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Effect of Shear Wall Openings on the Fundamental Period of Shear Wall Structures

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Abstract**—**A common approach in resisting lateral forces is the use of reinforced concrete shear walls in buildings. These walls represent the main elements to resist the lateral forces due to their large strength and stiffness. However, such walls may contain many openings due to functional requirements, and this may largely affect the overall lateral stiffness of them. It is thus of prime importance to quantify the effect of openings on the dynamic performance of the shear walls. SAP2000 structural analysis program is used as a main source after verifying the results. This study is made by using linear elastic analysis. The results are compared to ASCE7-16 code empirical equations for estimating the fundamental period of shear wall structures. Finally, statistical regression is used to fit an equation for estimating the increase in the fundamental period of shear-walled regular structures due to windows openings in the walls.

Keywords**—**Concrete, earthquake-resistant design, finite element, fundamental period, lateral stiffness, linear analysis, modal analysis, rayleigh, SAP2000, shear wall, ASCE7-16.

I. Introduction

REINFORCED concrete shear walls are the most frequently used form of lateral resisting structural elements. Shear wall systems are the most appropriate systems in moderate sized buildings up to 20 floors, and in low-rise construction [1]. They are not preferred in the case of high-rise buildings. The shear wall systems are not preferred in the open spaced structures or glazed exterior walls due to the architectural functions [2]. These systems offer good resisting performance and good stability for low- to mid-rise buildings because of small drift between floors and small un-damped fundamental period that make the buildings more rigid. Although the internal base shear force in this type of construction is generally more than that of the other resisting systems, the capacity of the shear wall systems can accept this large force induced by earthquakes. In the reality, patterns of windows or doors openings in the walls are required due to architectural functions. If this happens with very large openings, walls are coupled to each other by beams, referred as coupled shear walls. Also, these openings cause a variation in relative stiffness of wall with openings that extend from that of a solid wall to that of a flexible frame [3].

II. Fundamental Period

The structure oscillates back and forth due to free vibration when it is subjected to a horizontal displacement due to lateral load such as earthquake [4]. The time needed to complete one cycle of free vibration is known as the natural period, and its inverse is called the natural frequency. The fundamental period is a key parameter in defining the dynamic behavior of the structure. There are three techniques that are used to determine the natural period of the building: Theoretical models, numerical models and empirical formulas.

Empirical formulas are used first in the design process because the properties of the yet designed building cannot be computed, and the properties which are known at this stage are related to the construction material used, the lateral bracing system, and the height of the building. Since mass and stiffness of the building are required in theoretical and numerical models; these methods are usually done after preliminary design because they require more details in the calculations. The simplest model in applied theoretical method is called a single degree of freedom model. For this model the un-damped natural period can be calculated as:

$$T = 2\pi\sqrt{\frac{m}{k}} \tag{1}$$

where T is the fundamental period in seconds (s), m is the mass of the structure, and k the stiffness of the structure.

In theoretical models many methods were developed for calculating the fundamental period like Dunkerley's method [5], and the most famous of these methods is Rayleigh's method where this method is used as a rational method and the time period can be determined as:

$$T = \sqrt{\frac{4\pi^2}{g}\left(\frac{\sum_{i=1}^{n} w_i\,\delta_i^2}{\sum_{i=1}^{n} P_i\,\delta_i}\right)} \tag{2}$$

where n is the number of floors, w_i is the seismic weight of floor i, δ_i is the lateral displacement of each floor under the effect of P_i, g is the gravitational acceleration, and P_i is the total static load distributed over the area of the diaphragms.

III. Literature Review

Many studies were carried out [6]-[8] on the behavior of shear wall systems as the main bracing systems in the buildings, especially the fundamental period of shear wall structures. Most of these studies [6]-[8] did not concentrate on the effect of openings in the shear walls, and they only compared the measured periods of the buildings to the calculated period by using different codes empirical formulas. Some of researchers [6] tried to improve the codes formulas

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for estimating the fundamental period by using regression analysis to derive more conservative equations.

Sozen derived a theoretical equation by simplifying an equivalent uniform cantilever beam model with fixed distance between floors and equal floors masses, where the flexural behavior of the walls dominates the lateral response and the lateral bracing system is the shear wall system [6].

$$T = 6.25\frac{h_w}{l_w}n\sqrt{\frac{wh_s}{gpE_c}} \quad (3)$$

where h_w is the total wall height, l_w is the wall length, n is the number of floors, w is the unit floor weight, h_s is the typical floor height, g is the gravity acceleration, E_c is the concrete modulus of elasticity, and p is the ratio of wall area to tributary floor area in the direction of period calculation ($p = \sum\frac{A_w}{A_f}$, where $A_w = l_w t_w$, t_w is the wall thickness, and A_f is the tributary floor plan area for wall in the direction of calculation).

Goel and Chopra derived an equation for estimating the fundamental period of shear wall structures based on Dunkerley's method. Equation (4) is the final simplified equation developed based on the behavior of a cantilever beam with flexural and shear deformation [7].

$$T = c'\frac{1}{\sqrt{A'_e}}H \quad (4)$$

$$c' = 40\sqrt{\frac{p}{k\cdot G}} \quad (5)$$

where p is the average mass density (total building mass (m.H) divided by total building volume (A_B.H) and equals $\frac{m}{A_B}$ where m is mass per unit height and A_B is the building plan area), A'_e: is the equivalent shear area expressed as a percentage of A_B. $A'_e = 100.\frac{A_e}{A_B}$, and $A_e = \sum_{i=1}^{NW}\left(\frac{H}{H_i}\right)^2\frac{A_i}{\left[1+0.83\frac{H_i}{D_i}\right]}$, A_e: is the equivalent shear area assuming that the stiffness properties of each wall are uniform over its height, H_i , A_i, and D_i are the height, area and length of shear wall in the direction under consideration of the i^{th} shear wall and NW is the number of shear walls.

Goel and Chopra [7] calculated c' from regression analysis of the measured period data from motions of many buildings (recorded during 8 earthquakes, starting with 1971 San Fernando earthquake and ending with 1994 Northridge earthquake). Although c' could be calculated from building properties, the variation in properties shall be accounted among various buildings and for difference between building behavior and its idealization. By regression analysis, the upper limit of c' was found to be equal to 0.0026 and the lower limit was found to be equal to 0.0019.

Lee et al. proposed (6) by regression analysis on the basis of the measured period data from motions of real shear wall buildings [8].

$$T_R = \frac{0.4\left(H^{0.2}\right)}{\sqrt{L_w}-0.5} \quad (6)$$

where H is the height of the building in meters, and L_w is the total wall length in meter aligned in the direction of calculation.

Balkaya and Kalkan proposed (7) by using nonlinear regression analysis for numerical analysis results by using ETABS program for 80 different shear wall buildings in their local region built using tunnel form techniques with no beams or columns and only using cast in-place walls and slabs with almost the same thickness [9]. This equation can be applied onto two cases, squared one with the building long side divided by the short side is less than 1.5, and otherwise the buildings are considered as rectangular ones.

$$T = Ch^{b1}\beta^{b2}{\rho_{as}}^{b3}{\rho_{al}}^{b4}{\rho_{min}}^{b5}j^{b6} \quad (7)$$

where h is the total height of the building in meters, β is the ratio of long side to short side dimension, ρ_{as} is the ratio of short side shear wall area to total floor area, ρ_{al} is the ratio of long side shear wall area to total floor area, ρ_{min} is the ratio of minimum shear wall area to total floor area, and j is the polar moment of inertia of the plan $(I_{xx} + I_{yy})$.

The numerical coefficients values are as shown in Table I.

TABLE I
NUMERICAL COEFFICIENT VALUES FOR (7)

coefficient	Squared	Rectangular
C	0.158	0.001
b1	1.40	1.455
b2	0.972	0.17
b3	0.812	-0.485
b4	1.165	-0.195
b5	-0.719	0.17
b6	0.130	-0.094

Challah et al. derived (8) based on Dunkerley's method for determination of the fundamental period of shear wall buildings [10]. This considers only the flexural deformation for a cantilever beam model and ignores the shear deformation. It also adopts the assumptions of uniform floors heights and uniform floors masses.

$$T_f = 1.8n(n+1)\sqrt{\frac{mh^3}{EI}} \quad (8)$$

where n is the number of floors, h is the height of the building, m is the mass of typical floor, E is the concrete modulus of elasticity, and I is the moment of inertia of bracing shear walls system.

IV. NUMERICAL STUDY DESCRIPTION

This study is conducted by using two different regular floor layouts with different floor numbers and different central window opening sizes in shear walls. These two cases represent the two extremes with low to high ratio of shear walls. These layouts are modeled in SAP2000 structural analysis program [11]. The goals of this numerical study are to identify how the openings in the concrete shear walls affect the lateral stiffness and hence affect the fundamental period of those buildings. Such information is vital for the simplification of the modeling of the building. Finally, an equation will be derived to estimate the increase in the fundamental period of the building due to central window openings.

TABLE II
DIMENSIONS OF STRUCTURAL MEMBERS

Structural members type	Dimensions
Flat plate slabs thickness	20
Shear walls thickness	20
columns for 2 floors buildings	25×25
columns for 3 floors buildings	30×30
columns for 6 floors buildings	45×45
columns for 9 floors buildings	55×55
columns for 12 floors buildings	60×60

In this study, the concrete compressive strength is 24 MPa, and the end conditions for both columns and shear walls are assumed to be fixed supports. Linear modal analysis is used to find the fundamental period of these structures. The superimposed dead load is assumed to be 4 kN/m^2 as it is a typical value in Palestine. The mass source which it is taken into account in the calculation of the fundamental period is from dead load plus superimposed dead load only. The characteristics of all structural members that will be used are shown in Table II. In this table the dimensions are calculated according to the ACI318-14 code [12].

Fig. 1 shows the first building layout with dimensions between columns and shear walls in mm with total floor plan area equals to 121 m^2, while Fig. 2 shows the second building layout in mm with total floor plan area equals to 361 m^2.

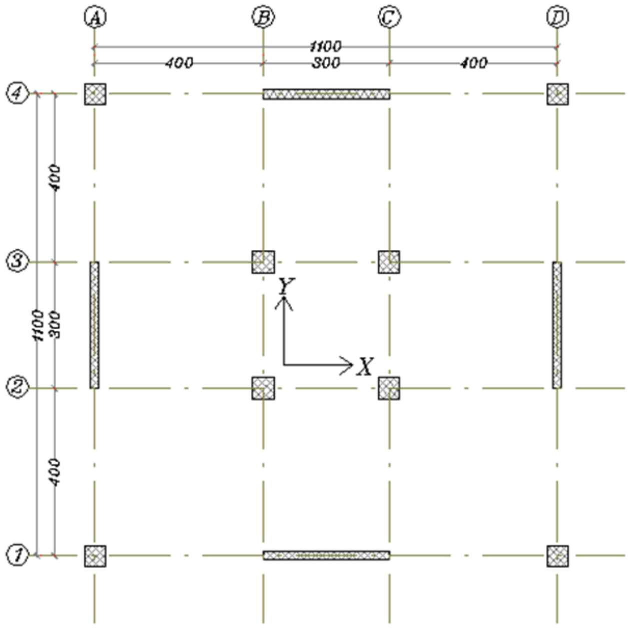

Fig. 1 First building layout

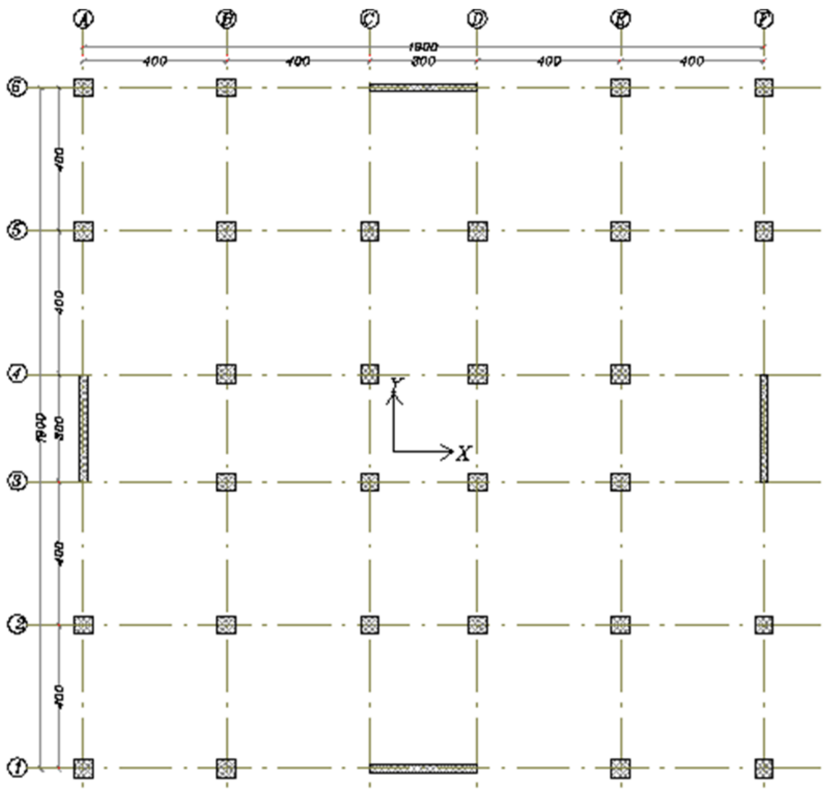

Fig. 2 Second building layout

V. Numerical Study Matrix of Parameters

The main parameters will include opening ratio in walls R_O, and moment of inertia ratio plus area ratio between the total walls with no openings to the total columns F; F can be calculated by using (9). Note that the effect of wall aspect ratio (wall height H/wall length B) appears in the F factor. The range of R_O is from 0% to 36% because this range includes the common practice window openings in reality. The range of H is from 6 m to 36 m as it is the most common buildings height in Palestine and B is fixed and equals to 3 m. The range of F is from 6.000 to 0.005.

$$F = \frac{\sum I_w}{\left(\sum \frac{H}{B}\right)^3 \sum I_c} + \frac{\sum A_w}{\left(\sum \frac{H}{B}\right) \sum A_c} \tag{9}$$

where I_w, I_c are the walls and columns moments of inertias respectively in the direction of the calculation, A_w, A_c are the walls and columns areas respectively, and H, B are the wall height and length respectively.

The model number in all matrices is named as: layout number- F, dimension of opening.4% R_O represents 0.6×0.6 m central window opening area, while 9% R_O represents 0.9×0.9 m central window opening area. Also, 16% R_O represents 1.20×1.20 m central window opening area, and 25% R_O represents 1.50×1.50 m central window opening area. Finally, 36% R_O represents 1.80×1.8 0m central window opening area. And all of these opening areas are from the total wall area. The results of the lateral displacement Δ are calculated due to assumed 1 kN/m^2 uniform distributed lateral load on the slabs for each floor.

The displacement ratio is defined as R_D. This R_D represents the lateral displacement of the top final slab in the case of openings in shear walls divided on the lateral displacement of the same top floor in the case of no wall openings. The period ratio is known as (R_T) and it represents the period of the building in the case of openings in shear walls divided by the period of the case of no openings in the walls.

VI. Results and Discussion for Both Layouts

The final results of the lateral displacement, lateral displacement ratio, period and period ratio are tabulated in Table III for the first layout and in Table IV for the second layout.

Fig. 3 shows the relationship between the central window opening ratio versus the lateral displacement ratio, and Fig. 4 shows the central window opening ratio versus period ratio, and these figures are for the first building layout. As shown in these figures, when the number of floors increased the effect of openings on the lateral displacement and on the fundamental period of shear wall structures decreased. This is because the shear wall undergoes a cantilever mode of deformation, where the effect of shear deformation is neglected by increasing the height of the building because of increasing the H/B of these walls. Table V summarizes the maximum opening ratio that can be neglected and the corresponding height of the building obtained from Fig. 3 if 5% is taken as a negligible variation in displacement ratio. Typical squared window opening of size 1.30×1.30 m which is commonly used in practice and represents 19% R_O of the total wall side area increases the R_D of the first layout to about 1.54, 1.27, 1.12, 1.07, and 1.06 in buildings heights equal to 6 m, 9 m, 18 m, 27 m, and 36 m respectively.

TABLE III
Final Results for the First Building Layout

Model number	Total height of building (m)	Δ (mm)	R_D	T (second)	R_T
1L-6.000,0	6	0.60	1.00	0.142	1.00
1L-6.000,6	6	0.63	1.05	0.146	1.03
1L-6.000,9	6	0.70	1.17	0.153	1.08
1L-6.000,12	6	0.81	1.35	0.165	1.16
1L-6.000,15	6	1.13	1.88	0.194	1.37
1L-6.000,18	6	1.71	2.85	0.238	1.68
1L-1.049,0	9	2.02	1.00	0.255	1.00
1L-1.049,6	9	2.08	1.03	0.259	1.02
1L-1.049,9	9	2.21	1.06	0.266	1.04
1L-1.049,12	9	2.43	1.20	0.279	1.09
1L-1.049,15	9	3.05	1.51	0.312	1.22
1L-1.049,18	9	4.16	2.06	0.366	1.44
1L-0.081,0	18	15.19	1.00	0.699	1.00
1L-0.081,6	18	15.36	1.01	0.701	1.00
1L-0.081,9	18	15.74	1.04	0.709	1.01
1L-0.081,12	18	16.47	1.08	0.725	1.04
1L-0.081,15	18	18.30	1.20	0.764	1.09
1L-0.081,18	18	21.49	1.41	0.829	1.19
1L-0.030,0	27	44.60	1.00	1.220	1.00
1L-0.030,6	27	44.93	1.01	1.226	1.00
1L-0.030,9	27	45.68	1.02	1.230	1.01
1L-0.030,12	27	47.13	1.06	1.251	1.03
1L-0.030,15	27	50.60	1.13	1.295	1.06
1L-0.030,18	27	56.62	1.27	1.366	1.12
1L-0.018,0	36	92.48	1.00	1.796	1.00
1L-0.018,6	36	93.07	1.00	1.798	1.00
1L-0.018,9	36	94.40	1.02	1.807	1.01
1L-0.018,12	36	96.91	1.05	1.826	1.02
1L-0.018,15	36	102.67	1.11	1.876	1.04
1L-0.018,18	36	112.59	1.22	1.953	1.09

The previous opening ratios of negligible variation can be found using period ratio curve from Fig. 4. Table VI summarizes this maximum negligible opening ratio and the corresponding height of the building.

Note that if the lateral displacement ratio curve will be used as a main curve to conclude results, then the results that will be obtained from this curve shall be less than those obtained from period ratio curve. Thus, if the lateral displacement ratio is ok, then the period ratio has to be ok due to the nature of the relationship between the period and the lateral stiffness.

Fig. 5 shows the relationship between the central window opening ratio versus the lateral displacement ratio, and Fig. 6 shows the central window opening ratio versus period ratio, and these figures are for second building layout. Table VII summarizes the maximum opening ratio in shear walls that may be neglected in the models and the corresponding height of the modeled building obtained from Fig. 5, and these results obtained if a 5% is taken as a negligible variation in displacement ratio.

TABLE IV
FINAL RESULTS FOR THE SECOND BUILDING LAYOUT

Model number	Total height of building (m)	Δ (mm)	R_D	T (second)	R_T
2L-1.714,0	6	1.68	1.00	0.231	1.00
2L-1.714,6	6	1.76	1.05	0.237	1.03
2L-1.714,9	6	1.91	1.14	0.248	1.07
2L-1.714,12	6	2.25	1.34	0.268	1.16
2L-1.714,15	6	2.90	1.73	0.307	1.33
2L-1.714,18	6	4.40	2.62	0.376	1.63
2L-0.300,0	9	5.11	1.00	0.395	1.00
2L-0.300,6	9	5.24	1.03	0.400	1.01
2L-0.300,9	9	5.50	1.05	0.410	1.04
2L-0.300,12	9	6.08	1.19	0.432	1.09
2L-0.300,15	9	7.16	1.40	0.471	1.19
2L-0.300,18	9	9.51	1.86	0.544	1.38
2L-0.023,0	18	29.28	1.00	0.949	1.00
2L-0.023,6	18	29.55	1.01	0.954	1.01
2L-0.023,9	18	30.08	1.03	0.963	1.01
2L-0.023,12	18	31.27	1.07	0.983	1.04
2L-0.023,15	18	33.43	1.14	1.020	1.07
2L-0.023,18	18	37.71	1.29	1.089	1.15
2L-0.009,0	27	75.81	1.00	1.571	1.00
2L-0.009,6	27	76.23	1.01	1.575	1.00
2L-0.009,9	27	77.02	1.02	1.583	1.01
2L-0.009,12	27	78.83	1.04	1.602	1.02
2L-0.009,15	27	82.14	1.08	1.639	1.04
2L-0.009,18	27	88.49	1.17	1.708	1.09
2L-0.005,0	36	147.75	1.00	2.242	1.00
2L-0.005,6	36	148.36	1.00	2.245	1.00
2L-0.005,9	36	149.72	1.01	2.252	1.00
2L-0.005,12	36	152.18	1.03	2.273	1.01
2L-0.005,15	36	156.99	1.06	2.312	1.03
2L-0.005,18	36	166.13	1.12	2.383	1.06

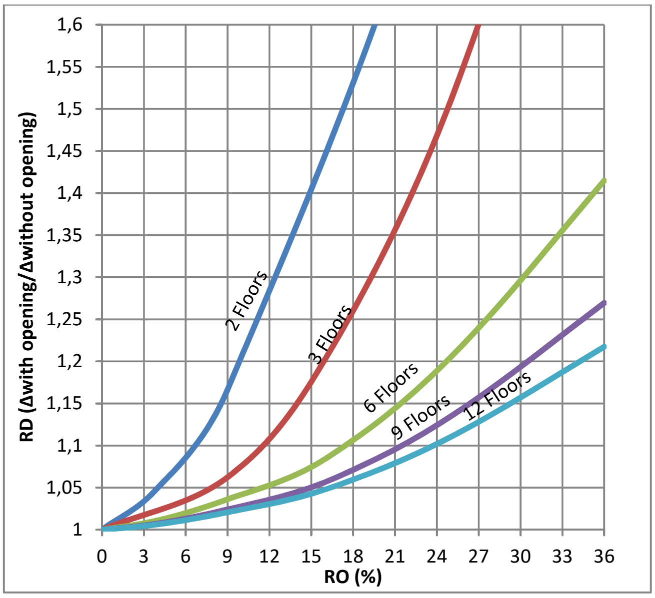

Fig. 3 Opening ratio versus displacement ratio for different number of floors for the first building layout

TABLE V
THE MAXIMUM RO WHICH CAUSES NEGLIGIBLE VARIATION IN RD AND THE CORRESPONDING BUILDING HEIGHT FOR THE FIRST BUILDING LAYOUT

Building height (m)	RO (%)
6	4.00
9	8.00
18	11.50
27	15.00
36	16.50

TABLE VI
THE MAXIMUM RO WHICH CAUSES NEGLIGIBLE VARIATION IN RT AND THE CORRESPONDING BUILDING HEIGHT FOR THE FIRST BUILDING LAYOUT

Building height (m)	RO (%)
6	6.50
9	10.00
18	18.00
27	22.00
36	27.00

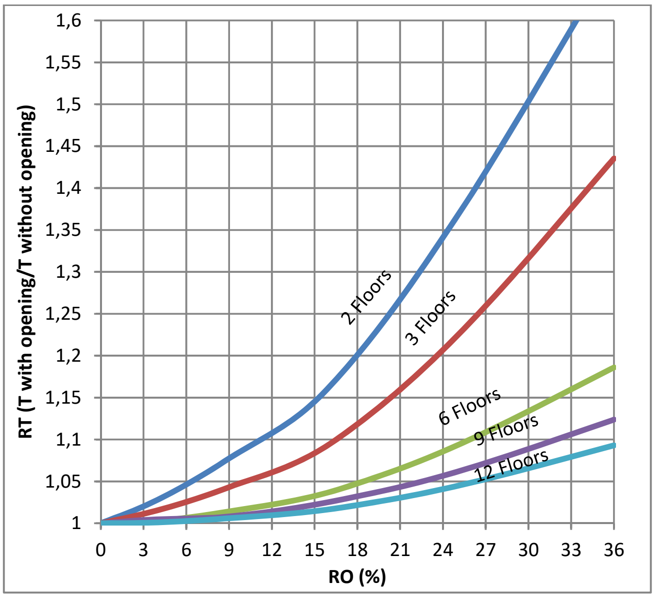

Fig. 4 Opening ratio versus period ratio for different number of floors for the first building layout

For typical squared window opening of size 1.30×1.30 m which is commonly used in the common practice and represents 19% R_O of the total wall side area increases the R_D of the second layout to about 1.42, 1.26, 1.08, 1.05, and 1.04 in buildings heights equal to 6 m, 9 m, 18 m, 27 m, and 36 m respectively.

TABLE VII
THE MAXIMUM RO WHICH CAUSES NEGLIGIBLE VARIATION IN RD AND THE CORRESPONDING BUILDING HEIGHT FOR THE SECOND BUILDING LAYOUT

Building height (m)	RO (%)
6	4.00
9	9.00
18	13.00
27	18.00
36	22.00

Fig. 6 shows the relationship between opening ratio and period ratio for the second building layout. Table VIII summarizes the maximum negligible opening ratio and the corresponding height of the building for the second layout.

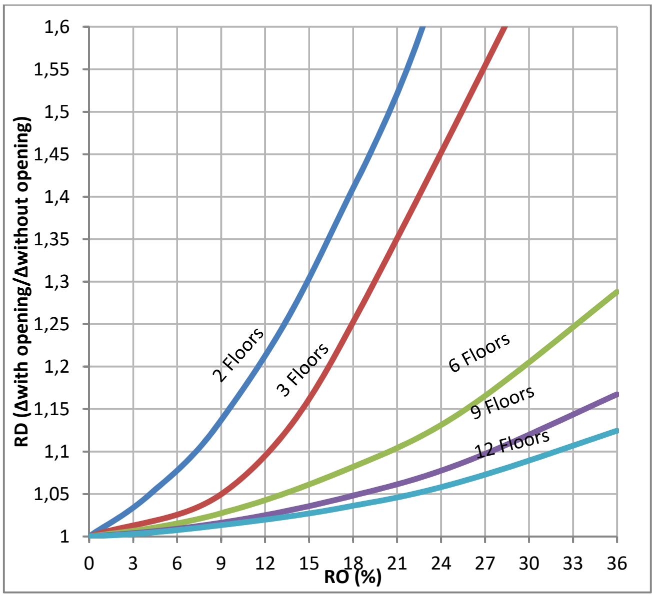

Fig. 5 Opening ratio versus displacement ratio for different number of floors for the second building layout

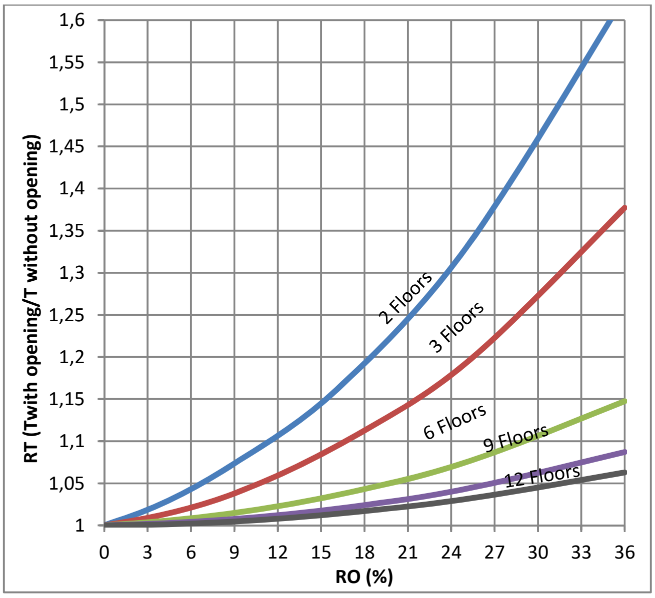

Fig. 6 Opening ratio versus period ratio for different number of floors for the second building layout

TABLE VIII
THE MAXIMUM RO WHICH CAUSES NEGLIGIBLE VARIATION IN RT AND THE CORRESPONDING BUILDING HEIGHT FOR THE SECOND BUILDING LAYOUT

Building height (m)	RO (%)
6	7.00
9	11.00
18	19.00
27	27.00
36	32.00

VII. Comparison to ASCE7-16 Empirical Code Formula

ASCE7-16 code has two equations that can be used to approximate the values of the fundamental period of shear wall structures. Equation (10) is the general equation and (11) is the more detailed equation [13].

$$T_{a-general} = C_t h^n \tag{10}$$

$$T_{a-detailed} = \frac{C_q}{\sqrt{C_w}} h^n \tag{11}$$

where C_t and n are numerical values depending on the structural system, in shear wall system they are 0.0488 and 0.75 respectively, h is the building height, and C_q is a numerical value and it is equal 0.00058 in meter units.

$$C_w = \frac{100}{A_B} \sum_{i=1}^{x} \frac{A_i}{\left[1+0.83\left(\frac{h_n}{D_i}\right)^2\right]} \tag{12}$$

where A_B is the area of base of structure, A_i is the web area of shear wall i, D_i is the length of shear wall, x is the number of shear walls in building effective in resisting lateral forces in the direction under consideration.

To compare the results from finite element to those from ASCE code, the ratio (R_{TM}), which represents the period from modal analysis divided by the code approximate period value, (T modal analysis/C_u T_a) is drawn against opening ratio (R_O). According to Table 12.8-1 in ASCE7-16, the coefficients for upper limits in calculating period are 1.40, 1.50, 1.60, and 1.70, where these values depend on the design spectral response acceleration parameter at 1 second, which is known as S_{D1} [10].

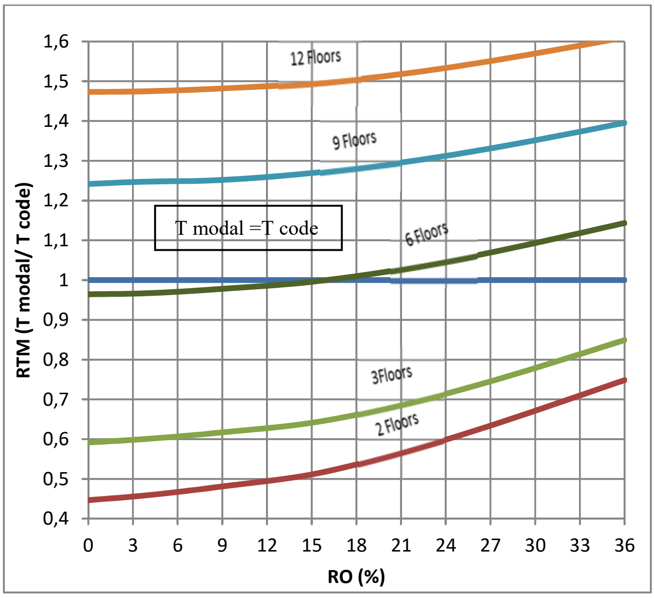

Fig. 7 Opening ratio versus period ratio (T modal/T code) for different number of building heights for the first building layout using general code formula

Fig. 7 shows the relationship for the first building layout while Fig. 8 shows the same relationship for the second building layout and these ratios are between opening ratios in walls versus the ratio between the periods from the modal analysis divided on the code value where C_u is taken as 1.7. From these figures it can be seen that the code value for estimating the fundamental period is not satisfied in low-rise low-rise shear wall buildings with openings as the code gives an approximate value of the period larger than the real one. Thus, when the period from the code general equation will be used, the design against earthquake load may be unreal in low-rise shear wall buildings.

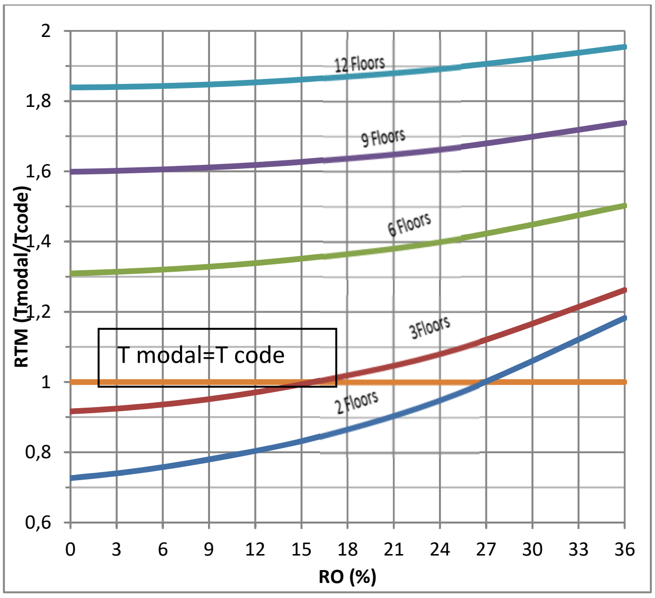

Fig. 8 Opening ratio versus period ratio (T modal/T code) for different number of building height for the second building layout using general code formula

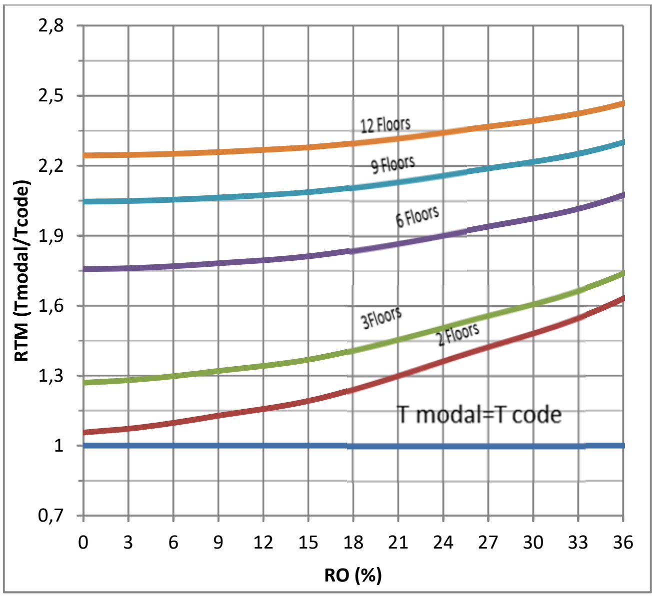

Fig. 9 Opening ratio versus period ratio (T modal/T code) for different number of building height for the first building layout using detailed code formula

When (11) is used to approximate the fundamental period, it will give more conservative results that leads to real design of the structure against the earthquake force; although it requires a lot of work compared to the general equation to calculate the factors in detailed equation.

Fig. 9 shows the results for the first building layout, while Fig. 10 shows the results for the second layout. These results are the relationships between opening ratios in walls versus the ratios between the periods from the modal analysis divided on the multiple of the code formula (11) values by C_u , and C_u is taken as 1.7. From these figures, it can be noticed that for all building heights the modal analysis will give larger values more than that of the detailed formula (11) values. Thus, the detailed code equation will lead to more conservative design against the earthquake forces, and it should be used in conceptual design phase instead of general code equation.

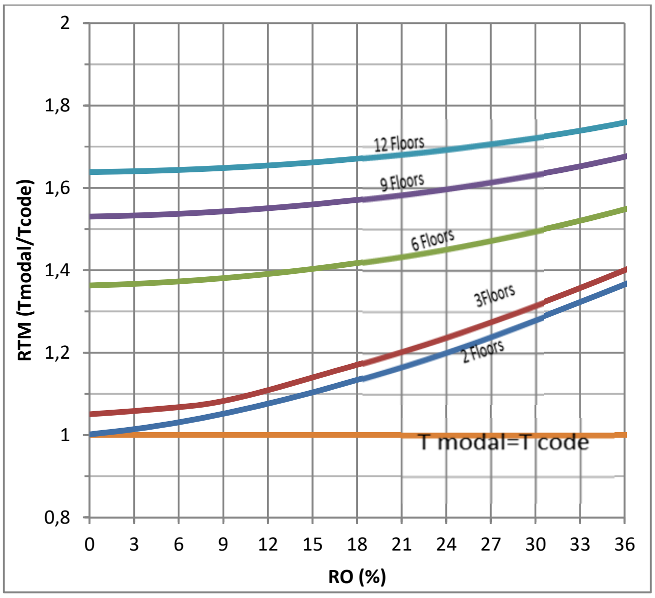

Fig. 10 Opening ratio versus period ratio (T modal / T code) for different number of building height for the second building layout using detailed code formula

VIII. Data Fitting

It is desired to have equation for period ratio that can be used to predict the increase in the fundamental period of shear wall regular buildings due to central window openings in walls for similar conditions. MATLAB software is used to develop such equation. After that, other independent results of finite element simulations data are used to verify the fitted equation. The primary variables for the equation were mentioned in Section V and they were selected to be the opening ratio (R_O), and moment of inertia ratio plus area ratio between the total walls with no openings to the total columns (F).

From Figs. 4-6, the suitable equation form is a polynomial function, but to make the equation looks simple and can be applied easily with acceptable error, the trend of the developed (15) will be a linear function of R_O. The final equation is:

$$1.00 \le R_T = m_1 R_O + m_2 \le 1.60 \qquad (13)$$

where R_T is the period ratio, it represents the period of building with openings in shear walls divided by the period of the same building in the case of no openings, and R_O is the opening ratio, it represents the area of the opening in the wall to the area of the wall. m_1 and m_2 are numerical coefficients. The values of these coefficients are calculated using th:

$$m_1 = 0.0123\, F^{0.3631} \tag{14}$$

$$m_2 = 0.9533\, F^{-0.008} \tag{15}$$

where F is the moment of inertia ratio plus area ratio between the total walls with no openings to the total columns $\left(\frac{\sum I_W}{\left(\sum\frac{H}{B}\right)^3 \sum I_c} + \frac{\sum A_W}{\left(\sum\frac{H}{B}\right)\sum A_c}\right)$, and H and B represent the shear wall height and shear wall length respectively for all walls in the building.

Equation (13) can be used as multiplication factor to the first mode fundamental period value of buildings when neglecting openings in shear walls modeling to modify the value of period, to consider the effect of opening in period calculation.

Fig. 11 shows the comparison between the finite element results and (13) results for the set of results which are used in the derivation of the equation. It is noticed that the differences between the SAP2000 results and the proposed (13) results are accepted with maximum percentage of relative error equals to 12.75%. The slope of the trend line equals 0.94, and the coefficient of determination (R^2) equals 0.92.

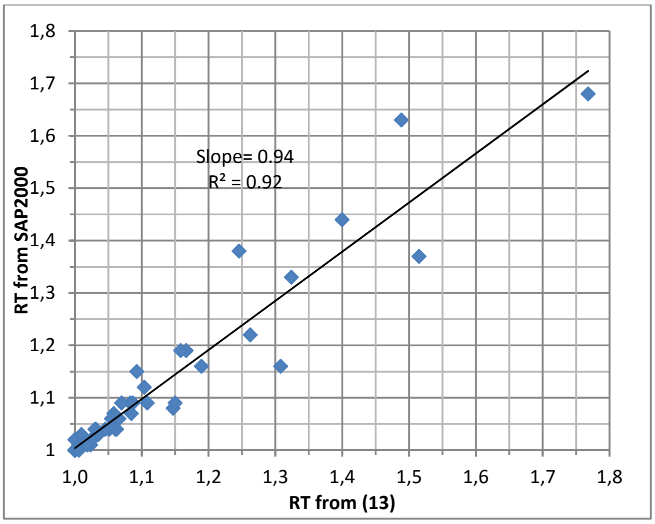

Fig. 11 Comparison between period ratio (RT) from both SAP2000 and (13) for data used in derived equation

For further verification and to check the validity of (13), independent data points from different cases were generated by using SAP2000. Table IX shows the matrix of parameters for eight independent models where the first four models are using the first building layout slab geometry and properties and the second eight models are using the second building layout slab geometry and properties.

TABLE IX
MATRIX OF PARAMETERS FOR THE INDEPENDENT MODELS

Model number	F factor
1L-0.534,13.7	0.534
1L-0.333,10	0.333
1L-0.145,17	0.145
1L-0.091,8.5	0.091
2L-0.153,4.2	0.153
2L-0.095,16	0.095
2L-0.051,11.7	0.051
2L-0.030,13.5	0.030

Table X shows the comparison between the finite element results and (13) results for the independent data used in verified equation. The maximum relative error noticed equals to 9.80% which it is accepted.

TABLE X
COMPARISON OF RESULTS BETWEEN SAP2000 AND THE DEVELOPED EQUATION FOR INDEPENDENT MODELS

Model number	R_T from SAP2000	R_T from (13)	Relative error $100\%.\frac{R_{T\,SAP}-R_{T\,Equatio}}{R_{T\,SAP}}$
1L-0.534,13.7	1.11	1.16	-4.50
1L-0.333,10	1.03	1.05	-1.94
1L-0.145,17	1.13	1.16	-2.65
1L-0.091,8.5	1.01	1.01	0.00
2L-0.153,4.2	1.1	1.00	9.09
2L-0.095,16	1.02	1.12	-9.80
2L-0.051,11.7	1.03	1.04	-0.97
2L-0.030,13.5	1.00	1.04	-4.00

IX. CONCLUSION

Based on this study, the following conclusions are drawn:

1- Openings in concrete shear walls have a major effect on the fundamental period and on the lateral stiffness of the structures. The case of always neglecting these openings in the modeling phase can lead to unreal design against earthquake load.

2- The effect of wall openings on the fundamental period of shear wall structures depend on the height of the building, and thus the (H/B) of the shear walls. If (H/B) of the walls is increased, then the value of the opening ratio that may be considered negligible will also increase.

3- The opening ratio which can be neglected in the modeling phase is in the range from 4.00% in 6 m building height to 22.00% in 36 m building height.

4- The ASCE7-16 general code formula for approximating the fundamental period gives values larger than modal analysis in low-rise shear wall buildings, while the detailed formula gives values lesser than modal analysis. When the general code equation is used in the equivalent static forces method, it may lead to unreal design against earthquake loads in the case of shear walls with openings in buildings and it is preferred to use the detailed equation in equivalent static forces method.

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