indeed, Equation 1 provides base shear ratios approximately twice as those obtained by the ETABS program for a 0.3-m SW thickness. However, Equation 4 is the best one among the three equations to estimate approximately the base shear ratios for both the intact and the cracked flat-plate R/C buildings. The results of base shear ratios by Equation 4 do not exceed 10% greater than those of the ETABS program for the cracked building.

Table 16 lists the base shear ratio for the intact ten-storey RCS building with different SW thicknesses for type-5 of SW position. Also, Table 17 lists the base shear ratio for the cracked ten-storey RCS building with different SW thicknesses for type-5 of SW position. In Tables 16 and 17, the results of the ETABS program show that decreasing SW thickness leads to a small decrease in the base shear ratio in both intact and cracked R/C buildings due to a decrease in building stiffness. Also, cracked buildings have less base shear ratios than intact buildings by approximately 10% for different SW thicknesses. Furthermore, it is shown that Equation 1 gives one value for base shear ratio for different SW thicknesses. However, Equations 2 and 4 provide different values of base shear ratios for different SW

**Table 16 Base shear ratio for the intact ten-storey RCS building**

| SW position | SW thickness (m) | Direction | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-5 | 0.40 | *x* | 0.0168 | 0.0279 | 0.0223 | 0.0192 |
| | | *y* | 0.0162 | 0.0279 | 0.0223 | 0.0192 |
| | 0.35 | *x* | 0.0162 | 0.0279 | 0.0209 | 0.0180 |
| | | *y* | 0.0156 | 0.0279 | 0.0209 | 0.0180 |
| | 0.30 | *x* | 0.0156 | 0.0279 | 0.0193 | 0.0166 |
| | | *y* | 0.0150 | 0.0279 | 0.0193 | 0.0166 |

**Table 17 Base shear ratio for the cracked ten-storey RCS building**

| SW position | SW thickness (m) | Direction | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-5 | 0.40 | *x* | 0.0156 | 0.0279 | 0.0223 | 0.0192 |
| | | *y* | 0.0154 | 0.0279 | 0.0223 | 0.0192 |
| | 0.35 | *x* | 0.0150 | 0.0279 | 0.0209 | 0.0180 |
| | | *y* | 0.0148 | 0.0279 | 0.0209 | 0.0180 |
| | 0.30 | *x* | 0.0144 | 0.0279 | 0.0193 | 0.0166 |
| | | *y* | 0.0142 | 0.0279 | 0.0193 | 0.0166 |

**Table 18 Base shear ratio for the intact six-storey SCS building**

| SW position | SW thickness (m) | Direction | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | *x* | 0.0157 | 0.0399 | 0.0233 | 0.0161 |
| | | *y* | 0.0143 | 0.0399 | 0.0233 | 0.0161 |
| | 0.35 | *x* | 0.0154 | 0.0399 | 0.0218 | 0.0151 |
| | | *y* | 0.0140 | 0.0399 | 0.0218 | 0.0151 |
| | 0.30 | *x* | 0.0150 | 0.0399 | 0.0202 | 0.0140 |
| | | *y* | 0.0136 | 0.0399 | 0.0202 | 0.0140 |

**Table 19 Base shear ratio for the cracked six-storey SCS building**

| SW position | SW thickness (m) | Direction | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | *x* | 0.0133 | 0.0399 | 0.0233 | 0.0161 |
| | | *y* | 0.0128 | 0.0399 | 0.0233 | 0.0161 |
| | 0.35 | *x* | 0.0129 | 0.0399 | 0.0218 | 0.0151 |
| | | *y* | 0.0124 | 0.0399 | 0.0218 | 0.0151 |
| | 0.30 | *x* | 0.0126 | 0.0399 | 0.0202 | 0.0140 |
| | | *y* | 0.0120 | 0.0399 | 0.0202 | 0.0140 |

thicknesses. Also, it is easily seen that Equations 1 and 2 highly overestimate the base shear ratio, but Equation 4 provides base shear ratios approximately similar to that obtained by the ETABS program for the intact building but overestimates it for the cracked building for different SW thicknesses. Indeed, Equation 1 provides base shear ratios approximately twice as those obtained by the ETABS program for a 0.3-m SW thickness. However, Equation 4 is the best one among the three equations to estimate approximately the base shear ratios for both intact and cracked flat-plate R/C buildings. The results of base shear ratios by Equation 4 do not exceed 25% greater than those of the ETABS program for the cracked building.

### *Six-storey R/C building*

Table 18 lists the base shear ratio for the intact six-storey SCS building with different SW thicknesses for type-6 of SW position. Also, Table 19 lists the base shear ratio for the cracked six-storey SCS building with

**Table 20 Base shear ratio for the intact six-storey RCS building**

| SW position | SW thickness (m) | Direction | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | *x* | 0.0171 | 0.0399 | 0.0233 | 0.0208 |
| | | *y* | 0.0162 | 0.0399 | 0.0233 | 0.0208 |
| | 0.35 | *x* | 0.0166 | 0.0399 | 0.0218 | 0.0195 |
| | | *y* | 0.0157 | 0.0399 | 0.0218 | 0.0195 |
| | 0.30 | *x* | 0.0160 | 0.0399 | 0.0202 | 0.0180 |
| | | *y* | 0.0151 | 0.0399 | 0.0202 | 0.0180 |

**Table 21 Base shear ratio for the cracked six-storey RCS building**

| SW position | SW thickness (m) | Direction | ETABS | Equation 1 | Equation 2 | Equation 4 |
|---|---|---|---|---|---|---|
| Type-6 | 0.40 | *x* | 0.0148 | 0.0399 | 0.0233 | 0.0208 |
| | | *y* | 0.0145 | 0.0399 | 0.0233 | 0.0208 |
| | 0.35 | *x* | 0.0143 | 0.0399 | 0.0218 | 0.0195 |
| | | *y* | 0.0140 | 0.0399 | 0.0218 | 0.0195 |
| | 0.30 | *x* | 0.0138 | 0.0399 | 0.0202 | 0.0180 |
| | | *y* | 0.0135 | 0.0399 | 0.0202 | 0.0180 |

different SW thicknesses for type-6 of SW position. Tables 20 and 21 list the base shear ratio of six-storey RCS buildings with different SW thicknesses for type-5 of SW position. In Tables 18, 19, 20, and 21, the results of the ETABS program show that decreasing the SW thickness leads to a small decrease in the base shear ratio in both intact and cracked R/C buildings due to low building stiffness. Also, cracked buildings have less base shear ratio than intact buildings by approximately 20% for different SW thicknesses. Again, it is shown that Equation 1 gives one value for base shear ratio for different SW thicknesses and different building cross sections because it does not take the building plan area into consideration. However, Equations 2 and 4 provide different values of base shear ratios for different SW thicknesses. Also, it is easily seen that Equations 1 and 2 highly overestimate the base shear ratio, but Equation 4 provides base shear ratios that are approximately similar to those obtained by the ETABS program for the intact building but overestimates it for the cracked building for different SW thicknesses. Indeed, Equation 1 provides base shear ratios approximately three times as those obtained by the ETABS program for a 0.3-m SW thickness. However, Equation 4 is the best one among the three equations to estimate approximately the base shear ratios for both intact and cracked flat-plate R/C buildings. The results of base shear ratios by Equation 4 do not exceed 25% greater than those from the ETABS program for SCS and do not exceed 40% greater than those from the ETABS program for RCS for the cracked buildings.

## Conclusions

The objective of this study was to identify an appropriate FE model of SW dominant flat-plate R/C buildings, which can be used to study its dynamic behavior. Three-dimensional models were generated and analyzed to check the adequacy of different formulas to estimate structural period of vibration via analyzing the dynamic response of low- and medium-height R/C buildings with different cross-sectional plans and different SW positions and thicknesses. In the present study, it is assumed that all materials are elastic for the intact buildings. Smeared cracks are assumed for cracked elements. Based on the numerical results, the following conclusions are drawn for SW dominant flat-plate R/C buildings:

1. Modeling of R/C buildings using block elements provides the most appropriate representation since it gives accurate results of fundamental periods and consequently reliable seismic forces. The finer the mesh, the more accurate the results.
2. Modeling of R/C buildings using shell elements for both columns and SWs provides acceptable results of fundamental periods (error does not exceed 10%). However, modeling of R/C buildings using frame elements for columns and/or SWs overestimates the fundamental periods of R/C buildings.
3. It is recommended to use FE programs instead of empirical formulas, e.g., Marc and Mentat, ETABS, SAP2000, to estimate the fundamental periods of R/C buildings. The ETABS program provides more accurate results than those obtained by SAP2000.
4. Empirical formulas often overestimate or underestimate fundamental periods of R/C buildings. Equation 1 provides misleading values of fundamental period for both intact and cracked R/C buildings. However, Equation 4 is the best one among the considered three equations to estimate approximately the fundamental periods of the cracked flat-plate R/C buildings. Also, only Equation 4 takes into account the area of the building in calculating the fundamental period of vibration.
5. Increasing the distance between parallel SWs changes the fundamental vibration mode from torsional to flexural mode due to an increase in torsional stiffness of the building.
6. Positioning of SWs on the perimeter of the R/C building or forming a closed section is the best position for minimum horizontal displacement under seismic loads due to high flexural and rotational stiffnesses of the buildings.

Further study is needed to investigate the modeling of asymmetric flat-plate R/C buildings under different seismic loads.

## Competing interests

The author declares that there are no competing interests.

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MA-BA is an associate professor who got his PhD degree in 2002 from The Earthquake Research Institute, The University of Tokyo, Japan and became an associate professor in 2007. He has published more than 20 papers in the field of structural engineering, structural analysis, earthquake engineering, and structural health monitoring using changes in static and dynamic characteristics. He is a previous member of the Japan Society of Civil Engineers. He reviewed many papers for international journals. He is an associate professor of Structural Engineering at the Civil Engineering Department of Assiut University, Egypt. He is currently working as an engineering counselor at the general project management of Al-Jouf University, Saudi Arabia.

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